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LIFE CYCLE ASSESSMENT OF GRAIN MAIZE IN INTENSIVE, CONVENTIONAL CROP PRODUCTION SYSTEM

Małgorzata Holka, Jerzy Franciszek Bieńkowski*, Janusz Jankowiak, Radosław Dąbrowicz

Institute for Agricultural and Forest Environment, Polish Academy of Sciences,
Department of Agricultural Systems, 60-809 Poznań, Bukowska 19, Poland
*Corresponding author. E-mail: jerzy.bienkowski@isrl.poznan.pl

ABSTRACT

The life cycle assessment (LCA as defined by Caffrey and Veal in 2013) of grain maize production was performed in two large-scale farms, located in the Wielkopolska region (Poland) during the years 2011-2013. The stages of crop cultivation and harvest exerted biggest influence on the values of acidification, eutrophication and global warming potentials. Abiotic depletion potential for mineral resources was most dependent on the processes of manufacturing and transport of means of production. The largest source of environmental threats came from fertilization. Transport of grain for sale had a small share in the total impact category indicators' values. The value of land use by grain maize in the studied farms was lower than the averages for Poland and the European Union (EU). Normalization of impact indicators showed that lifecycle environmental burden of grain maize production, was mainly associated with soil acidification followed by eutrophication and global warming.

Key words: maize production, environmental burden, impact category indicators, life cycle assessment.

INTRODUCTION

Maize is one of the most-produced cereals in the world (FAOSTAT, 2016). In Poland, it is also an agriculturally important crop. In 2014, the acreage of grain maize in the country was about 678 thousand hectares, and production amounted to 4.5 Mt (CSO, 2016). Maize grain is an important feed because of the high nutritive value in the feeding of pigs and poultry, as well as being a highly demanded feedstock for food purposes, such as the production of corn flour, grits and starch. The popularity of this crop is due to the high yield per unit area, low requirements for soil quality and for its position in the crop rotation. Its high production of dry matter is associated with high water requirements. As a thermophilic plant it also needs appropriate thermal conditions. Availability of many varieties, with different earliness of maturing depending on the climatic conditions of the region, contributes to its successful cultivation throughout the country. In terms of yield, this crop is known as being responsive to technical inputs what makes this feature particularly useful to be employed by intensive production technologies. In comparison to other cereals, it has high nutrient requirements and is more susceptible to weeds, diseases and pests. Therefore, in grain maize cropping it is necessary to use the appropriate level of fertilization and chemical protection (Sulewska, 2007).

The processes of an intensive agricultural production have an adverse impact on the environment. The use of large amounts of fertilizers, plant protection products, diesel and machinery contributes to the depletion of non-renewable resources and environmental pollution. Emissions of nitrogen gaseous forms such as ammonia (NH_3) and nitrogen oxides (NO_x) lead to soil and water acidification and water eutrophication (Bieńkowski, 2010; Filipek and Skowrońska, 2013; Marcinkowski, 2010). The release of nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) to the atmosphere contributes to the greenhouse effect (Bouwman et al., 2002). The share of agriculture in the global anthropogenic gaseous emissions amounts to 93% of NH_3, 36% of N_2O, 27% of NO_x, 49% of CH_4, 15% of CO_2 (Norse, 2003). In the EU Action Plan for achieving the reduction of gaseous pollutants was assumed that emissions of

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greenhouse gases emissions (GHG) from agriculture should be reduced by 30 percent below 2005 levels by 2030 (European Council Conclusions, 2014).

In efforts to achieve the best possible production and economic results, agriculture must take into account the requirements for the prevention of environmental pollution and conservation of natural resources. This creates the need to enhance and update the state of knowledge on the impact of agricultural production on the environment. Environmental threats may not result only from processes on the farm, but also from those that are associated with manufacturing the means of production and product disposal management. A comprehensive assessment of the potential environmental risks throughout the production chain, from the extraction and processing of raw materials, through the manufacturing, distribution and utilization, until the final waste management, is made possible by the application of the Life Cycle Assessment (LCA) methodology (Caffrey and Veal, 2013). A review of the recent literature shows that for evaluating the impact of global warming potential in crop production by using the LCA method, one has to take into account apart from emissions of GHG also the possibility of avoiding GHG emission due to CO_2 sequestration in soil (Faber et al., 2012; Knudsen et al., 2013).

