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Greenhouse gas emissions from winter wheat cultivation for bioethanol production in Poland

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Abstract
The production of ethanol from winter wheat, in accordance with the EU Renewable Energy Directive (2009/28/EC, RED), requires an estimation of the levels of greenhouse gas emissions (GHG) from biofuels, as well as a comparison of the values of emission savings as opposed to fossil fuels. In this paper, calculations were made into possible reductions of agricultural and GHG emissions in full Life Cycle Assessments (LCA) of bioethanol, which was produced from winter wheat. The study focused on an optimisation of nitrogen fertilisation for winter wheat, the selection of fertilisers with lower emissions arising from their production, as well as an increase of the sequestration of organic carbon in the soil by the use of reduced or no tillage systems. The results show that achieving a 50% reduction of GHG emissions in LCA of bioethanol produced from winter wheat is possible with an annual dose of 90 kg nitrate (N) per ha, regardless of which N fertiliser was applied. Additionally, an improvement in crop cultivation through the use of reduced or no tillage systems decreased the emissions by 53-69%, respectively. However, an annual application of 160 kg N per ha results in a saving of GHG emissions above 50% only in no tillage cultivation.

Key words: Winter wheat, ethanol, GHG emissions, emissions reductions, organic carbon sequestrations, RED.

Introduction

The European Union (EU) Directive 2009/28/EC (RED) promotes the use of energy from renewable sources [2]. The replacement of fossil fuels with biofuels saves natural resources of energy, as well as contributes to a solution for greenhouse gas emission problems from traditional energy sources. However, certain conditions should be met. The cultivation of raw materials for energy purposes, so far, is the only area of agricultural production in which the EU regulates in detail, i.e. the requirements for volume and limitation of greenhouse gas emissions (GHG). In addition, EU indirectly regulates the increase of sequestration of organic carbon in the soil by improving cultivation [2, 3]. EU member states have to prove that the emissions from biofuel production are equal or at least lower than the emissions in the regional values in Annex V part D of the RED [2]. If this applies, the producers of biofuel could use the relevant default values from this annex. They can also use values measured and calculated by themselves. In compliance with the RED, the actual value of GHG emission for cultivation of winter wheat was calculated, for the administrative regions in Poland (NUTS 2 level). The computed value for wheat was 22.91 g CO_2 eq. MJ^{-1}, and was slightly lower than 23 g CO_2 eq. MJ^{-1}, which is the default value according to RED [2]. With this level of emissions from fertiliser production in Poland, it is possible to achieve the minimum level of savings of GHG emissions required by the RED, e.g. 35% from 1 April 2013, as compared to fossil fuel. However, to achieve the mandatory targets specified by RED to save at least 50% emissions from 2017 and 60% from 2018, it is necessary to search for a further reduction of GHG emissions in the life cycle of bio-ethanol produced from winter wheat. In the structure of agricultural emissions, a significant contribution originated from emissions of the application and production of nitrogen fertilisers (N fertilisers). This is mainly due to nitrous oxide (N_2O) emissions. It is essential to find out which level of savings in agricultural emissions could be achieved in winter wheat cultivation through an optimum dose of N fertiliser and application of fertilisers with the lowest emission during the production process. Based on the RED regulations, it is possible to influence the emission level in the life cycle of winter wheat through an increase of carbon sequestration as a result of improved cultivation of the raw material. There has been a growing concern about soil productivity and the impact of agricultural management practices on the environment [6]. The examples of such practices are two tillage systems: conventional and conservation. Conventional tillage leaves no more than 15% of the ground covered with crop residues. The alternative for conventional tillage is conservation tillage that minimises the disruption of the soil structure and covers 15% or more of the soil surface with crop residues. Depending of the level of simplification, conservation tillage is divided into reduced (minimal) and no tillage systems. Reducing the intensity of soil cultivation lowers the energy consumption and the emission of carbon dioxide (CO_2), while the level of carbon sequestration is raised through an increase in the soil organic matter (SOM) [4]. The methodology for a carbon stock calculation is described in the RED [2]. The aim of the present study was to assess: (i) value and structure of agricultural GHG emissions from winter wheat cultivation, (ii) optimum N application resulting in the lowest GHG emissions by using selected fertilisers with the lowest emissions arising in their production and (iii) value of savings of GHG emissions in the life cycle of winter wheat through the use of improved cultivation such as reduced tillage and no tillage systems.

