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Optimization and risk analysis of greenhouse gas emissions depending on yield and nitrogen rates in winter wheat cultivation

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Abstract

Biofuel producers are obligated to achieve certain level of greenhouse gas emission (GHG) reduction in the lifecycle of biofuels in reference to fossil fuels. The current emission reduction level is at least 35% and will increase up to 50% since January 2017 for the existing plants and at least to 60% for a new installations. At the farming stage it is possible to achieve some emission savings in the lifecycle of biofuels with reference to the agricultural feedstock production. In this study GHG emission optimization was investigated with regard to winter wheat yield and N fertilization rate while considering bioethanol production. Using desirability of optimization, risk analysis and uncertainty assessment, it was proved that the GHG emission attributed to winter wheat cultivation can be reduced by 1.7 g CO_2 eq. MJ^{-1} of ethanol produced. This can be achieved primarily with yield increase by 7.9% compared to the median, while changes in N fertilization is of less importance. By selecting winter wheat from farms producing higher yields (5,200-6,929 t ha^{-1}) it is possible to decrease the uncertainty regarding the GHG emissions from 2% to 1%.

Key words: Winter wheat, greenhouse gas emission, GHG emission reduction, bioethanol, optimization, risk, uncertainty.

Introduction

Biomass is often considered a carbon neutral feedstock, but there is a significant amount of greenhouse gas (GHG) emissions that are released during the biomass production and conversion to biofuels. Biofuels must have a potential to save at least 35% GHG emissions compared to fossil fuel, in order to fulfill the EU targets for renewable energy in the transportation sector set in the Renewable Energy Directive (RED) [1]. Future emission thresholds are even more ambitious by increasing this value up to 50% for existing and 60% for new plants, respectively.

For ethanol produced from winter wheat, the feedstock growth at farm has a significant contribution to the total greenhouse gas emissions. According to the Annex V of the RED the default value attributed to wheat cultivation is 23 g CO_2 eq. MJ^{-1} of ethanol produced[1], which amounts to 33% of total GHG emissions (when unspecified fuel is assumed for the ethanol processing plant). Searching any opportunity to decrease the GHG emissions at farming level is of a great concern, especially when the proposal of an amendment to the RED, indicates additional GHG emissions from indirect land use change to be taken into account in the life cycle of biofuels [2].

It was previously studied that when optimal N rates are applied and improved management practices used (to increase soil organic carbon stocks), the GHG emission savings could be increased by 2.3-4.0 g CO_2 eq. MJ^{-1} of ethanol produced from winter wheat compared to fossil fuels [3]. These refer mainly to the application of N fertilizer assortments with low GHG emissions in the industrial stage of the fertilizer production. Less significant, but still important are emission savings from optimized N rate application. Initial optimization [3] for production function $Yd = f(N_{rate})$ resulted in N fertilizer application ranging 90-160 kg ha^{-1}. However, more specific optimization assessment is required including risk and uncertainty analysis. Focus of this study in on the desirability of optimization with the objective function to decrease the GHG emissions from agricultural feedstock production, including risk analysis for the independent variables, and uncertainty assessment for the optimized GHG reduction.

Materials and Methods

The calculations of greenhouse gas emissions for ethanol production were performed using BIOGRACE tool with emission allocation for ethanol and dried distillers grains with solubles (DDGS) [4]. Default data from BIOGRACE were used for ethanol industrial production (with unspecified processing fuel), distribution and transportation. For winter wheat production survey data from 272 Polish farms growing winter wheat were used, which is 3% of the total number of farms growing wheat for bioethanol production [3]. For the optimization of GHG emissions at the stage of winter wheat cultivation the Design Optimization Procedures were applied using STATGRAPHICS software. The optimized dataset (n = 14) comprises farm data that fulfill the GHG emission requirement of 23 g CO_2 eq. MJ^{-1} or below (which is a default value for winter wheat ethanol given in the Annex V of RED). Risk analysis was conducted for the optimized dataset; the best fitting probability distributions were estimated using @Risk from the Palisade Decision Tools software. Next, the probability distributions were used to model random distributions with Monte Carlo simulation using 10,000 iterations. Finally, for the farm survey data and optimized dataset, uncertainty in GHG emissions were estimated using t-factor method with 95% confidence internal.

Results and Discussion

The results of the optimization analysis $E_{GHG} = f(Yd, N_{rate})$ for wheat ethanol showed that reaching the default GHG emission level of 23 g CO_2 eq. MJ^{-1} or below is only possible with winter wheat yields and N fertilization as given in Table 1.

Table 1. Winter wheat yields and N fertilization rates for optimized GHG emission levels.