By identifying potential environmental effects for each stage of the life cycle of crop production, it is possible to provide a basis for improving technologies that will help to reduce the overall impact of production processes. Due to these reasons the study was undertaken, which was specifically aimed at the assessment of the environmental impact of intensive grain maize production.

MATERIAL AND METHODS

The study was conducted during the years 2011-2013, in two agricultural farms: Trzebiny (Farm 1) and Długie Stare (Farm 2), located in the Leszno district, Wielkopolska region. Farms belong to the Długie Stare Agricultural Company Ltd., which is one of the strategic companies of the state Treasury. The company focuses on the cultivation of cereals, oilseed rape and sugar beet, and an animal production - milk production, breeding pregnant heifers and beef cattle.

Both farms in which studies were conducted have an area of about 500 hectares of agricultural land (AL) (Table 1). They run an intensive agricultural production as is shown by the level of mineral fertilizers (NPK), which is higher than the average in Poland of 129.3 kg ha^{-1} UR (CSO, 2014). Also, total cereal yields were higher, in Farm 1 and Farm 2 by 54.8% and 80.6%, respectively than the average given for the country. The average shares of cereals in the sowing area were 51.9% and 61.1% for Farm 1 and Farm 2, respectively. Industrial plants (roots and oil crops) were cropped on 16.5% of the cultivated area in Farm 2 and on 27.0% in Farm 1. To supply sufficient amount of forage for livestock production, both farms also have a fraction of arable land allocated to annual and perennial fodder crops.

Table 1. Characterization of the studied farms (averages from the years 2011-2013 ± standard deviation)

Specification	Farm 1	Farm 2
Area AL (ha)	492.29	516.24
Livestock density (AU ha^{-1})	0.66 ± 0.01	0.72 ± 0.03
NPK fertilization (kg ha^{-1} AL)	245.94 ± 43.61	269.80 ± 14.71
Cereal yield (dt ha^{-1})	56.4 ± 5.1	65.8 ± 2.3
Cropping pattern (%)		
- cereals	61.1 ± 8.2	51.9 ± 5.5
- root crops	7.9 ± 1.2	12.0 ± 4.4
- oil plants	12.9 ± 10.7	15.0 ± 8.1
- annual fodder crops	13.4 ± 4.6	10.6 ± 6.9
- perennial fodder crops	4.7 ± 4.1	10.5 ± 0

In both farms, maize is grown in two cropping rotations: 1) maize - winter wheat - winter rape - winter wheat and 2) maize - winter rye/triticale - maize - winter rye/triticale. About 30 tones of manure is applied per 1 hectare before maize sowing. During harvest, the straw is chopped and distributed on the field surface. Harvested maize grain is mostly for sale.

The main data source for the analysis came from the documentation on technological operations from the farms and direct interviews with the farms' managers. The data was collected in specially prepared registration forms. They included the details on crop cultivation practices and agricultural production inputs: seeds, fertilizers, plant protection products, fuel, engine fuel, lubricants and agricultural machinery.

The study was performed according to the LCA methodology which is composed of four phases: 1) the goal and scope definition, 2) the inventory analysis, 3) the impact assessment, and 4) the interpretation (Brentrup et al., 2004). In the first phase, research objective, the system boundaries and a functional unit were defined. The inventory analysis, so-called Life Cycle Inventory (LCI), was carried out by collecting input and output data for the analyzed system. This was the basis for performing the Life Cycle Impact Assessment (LCIA) which included: the selection of impact categories and impact category indicators, the classification and the characterization. In the last phase, conclusions were made according to the objective of the study.

LCA was carried out from "cradle-to-farm gate", i.e. from the manufacturing of means of production through to the process of crop cultivation, harvesting and transport of grain to the customer (the company that exports the cereals), without the stage of use and waste management. Two functional units were adopted: 1 hectare - expressing the intensity of the maize production system and 1 ton of grain - which is a measure of its effectiveness. The CML methodology, based on midpoint approach, was applied in the LCIA (Guinée et al., 2002). It included the following impact category indicators: global warming potential (GWP_{100}), so-called "carbon footprint", the eutrophication potential (EP), the acidification potential (AP), the photochemical ozone creation potential (POCP), the abiotic resources depletion potential for minerals (ADP minerals) and for fossil fuels (ADP fossil fuel), as well as land use and pesticide use.

