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EFFICIENCY OF DEEP FERTILIZER PLACEMENT IN MAIZE IN TERMS OF SUSTAINABLE DEVELOPMENT CRITERIA[1]

Key words: maize, fertilization, sustainability assessment, Analytic Hierarchy Process, Life Cycle Assessment

ABSTRACT. Ensuring sustainable agricultural production technologies is becoming increasingly important in the face of the observed climate change and need to reduce the harmful environmental impact of agriculture. The aim of the study is a comparative assessment of the deep fertilizer placement method with surface broadcast application of fertilizers as regards overall sustainability. To reach this goal, based on the results of field experiments and expert opinions, the values of sustainability indicators (economic, environmental and social aspects) were determined. The AHP (analytical hierarchy process) method was applied to comparative assessment. The conducted analysis showed that economic, environmental and overall sustainability assessment are conditioned by productivity achieved. In the first year of the experiment, when the yield increase was not achieved, in terms of sustainability criteria considered, the surface broadcast application of fertilizers was determined to be preferred as compared to the deep fertilizer placement method. On the other hand, in the second year of research with yield increase, the practice with the deep application of mineral fertilizers resulted in a better performance than surface broadcast fertilization, while showing a similar overall performance in the case of natural fertilizers.

INTRODUCTION

The implementation of innovative agricultural production technologies, reducing the environmental impact, in accordance with the idea of sustainable agriculture, requires taking conflicting objectives into consideration. Therefore, to conduct evaluations of innovations in agriculture, multiple-criteria decision making (MCDM) methods are increasingly used [Król-Badziak, Księżak 2019]. Multi-criteria methods allow to evaluate farming practices by considering economic, environmental and social aspects, leading to overall sustainability performance [Craheix et al. 2016]. There is a wide range of MCDM methods that can be applied in agriculture, and the Analytic Hierarchy Process (AHP) is

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one of them [Wota 2005]. Two main advantages that come with the AHP method are: the possibility of a quantitative and qualitative comparison of criteria as well as the introduction of a consistency test of judgments [Wota 2005, Saaty 2008]. It is indicated that the deep placement of fertilizer improves nutrient uptake, leading to the possibility of a fertilization dose reduction and, consequently, a limitation of its negative impact on the environment [Bautista et al. 2001]. Moreover, localized fertilization may reduce water pollution caused by surface runoff. At present, the most common method of fertilizer application is surface broadcast fertilization (SB), where fertilizers are distributed on the soil surface and are not concentrated near the roots, which may make nutrients not readily available to the plants and be less effective [Stanisławska-Glubiak, Korzeniowska 2010]. Subsequently, work which focuses on the increase of fertilization effectiveness, and the sustainability assessment of proposed fertilization application methods has been undertaken.

The aim of the study is the sustainability assessment of maize cultivation with deep fertilizer placement (DP) and the surface application of fertilizers (SB) using the AHP method. In Poland, maize is a crop species with considerable economic importance. In 2017, it accounted for 11% of the total sown area. Grain maize accounting for almost 13% of total cereal production, while maize for green fodder has a 73% share in the total structure of field green fodder crop production in Poland [GUS 2018]. In terms of the consequences of climate change that has been observed from the second half of the 20th century, temperature increase may be beneficial for thermophilic plants – maize being one of them [Górski, Kozyra 2011].

RESEARCH MATERIAL AND METHODS

The study aimed to evaluate and compare the sustainability of two fertilization application methods: deep fertilizer placement (DP) and surface broadcast fertilization (SB) in maize cultivation. The commonly used MCDM (Multi-Criteria Decision Making) method, the AHP method, developed by Thomas L. Saaty [1994], was adopted for comparative assessment. This method enables the evaluation of a given alternative in comparison to another option [Jankowski, Ziemba 2015]. It is based on a hierarchy structure, from the goal (at the top), through the criteria and subcriteria presented on subsequent levels to decision alternatives (the lowest level) [Saaty 2008]. The conducted multi-criteria assessment followed the four steps presented below.

STEP 1. DESCRIPTION OF ALTERNATIVES. The study was based on the results of two field experiments conducted in the scope of the LCAgri project with the aim to assess the effectiveness of low-carbon practices at two Agricultural Experimental Stations (AESs) of the Institute of Soil Science and Plant Cultivation, in 2017 and 2018 [Kozyra et al. 2017]. The research at AES in Grabów (the Masovian Voivodship), with silage maize cultivation, involved innovative equipment (constructed in the scope of the AZOMAIS project), which allowed simultaneous sowing and the application of specialized fertilizer in the form of small granules (placed at a 5 cm depth) and super-granules (placed at a 30 cm depth) [AZOMAIS 2014]. The research at AES in Werbkowice (the Lublin Voivodship) with grain maize cultivation involved a slurry tanker that could provide direct injection.