Emissions with allocation for DDGS (CO_2 eq. MJ^{-1} of bioethanol)	Yield (kg ha^{-1})	N application rate (kg ha^{-1})
23	6.115	129
21	6.400	116
19	6.696	104

The GHG emissions, yields and N rate were linearly dependant according to the equation:

$$E_{GHG} = 29.8 - 0.00302\ Yd + 0.0903\ N_{rate};\quad R^2=79.6$$

where: E_{GHG} – greenhouse gas emissions with allocation, Yd – yield, N_{rate} – N application rate.

The model is statistically significant ($p \leq 0.05$) and the explanatory variables are not correlated ($r < 0.5$), thus they could be used as independent variables. The estimated optimal N fertilization rates (Table 1) are more narrow compared to the range obtained early using a boundary line approach (90-160 kg N ha^{-1}) [3]. The response surface for GHG emissions depending on the explanatory variables is presented in Fig. 1.

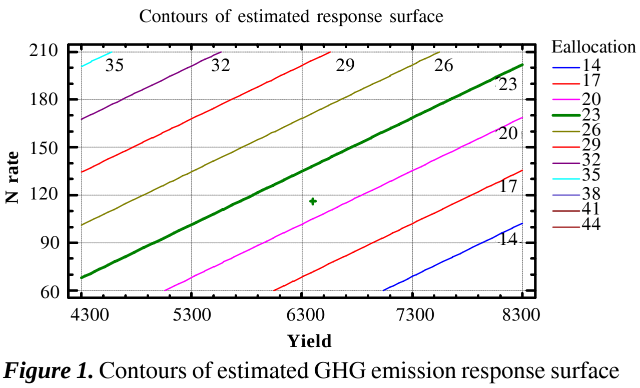

Figure 1. Contours of estimated GHG emission response surface (green point = optimal value).

GHG emissions related to winter wheat cultivation for ethanol production in Poland amounts to 22.9 g CO_2 eq. MJ^{-1} of ethanol, which is the average for all farms surveyed, and is very close to the RED default value [1]. The results of the present study (Table 1, Fig. 1) suggest that further emission reduction by 2 g CO_2 eq. MJ^{-1} would be possible, resulting in total bioethanol emission of 21 g CO_2 eq. MJ^{-1}. The ranges of yields and N rates relevant for the GHG emission of 21 g CO_2 eq. MJ^{-1} can be found in Fig. 1. The optimization (Table 1) would require yield of 6,400 kg ha^{-1} (increase by 4.7% compared to the median of farm survey data) and 116 kg N ha^{-1} (10% N rate reduction). Reaching the GHG emission level of 19 g CO_2 eq. MJ^{-1} does not seem technically feasible; that would require producing median yield of 6,696 kg ha^{-1} with much more efficient fertilization (104 kg N ha^{-1}). Such yield level is close to the upper quartile of the farm survey data, which means low probability of reaching this in normal agricultural practice. Therefore, further analysis was performed for data ensuring the GHG emission level of 21 g CO_2 eq. MJ^{-1}.

Desirability value close to 1 (Fig. 2) indicates that the optimization target of 21 g CO_2 eq. MJ^{-1} was reached in 14 farms (5.2 % of farm survey data). It was important to check if the risk analysis for GHG emissions, yields and N rates would show much different results for the entire farm survey data and the optimized dataset (Table 2).

Analyzing the statistics (Table 2), it can be found that the farm survey data present skew distribution while the optimized dataset is more symmetric. The simulations indicate that possible GHG emission savings for optimized data is 1.7 CO_2 eq. MJ^{-1} in reference to medians (22.9–21.2). Such savings could be achieved with median yield increase by 481 kg ha^{-1}. The increase value amounts to 19.5% for 5th percentile of yields and would shrink to 7.9% for the median yield. For 95th percentile it was found that yield in optimized dataset was lower compared to farm survey data, which indicates that yield maximization is not advisable practice to decrease GHG emissions, especially in farms producing yields above the median yield. The adjustment of N fertilization rates for winter wheat was proved to be ineffective attempt for GHG emission optimization; the statistics for N rates in both datasets (farm survey and optimized dataset) are quite similar.