Indicators for the analyzed impact categories: GWP_{100}, AP, EP, POCP, ADP minerals and ADP fossil fuel were calculated by using Equation 1 (Guinée et al., 2002).

$$I_{cat} = \sum_i (m_i \times CF_{cat,i}) \qquad (1)$$

where:

I_{cat} – an impact category indicator;

m_i – the amount of the i-th substance used or emitted;

$CF_{cat,\,i}$ – an impact category characterization factor for the substance.

Another indicator, the use of land resources was expressed by the ratio of an area unit to the yield obtained.

For the purpose of extending a scope of interpretation of the impact assessment of maize for grain, the normalization procedure was carried out. It is an optional step of the LCA which indicates the contribution of the specific impact categories in the general environmental problem. Normalized impact category indicators (NI_{cat}) were calculated as the ratio of the product of the average value of the category indicator for the farms (Icat) and grain maize production in Europe (P) to the value of the reference impact category indicator in Europe in 2005 (IRcat) (Sleeswijk et al., 2008), as shown in the equation below:

$$NI_{cat} = \frac{I_{cat} \times P}{IR_{cat}} \qquad (2)$$

Within the production system boundaries, three stages of the life cycle were distinguished: upstream, core and downstream processes (Figure 1). The analysis of the upstream processes was related to the production and distribution of the means of agricultural production (fertilizers, plant protection products, seeds, energy and agricultural machinery). Core processes included the technological operations of grain maize production on the farm: cultivation, sowing, fertilization, plant protection, harvesting and internal transport. In turn, the analysis of the stage of downstream processes was focused solely on the transport of grain for sale. Environmental impact of each process through the whole production chain was analyzed on the basis of materials and energy inputs, as well as emissions pollutant substances to the environment. The impact category indicators of the upstream processes were calculated by using information from the manufacturers, Agribalyse® database and literature (Audsley et al., 2009; Colomb et al., 2013; Harasim, 2002; Jayasundara et al., 2014). The processes of agricultural production were assessed based on detailed data from the farms. Direct and indirect emissions of N_2O associated with the use of natural and mineral fertilizers, and crop residues were estimated based upon the EMEP/EEA guidebook (EMEP/EEA, 2013) and IPCC (2006) methodology. In the calculations of greenhouse gas emissions from manure, only the gas losses generated at the stage of application of manure on the field were included. Emissions occurring in the buildings and during the storage of manure were attributed to animal production. Due to the nutritional benefits of manure to plants extended over the 2-4 years (as a result of decomposing dung and plant material) environmental impacts accompanying the application of manure were allocated between maize and subsequent crops based on the indicators of N and P fertilizer equivalent values of manure (Maćkowiak, 1999). Gaseous emissions from combustion of fuel during field and transport operation were calculated according to the amount of fuel consumed and emission factors given by Emission Inventory Guidebook (EMEP/EEA, 2013). The carbon sequestration potential within a 100-year time frame associated with maize cultivation was estimated as the equivalent of 10% of carbon inflow surplus in the soil over carbon outflow calculated for cultivation of winter wheat being adopted as the reference crop and with an assumption of all its straw ploughed (Petersen et al., 2013). Data on the production of maize for grain in Poland and Europe were obtained from CSO (2016) and EUROSTAT (2016) databases.