Materials and Methods

Winter wheat in the near future might be grown for biofuel production. It was assumed that there is no difference in agricultural practises for biofuel purposes as compared to food and feed purposes.

Data sources: The study was based on surveys, which have described GHG emissions from the production of N fertilisers in Poland. The cultivation winter wheat was defined in a survey conducted randomly on 272 agricultural holdings, which produce or were capable of producing raw materials intended for bio-fuels. The sample represented 3% of all the farms of Poland. The winter wheat was cultivated on various soils types under various weather conditions between 2005 and 2010, with the exception of extreme conditions (especially farms located on areas exposed to floods and seeping groundwater in 2010). For each farm, a questionnaire was completed based on the information from individual interviews with the farmer. The questionnaire included the following main parts: (1) General information about farm: building and construction, mechanical equipment of the farm with information on machinery type, livestock production; (2) Characteristics for each plot of the farm (soil quality, soil carbon stock); (3) Crop specific data for every plot (cultivated area, yield); (4) Subsidised area (according to the rules of CAP); (5) Crop and seed prices; (6) Fertiliser and crop protection doses; (7) Crop cultivation practices for each plot, concerning operation details, such as timing, machinery usage, efficiency and fuel consumption, raw materials, rented operations.

The questionnaires provide our analysis with the following parameters for the winter wheat: soil type, crop areas, yields, moisture, nitrate (N), phosphorus pentoxide (P_2O_5), potassium oxide (K_2O) and lime (CaO) fertilisation rates, amount of pesticides (kg active ingredients) and fuel use. These parameters were assessed as averages between 2005 and 2010, in order to approach the current situation as optimally as possible. Straw yields were estimated according to the yields of seeds. The mean data obtained was compared with data from the EU database of JRC [5].

Methods: An assessment for agricultural and GHG emissions in the life cycle of winter wheat (Eth_W) calculator Biograce [1] was used following the methodology of the RED and the EU Fuel Quality Directive (FQD) (2009/30/EC) [3]. Agricultural emissions and the structure of GHG emissions were estimated on the basis of mean values, characterising the technology of cultivation on the sample of 272 farms. Estimations of emissions and emission savings were conducted by using Eth_W Biograce. In our calculations, default values for processing, transport and natural gas as technological fuel were used. In an assessment of carbon (C) stocks, the recommended methodology was applied; however, instead of using default soil organic carbon (SOC_{ST}) for High Activity Clay Soils (HACS), the results from our own database were used. Values of SOC_{ST} from the Biograce calculator are 50 and 95 t C ha^{-1} for cold, temperate, dry and moist climates, respectively. The value of the SOC_{ST} in Poland is on average 41 t C ha^{-1} and it is independent from the climatic zone. Taking into account this value, we estimated the annual C change for HACS soils for reduced and no tillage systems. The mean computed values of HACS are 0.126 and 0.614 t CO_2 ha^{-1} yr^{-1}, respectively, for reduced and no tillage practices. These values were calculated in relation to conventional tillage systems. The incorporation of straw into the plough soil in farms with a conservation tillage system is obligatory in Poland under Cross-Compliance (CC) requirements, and is in line with Good Agricultural and Environmental Conditions (GAEC). Farms without animal production account for 40% of farms in Poland. The optimal rates of N for winter wheat yields were obtained by the boundary line approach. A scatter plot was drawn between yields and nitrogen rates for 272 observations. Data points (boundary points) which were located on the outer rim of the study area were chosen. Polynomial and two segment linear regressions were fitted. The lower optimal N rate was obtained as the break point of the segment linear regression. The upper optimal N rate was obtained as a maximum of polynomial regression.