The identified above GHG emission savings are lower compared to those resulting from using N fertilizer assortments with lower GHG emission attributed to its industrial production [5], which were estimated at 2.3 g CO_2 eq. MJ^{-1}. The combined effect

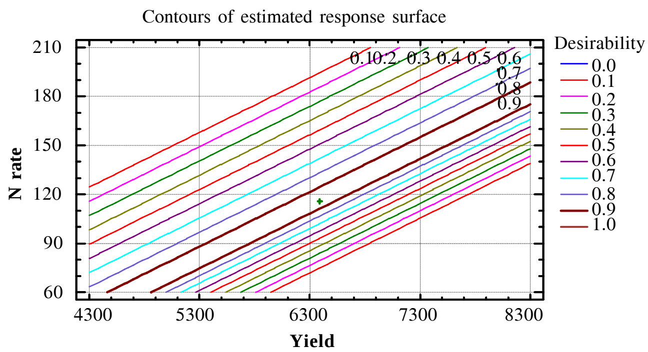

Figure 2. Desirability contours for optimization target 21 g CO_2 eq. MJ^{-1} (green point = optimal value).

Table 2. Statistics based on risk analysis for GHG emission, yield and N fertilization for 10,000 iterations of Monte Carlo simulation.

Statistics	Emission (g CO_2 eq. MJ^{-1})		Yield (kg ha^{-1})		N rate (kg ha^{-1})	
	Farm survey	Optimized	Farm survey	Optimized	Farm survey	Optimized
Mean	22.9	21.2	6,106	6,565	129	125
5th percentile	16.7	20.8	4,350	5,200	66	78
Median	23.0	21.2	6,084	6,565	125	119
95th percentile	28.7	21.5	7,933	6,929	202	192

of using both, the low-GHG emission N fertilizer and increasing the winter wheat yield at the fertilization rate of 120 N kg ha^{-1}, may reduce the total GHG emissions at the crop cultivation stage by 4 g CO_2 eq. MJ^{-1} of bioetanol.

According to the RED, more strict GHG emission targets for biofuels, at least 50% will become effective since January 2017 and at least 60% for new installations. As indicated above, yield increase could be an option for some farms, however, yield increase by 7.9% in reference to the median, in such a short time would require 2% annual yield growth of winter wheat. This may not be feasible in agricultural practice. Alternatively, in order to minimize the GHG emissions at the crop production stage, a controlled procedure for the purchase of biofuel agricultural feedstock could be used. Based on the comparison of farm survey data and the optimal dataset (Table 2), it is recommended that winter wheat yield should be at the range of 5,200-6,929 kg ha^{-1} (Me = 6,565) and N rate of 78-192 N kg ha^{-1} (Me = 119). The investigation of the N rate and yield reaction curve may be useful in order to fulfill these recommendations (Fig. 3).

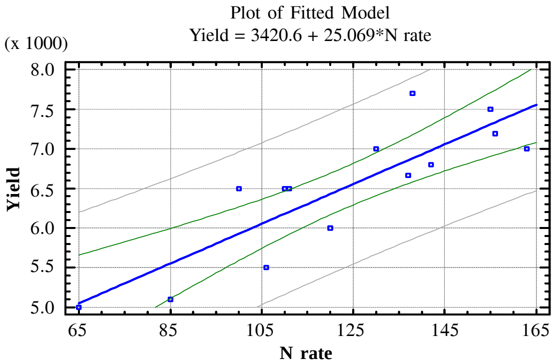

Figure 3. N fertilizer dose dependence of the yield of winter wheat for the optimized data (R^2 = 73.3%).

It is also important to assess the uncertainty of the GHG emission reduction. For both data sets the achieved results were not different substantially (Table 3). Agricultural feedstock of higher yields (5,200-6,929 t ha^{-1}) decrease the uncertainty regarding the GHG emission from 2% (farm survey data) to 1% (optimized dataset).

Table 3. Uncertainty of the GHG emissions from agricultural feedstock production.

Statistics	Farm survey data	Optimized dataset
Mean	22.9	21.2
Standard Deviation	3.66	0.231
Count of data	272	14
t-factor (95% CI)	1.96	2.160
Uncertainty @ 95% CI	0.435	0.133
% Uncertainty	2	1

CI - confidence interval; t-factor – Student's t-value; uncertainty @ - uncertainty in absolute value.

Conclusions

It is possible to reduce the greenhouse gas emissions from biofuels with regard to agricultural feedstock production by yield or N rate optimization. For winter wheat ethanol the relevant GHG emission reduction could be 1.7 g CO_2 eq. MJ^{-1}. The risk analysis proved it could be primarily achieved by 7.9% yield increase compared to the median yield of farm survey data while N rate optimization has not much impact on GHG emission reduction from winter wheat growing. By selecting agricultural feedstock of higher yields (5,200-6,929 t ha^{-1}) it is possible to decrease the uncertainty regarding the GHG emissions from 2% to 1%.

Acknowledgements

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