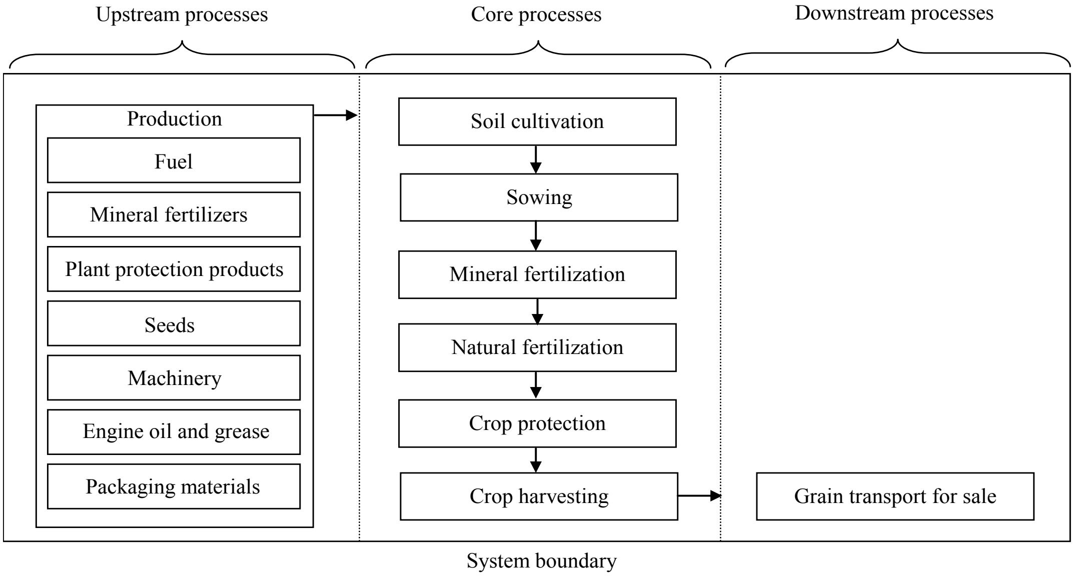


Figure 1. Processes along the life cycle of grain maize production within system boundary

RESULTS AND DISCUSSION

Within the LCI phase, the inventory tables for the system of maize grain production in each of the studied farms were created. The input data were quantities of utilized materials and energy (Table 2). Higher values of impact categories indicators in relation to the functional units of 1 hectare and 1 ton of grain were found in Farm 2 (Table 3). It can be assumed that this was due to differences in the level of fertilization between farms. The average value of the GWP_{100} for both farms per 1 ha amounted to 3041.3 kg CO_2 eq. and in terms of 1 t of grain - 313.9 kg CO_2 eq. These results are comparable with the Canadian ones (Jayasundara et al., 2014). GWP_{100} indicator for different counties of Ontario ranged from 243 to 353 kg CO_2 eq. t^{-1}. Lower emissions of GHG were related to increasing grain yields and the lower N fertilization. In the case of intensive production of maize in China, with a more than 2-fold higher level of N fertilizer and lower grain yield by 2.1 t than in the studied farms, the GWP_{100} amounted to 4436.0 kg CO_2 eq. per 1 ha, and in relation to 1 t of grain - 621.0 kg CO_2 eq. (Chen et al., 2014). In the United Kingdom the value of GWP_{100} indicator was even higher (650 kg CO_2 eq. t^{-1}). In comparison to the studied farms there were also higher values of the EP (2.8 kg SO_2 eq. t^{-1}), the ADP (for minerals and fossil fuels in total 1.3 kg Sb eq.) and land use (0.141 ha t^{-1}). However, the AP indicator (1.6 kg SO_2 eq. t^{-1}) was lower (Williams et al., 2006).

Table 2. Inventory data of agricultural inputs per 1 ha of maize grain production in the analyzed farms (averages from the years 2011-2013)

Specification	Unit	Farm 1	Farm 2
Seeds	kg	25.6	25.8
Nitrogen fertilizer (N)	kg	90.1	117.6
Phosphorus fertilizer (P_2O_5)	kg	9.3	14.3
Potassium fertilizer (K_2O)	kg	0	35.6
Natural fertilizer (N)	kg	169.3	156.7
Natural fertilizer (P_2O_5)	kg	125.1	93.3
Natural fertilizer (K_2O)	kg	306.1	214.5
Herbicides (a.i.)	kg	2.1	2.3
Tractors and mobile machinery	kg	15.0	15.3
Machines and equipment	kg	17.3	12.5
Spare parts and materials for the repair	kg	10.1	8.7
Diesel oil	l	101.6	103.5
Gear oil	l	0.7	0.7
Engine oil	l	1.0	0.7
Liqiud refrigerant and others	l	0.4	0.4
500 kg bulk polypropylene woven bag	kg	0.3	0.1