Results and Discussion

Cultivation methods for winter wheat in Poland are the same as in other EU countries. Table 1 compares results from winter wheat with the data from the JRC consortium that are relevant in calculating default GHG emissions from biofuel according to the RED methodology. The JRC data was taken from the Excel file that can be downloaded from JRC website [5]. In Table 1, it can be observed that in Poland, when comparing the numbers in JRC yield, moisture content, dose of N, P_2O_5, K_2O and CaO fertilisers, seeds and N_2O, field emissions are higher. A general explanation can be given for these observations. Farmers endeavour to maximise their yields; therefore, the application of seeds and all fertilisers are higher than in other countries. The high doses of P_2O_5, K_2O and CaO fertilisers are the effects of the low quality of soil occurring in Poland. A higher application of N fertiliser per hectare results in a higher N_2O field emission.

Table 1. Parameters values for winter wheat. Average data from Poland compared against JRC values.

Parameter	Unit	Poland	JEC values [6]
Yield	kg $ha^{-1}yr^{-1}$	5950	5200
Moisture content	%	15	13.5
Diesel use	MJ ha^{-1} yr^{-1}	3435	3716
N-fertiliser	kg ha^{-1} yr^{-1}	117	109.3
Manure	kg N ha^{-1} yr^{-1}	-	-
P_2O_5-fertiliser	kg ha^{-1} yr^{-1}	50	21.6
K_2O-fertiliser	kg ha^{-1} yr^{-1}	56	16.4
CaO-fertiliser	kg ha^{-1} yr^{-1}	124	-
Pesticides	kg s a. $ha^{-1}yr^{-1}$	1.9	2.3
Seeds	kg ha^{-1} yr^{-1}	221	120
N_2O field emission	kg N_20 $ha^{-1}yr^{-1}$	3.04	1,84

The structure of agricultural emissions for GHG, assuming a weighted average of emissions from the production of fertilisers (3414.2 g CO_2 eq. kg^{-1}), indicates that the application and production of N fertilisers had the biggest impact on emissions (Fig. 1). In the near future, further reductions of GHG emissions in the production of N fertiliser will be difficult to achieve in Poland. In theory, it is possible to reduce agricultural emissions by optimising the dose and selection of the N fertilisers with lower emissions arising from their production.

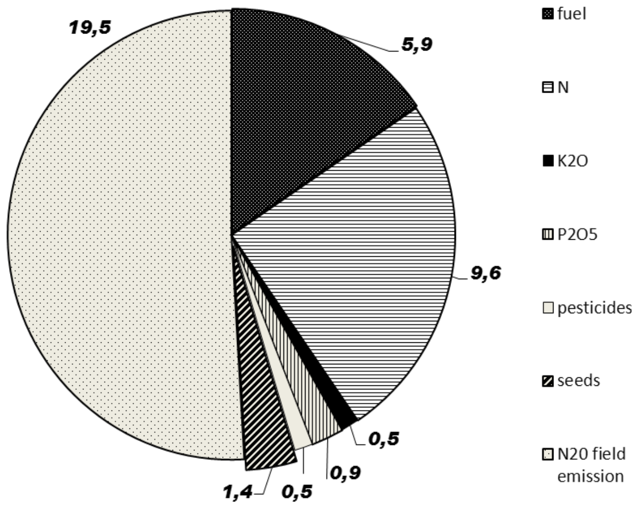

Figure 1. The structure of agricultural emissions from winter wheat cultivation in Poland (g CO_2 eq. MJ^{-1}).

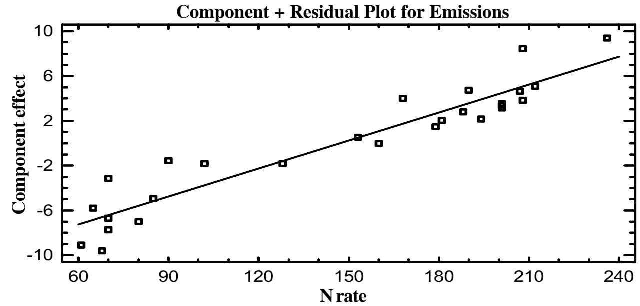

Figure 2. Component effects of N rates on agricultural emissions of GHG (first stepwise regression variable; $R^2 = 63.1\%$).