Table 3. Values of impact category indicators per functional units in the analyzed farms (averages from the years 2011-2013)

Impact category indicator	Farm 1		Farm 2		Mean	
	1 ha	1 t	1 ha	1 t	1 ha	1 t
GWP_{100}, kg CO_2 eq.	2887.4	296.8	3195.3	331.1	3041.3	313.9
AP, kg SO_2 eq.	63.8	6.6	76.4	7.9	70.1	7.2
EP, kg PO_4 eq.	15.6	1.6	18.1	1.9	16.9	1.7
POCP, kg C_2H_4 eq.	0.37	0.04	0.42	0.04	0.40	0.04
ADP minerals, kg Sb eq.	0.006	0.001	0.009	0.001	0.008	0.001
ADP fossil fuel, kg Sb eq.	2.5	0.3	2.9	0.3	2.7	0.3
Land use, ha t^{-1}	-	0.103	-	0.104	-	0.103
Use of plant protection products, kg a.i.	2.1	0.22	2.3	0.23	2.2	0.23

GWP_{100}: global warming potential; AP: acidification potential; EP: eutrophication potential; POCP: photochemical ozone creation potential; ADP minerals: abiotic resources depletion potential for minerals; ADP fossil fuel: abiotic resources depletion potential for fossil fuels.

It has to be noted that the use of manure has a two-way influence in the formation of the GWP values. Greenhouse gaseous emissions from manure lead one side to increase in GWP_{100}. On the other side, the retention of CO_2 in the soil due to increased inflow of organic matter, contributes to its reduction. The difference between anthropogenic GWP and CO_2 sequestration by soils is described as a net GWP_{100}. Taking into account the differences between the GHG emissions, expressed by GWP_{100}, and changes in soil carbon makes the net GWP_{100} of maize production lowered by over 60% compared to baseline levels (Figure 2). Its value in Farm 1 amounted to 878.4 kg CO_2 eq. ha^{-1} and in Farm 2 - 1226.8 kg CO_2 eq. ha^{-1}. The importance of the carbon sequestration process in reducing the greenhouse effect was also emphasized by Krasowicz et al. (2011).

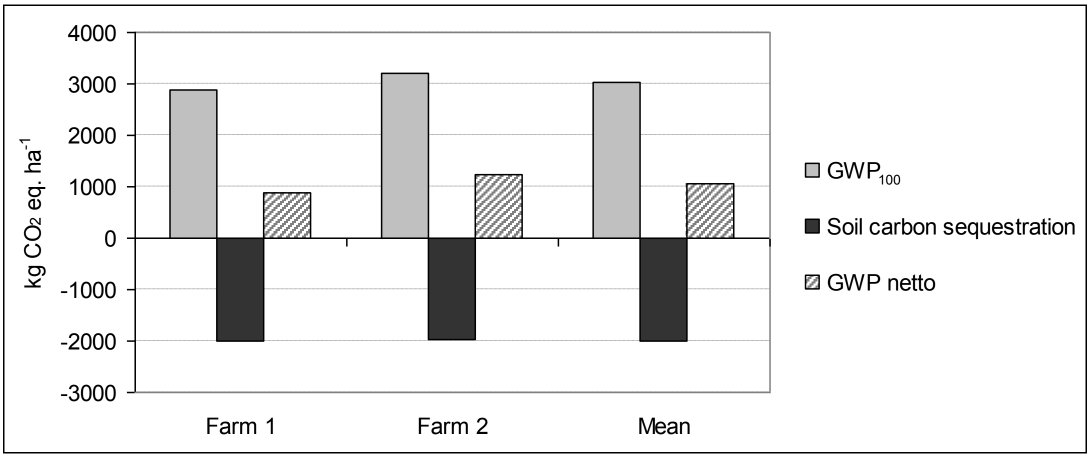
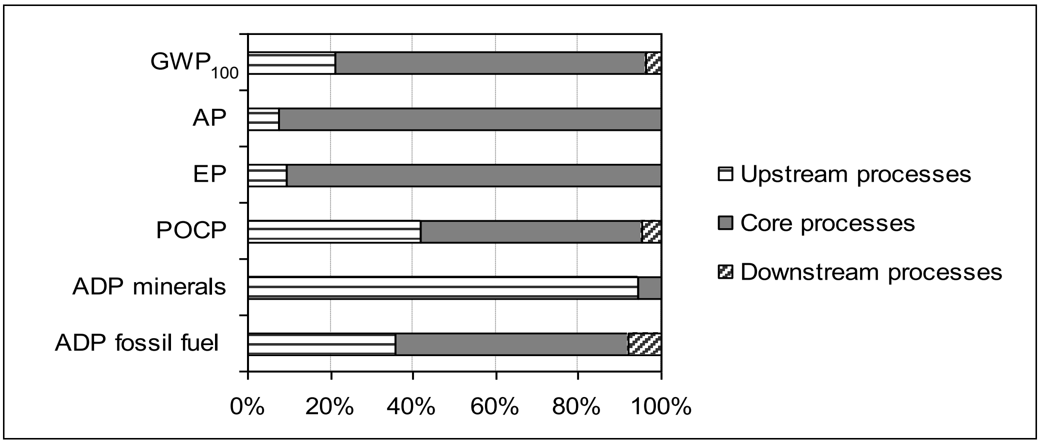


Figure 2. Changes of the GWP_{100} indicator value for grain maize production after accounting for the soil carbon sequestration (averages from the farms for the period 2011-2013)

All of the impact categories indicators, excluding the ADP minerals, depended mainly on the stage of core processes associated with the cultivation and harvesting of maize (Figure 3). While the abiotic resources depletion potential for minerals depended mainly on the stage of upstream processes, namely the production and transport of agricultural means of production. The downstream processes had the lowest contribution to the all analyzed environmental impact potentials. This stage linked with the fuel consumption and the use of machinery in the transport of maize grain, gave only some importance to the indicators of ADP fossil fuel, POCP and GWP_{100}.

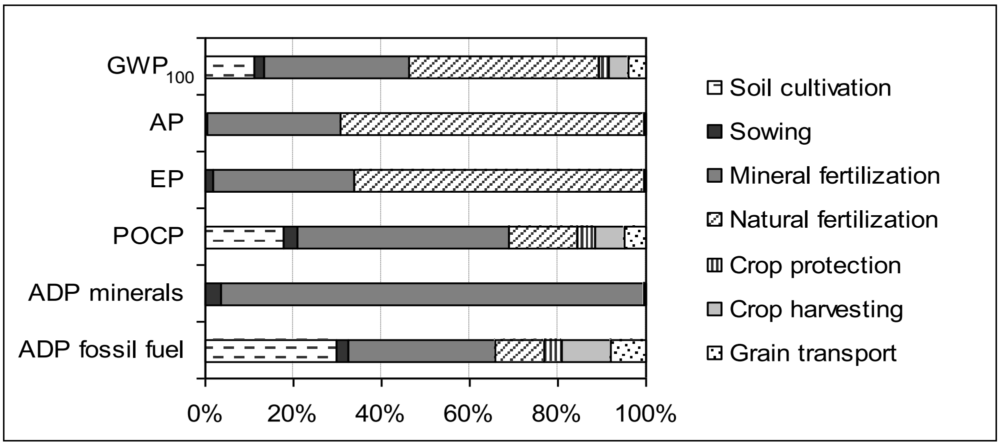


GWP_{100}: global warming potential; AP: acidification potential; EP: eutrophication potential; POCP: photochemical ozone creation potential; ADP minerals: abiotic resources depletion potential for minerals; ADP fossil fuel: abiotic resources depletion potential for fossil fuels.

Figure 3. Shares life cycle stages in the impact category indicators for grain maize production (averages from the analyzed farms for the period 2011-2013)

Within the range of technological processes, natural and mineral fertilization had the greatest impact on the GWP_{100}, AP, and EP.

The values of other impact category indicators (POCP, ADP minerals, ADP fossil fuel) depended mainly on mineral fertilization (Figure 4).



GWP_{100}: global warming potential; AP: acidification potential; EP: eutrophication potential; POCP: photochemical ozone creation potential; ADP minerals: abiotic resources depletion potential for minerals; ADP fossil fuel: abiotic resources depletion potential for fossil fuels.