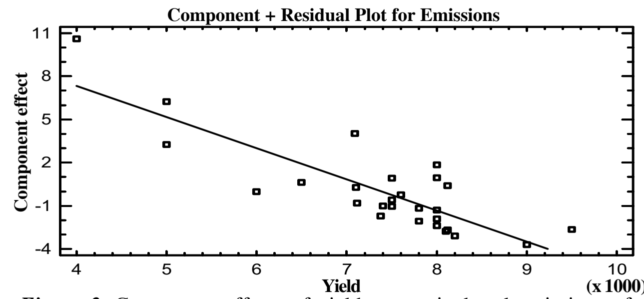

Figure 3. Component effects of yields on agricultural emissions of GHG (second stepwise regression variable; $R^2 = 85.6\%$).

The nitrogen reaction curve fitted as boundary line was used to calculate the linear multiple regression between agriculture GHG emissions vs. yield and N rates. The estimation of this relation was possible because yields and N rates are weakly correlated ($r<0.5$). The ranges of data were: GHG emissions without allocations 13.2-29.9 g CO_2 eq. MJ^{-1}, grain yield 4000-9500 kg ha^{-1} (moisture content 15%) and N rates 61-236 kg ha^{-1}.

The regression between the emission of GHG emissions and grain yield gave the following equation:

$$\text{Emissions} = 24.5572 - 0.00216807*\text{Yield} + 0.0833057*\text{N rates};\ R^2 = 85.\ 6\%$$

The regression was statistically significant for both independent variables, which had different effects (Figs 2 and 3).

The optimal dose of fertiliser for the studied farms ranged from 90 to160 kg N $ha^{-1}yr^{-1}$. The high upper value in this range comes from the fact that polynomial regression between yield and N rates was flat. At a mean yield of winter wheat at 5.95 t ha^{-1} and application of 90 kg N $ha^{-1}yr^{-1}$, the emissions may achieve only a 50% reduction in GHG emissions, regardless of the fertiliser applied (Table 2). This was a 27 kg N $ha^{-1}yr^{-1}$ lower dose than the average application collected from the surveyed farms. An increase of an application to 160 kg N $ha^{-1}yr^{-1}$ (used in 20% of investigated farms) lowered emissions from 39 to 43% (Table 3).

Improved cultivation by the implementation of reduced tillage e.g. leaving 30% of crop residue on the field, and an application of 90 kg N per hectare, can annually reduce emissions from 53 to 56% (Table 4). A higher dose of N fertiliser of e.g. 160 kg resulted

Table 2. Estimations of GHG emissions for winter wheat applying 90 kg N ha $yr^{-1.}$

Fertiliser	CO_2 eq. kg^{-1} N	CO_2 eq. MJ^{-1} (without allocation)	CO_2 eq. MJ^{-1} (with allocation)	Reduction in %
Ammonium sulphate	3494.5	32.25	19.19	52
Urea ammonium nitrate solution (UAN)	3080.0	31.42	18.70	53
Ammonium nitrate	4007.6	33.25	19.78	52
Calcium ammonium nitrate (CAN)	5012.0	35.22	20.96	50
Multicomponent NPK	3188.7	31.63	18.82	53

Table 3. Estimations of GHG emissions for winter wheat applying 160 kg N ha $yr^{-1.}$

Fertiliser	CO_2 eq. kg^{-1} N	CO_2 eq. MJ^{-1} (without allocation)	CO_2 eq. MJ^{-1} (with allocation)	Reduction in %
Ammonium sulphate	3494.5	45.43	27.04	43
Urea ammonium nitrate solution (UAN)	3080.0	43.98	26.17	44
Ammonium nitrate	4007.6	47.23	28.11	42
Calcium ammonium nitrate (CAN)	5012.0	50.75	30.20	39
Multicomponent NPK	3322.5	44.83	26.68	43

Table 4. Estimation of GHG emissions from winter wheat in the reduced tillage system (C sequestration of 0.1260 t CO_2 ha^{-1} yr^{-1}) depending on the applied fertiliser (dose 90 kg N $ha^{-1}yr^{-1}$).