Figure 4. Shares of different technological operations in the impact category indicators for grain maize production (averages from the analyzed farms for the period 2011-2013)

As shown in Figure 5, emissions associated with the use of natural and mineral fertilizers contributed 39.0% and 22.2% respectively to the total GHG emissions. Emissions from fuel (12.3%), machinery (10.5%) and N fertilizer production (9.5%) were of less importance. The use of plant protection products, seeds, phosphate and potassium fertilizers altogether accounted for only 3.5%. Likewise, a large share of field emissions from N fertilization (25%) and the dominant role of GHG emissions from N fertilizer production (23%) were noticed in New Zealand (MAF, 2011). The life cycle analysis of maize production in the United States showed that the most important source of impact on the greenhouse effect, as well as the acidification and the eutrophication were field emissions followed by technological operations and agrochemicals (Kim et al., 2009).

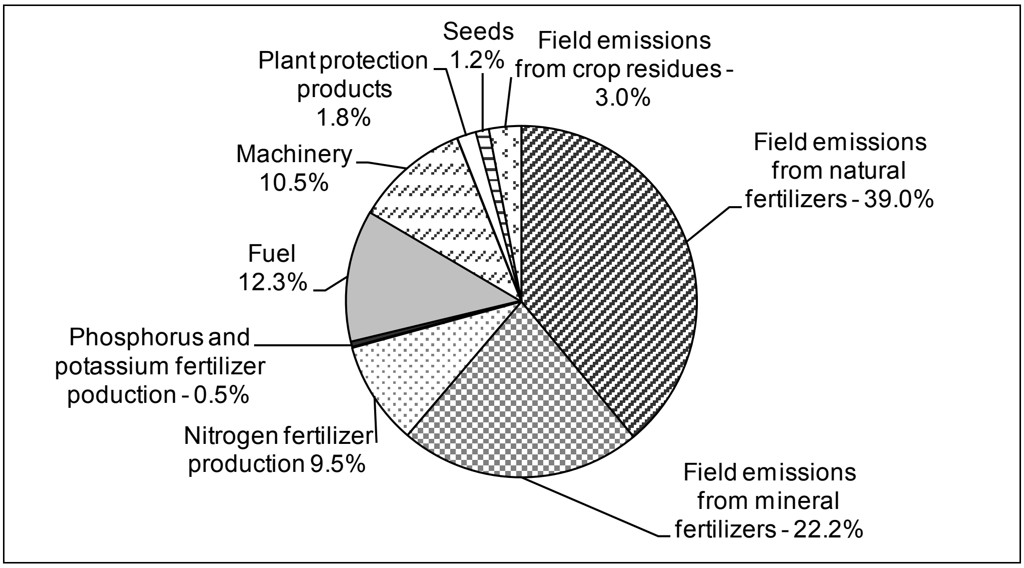


Figure 5. Shares of different sources of GHG emission from grain maize production (averages from the analyzed farms and the years 2011-2013)

The indicator of land use for the production of 1 t of maize grain in farms had an average value of 0.103 ha $year^{-1}$ and was lower when compared to the same indicator calculated for Poland (28.0%) and the European Union (29.5%) (Figure 6). Differences between these indicators could be explained not only by the type of production technology but also by the natural factors such as soil quality, climate, terrain and water conditions, which altogether determine the potential productivity of crops (Schenck et al., 2008).

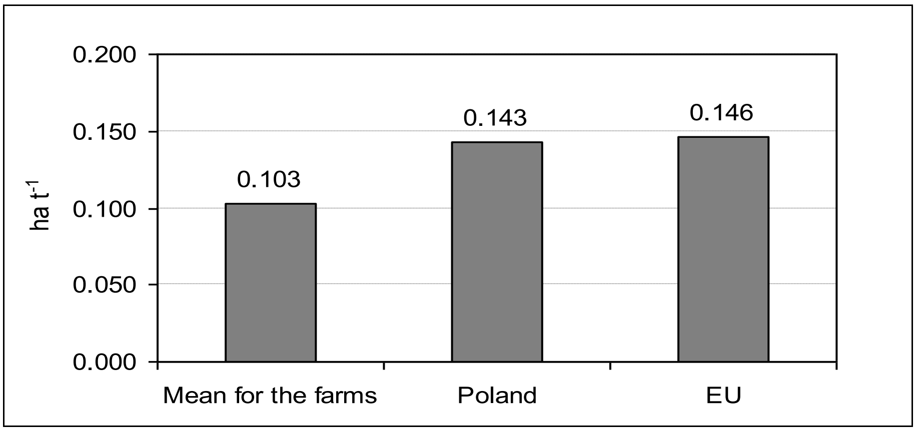
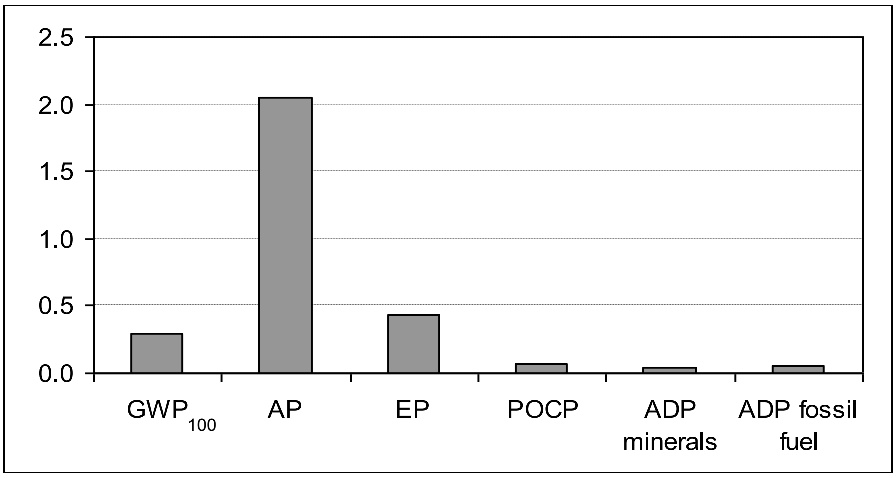


Figure 6. Land use indicator of grain maize production for the analyzed farms, Poland and the EU (averages from the years 2011-2013)

By applying the normalization procedure to the life cycle impact profile of the grain maize soil acidification was identified as the greatest environmental threat for the intensive production system of grain maize (Figure 7). The analyzed production system had also a large potential impact on the eutrophication and the global warming effect.



GWP_{100}: global warming potential; AP: acidification potential; EP: eutrophication potential; POCP: photochemical ozone creation potential; ADP minerals: abiotic resources depletion potential for minerals; ADP fossil fuel: abiotic resources depletion potential for fossil fuels.

Figure 7. Normalized values of the impact category indicators of grain maize production (averages from the analyzed farms for the period 2011-2013)

CONCLUSIONS

Intensive production system of grain maize induces emissions of GHG and other harmful substances to the environment. In view of the requirements of the EU policy on the environmental protection, it is essential to find solutions for reducing the negative impacts of crop cultivation. LCA indicates the sources of environmental impacts throughout the production cycle, thereby allowing the ways of their reduction to be determined.

In grain maize production, the use of natural and mineral fertilizers had the most important contribution to the environmental impacts. Introducing new production technologies and optimization of fertilizer use could be very important factors for reducing emissions from fields and lowering the consumption of raw materials in mineral fertilizer production. Furthermore, we should also seek opportunities to increase the efficiency of industrial processes at the stage of manufacturing of means of production, especially in the production of N fertilizers. Taking action to mitigate the environmental impacts of grain maize production it would also be essential to reduce its adverse effects on soil acidification, followed by eutrophication and the global warming potential.

Crop production is accompanied by a variety of ecosystem services, such as maintaining the soil quality by carbon accumulation. In maize cultivation, carbon inputs to soil from the applied natural fertilizers and plant residues ploughed in may lead to increased soil carbon sequestration which will counteract global warming effects by removing CO_2 from the atmosphere.

The presented data could be a part of the source basis for the environmental assessment of products locally manufactured, for which maize is the primary raw material in industrial processes. LCA of grain maize production, based on the analysis of specific technology, may supplement an inventory data for food-processing industry to characterize the ecological profile of their final products using the LCA approach.

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