Fertiliser	CO_2 eq. kg^{-1} N	CO_2 eq. MJ^{-1} (without allocation)	CO_2 eq. MJ^{-1} (with allocation)	Reduction in %
Ammonium sulphate	3494.5	32.25	19.19	56
Urea ammonium nitrate solution (UAN)	3080.0	31.42	18.70	56
Ammonium nitrate	4007.6	33.25	19.78	55
Calcium ammonium nitrate (CAN)	5012.0	35.22	20.96	53
Multicomponent NPK	3188.7	31.63	18.82	56

in a reduction of emission from 42 to 47% (Table 5). In both applications, the lowest rates of emission saving were found for calcium ammonium nitrate (CAN), and the highest for urea ammonium nitrate solution (UAN) and multicomponent NPK. The introduction of a no tillage system, leaving the total amount of crop residues on the field, and a dose of 90 kg N ha yr^{-1} resulted in savings of 66-69% for GHG emissions (Table 6). A higher dose of N caused a GHG reduction from 55 to 60% (Table 7). Similarly to reduced tillage, the lowest reduction occurred when CAN was applied. The highest decline of emission was observed for UAN. However, the cultivation of winter wheat in a no tillage system under Polish conditions is less likely than corn cultivation. Therefore, it seems more probable that farms producing wheat for fuel purposes will be more inclined to use rather reduced tillage system combined with optimisation of the doses of N fertiliser.

Table 5. Estimation of GHG emissions for winter wheat in the reduced tillage system (C sequestration of 0.1260 t CO_2 ha^{-1} yr^{-1}) depending on the applied fertiliser (dose 160 kg N $ha^{-1}yr^{-1}$).

Fertiliser	CO_2 eq. kg^{-1} N	CO_2 eq. MJ^{-1} (without allocation)	CO_2 eq. MJ^{-1} (with allocation)	Reduction in %
Ammonium sulphate	3494.5	45.43	27.04	46
Urea ammonium nitrate solution (UAN)	3080.0	43.98	26.17	47
Ammonium nitrate	4007.6	47.23	28.11	45
Calcium ammonium nitrate (CAN)	5012.0	50.75	30.20	42
Multicomponent NPK	3322.5	44.83	26.68	47

Table 6. Estimation of GHG emissions for winter wheat in the no tillage system (C sequestration of 0.6142 t CO_2 ha^{-1} yr^{-1}) depending on the applied fertiliser (dose 90 kg N $ha^{-1}yr^{-1}$).

Fertiliser	CO_2 eq. kg^{-1} N	CO_2 eq. MJ^{-1} (without allocation)	CO_2 eq. MJ^{-1} (with allocation)	Reduction in %
Ammonium sulphate	3494.5	32.25	19.19	68
Urea ammonium nitrate solution (UAN)	3080.0	31.42	18.70	69
Ammonium nitrate	4007.6	33.25	19.78	68
Calcium ammonium nitrate (CAN)	5012.0	35.22	20.96	66
Multicomponent NPK	3188.7	31.63	18.82	69

Table 7. Estimation of GHG emissions for winter wheat in the no tillage system (C sequestration of 0.6142 t CO_2 ha^{-1} yr^{-1}) depending on the applied fertiliser (dose 160 kg N $ha^{-1}yr^{-1}$).

Fertiliser	CO_2 eq. kg^{-1} N	CO_2 eq. MJ^{-1} (without allocation)	CO_2 eq. MJ^{-1} (with allocation)	Reduction in %
Ammonium sulphate	3494.5	45.43	27.04	59
Urea ammonium nitrate solution (UAN)	3080.0	43.98	26.17	60
Ammonium nitrate	4007.6	47.23	28.11	58
Calcium ammonium nitrate (CAN)	5012.0	50.75	30.20	55
Multicomponent NPK	3322.5	44.83	26.68	59

Conclusions

A reduction of 50% for GHG emissions in the life cycle of bioethanol produced from winter wheat is possible with an annual dose of 90 kg N per hectare regardless of the type of N fertilisers. An improvement of cultivation methods trough implementation of reduced or no tillage systems and application of 90 kg N results in savings of GHG emissions by 53-69%. In the case of an application of 160 kg N per hectare, savings of GHG emissions were above 50%, and were only possible to obtain in no tillage system.

Acknowledgements

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