Table 1. The main characteristics of the analyzed field experiments

Specification	Mineral fertilization in silage maize cultivation (AES in Grabów)				Natural fertilization in grain maize cultivation (AES in Werbkowice)			
	2017		2018		2017		2018	
	DP	SB	DP	SB	DP	SB	DP	SB
Area [ha]	1.0	1.9	1.0	1.9	15.2	13.3	15.2	13.3
Yield [t/ha]	33.2	34.3	51.1	40.2	7.3	8.0	9.0	8.0
Difference*	(-3%)		(+27%)		(-9%)		(+13%)	
N_{min} [kg/ha]	120	120	120	115	72	72	67	67
$P_2O_{5\,min}$ [kg/ha]	60	70	60	70	0	0	0	0
K_2O_{min} [kg/ha]	120	120	120	121	0	0	0	0
Slurry [m^3/ha]	0	0	0	0	30	30	30	30

* Difference shows differences in obtained yield (expressed in %) between DP in relation to SB (100%)
Source: LCAgri, http://www.lcagri.iung.pl/pl

The surface application of fertilizer was considered as comparative practice. As part of the experiments, the production, economic and environmental effects of the DP and SB fertilization method were monitored. The main characteristics of the analyzed field experiments are presented in Table 1.

STEP 2. SUSTAINABILITY CRITERIA SELECTION. In the scope of multi-criteria analysis, 9 sustainability indicators were determined: 3 economic, 3 environmental and 3 social criteria [Craheix et al. 2016, Król-Badziak, Księżak 2019, Król-Badziak et al. 2021].

STEP 3. ECONOMIC, ENVIRONMENTAL AND SOCIAL ASSESSMENT. The economic dimension consists of the following indicators: (1) gross margin – GM, (2) economic independence – EI and (3) economic efficiency – EE. The GM was calculated as the difference between the production value and variable costs. EI determines the ratio of gross margin to direct payments, while EE determines the ratio of gross margin to variable costs [Craheix et al. 2016]. The higher the value of the economic indicator, the better the economic evaluation of the fertilizer application method. The production value was determined by adding, to the yield value (grain or green matter), the value of direct payments including single area payment and greening payment [IERiGŻ-PIB 2019, WMODR 2019]. The variable costs considered the costs of: seed material, fertilizers, plant protection products, fuel and employed labour. The amount of inputs was determined on the basis of their actual consumption. The purchase cost of inputs was based on the actual purchase prices, while the price of fuel and labour based on IERiGŻ-PIB [2017, 2018, 2019] and Aldona Skarżyńska [2019].

Life Cycle Assessment was applied for the comparison of two fertilization application methods using SimaPro 8.5.2.0 software [Goedkoop et al. 2016]. The environmental dimension consists of the following indicators: (1) global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP), and they were established

based on the CML-IA baseline (v3.05) method. The functional unit was determined as 1 kg of crop yield. The lower value of the environmental indicator means better environmental performance of the fertilizer application method. A cradle-to-farm gate perspective was adopted, considering soil tillage, fertilization, sowing, plant protection product application and harvesting. In silage maize production, transport was considered additionally. The emissions, due to the combustion of diesel fuel and indirect emissions (related to the production and transport of inputs) were estimated using the Ecoinvent v3.4 database [Wernet et al. 2016]. Direct and indirect N_2O emissions as well as CO_2 emissions from urea application were calculated based on IPCC methodology [De Klein et al. 2006]. The study assumes a reduction of indirect N_2O emissions associated with the volatilization of ammonia, resulting from the reduction of NH_3 emissions by 48% and 97%, respectively for mineral and natural deep fertilization [Domingo et al. 2014, Ti et al. 2019]. Nitrogen content in slurry was adopted for 3.4 kg of N per m^3 of slurry [Pietrzak 2013]. Emissions related to the production of slurry, foliar fertilizers and changes in soil organic matter are not included. The amount of inputs was determined on the basis of their actual consumption, while mass and estimated machine life were collected from catalogues and literature [CDR 2020, Bochu et al. 2013, Koch, Salou 2015].

The social dimension consists of the following indicators: (1) contribution to local employment determined as annual labour time (h/ha), based on results from experimental fields, (2) complexity level related to number of field operations, machinery and equipment required determined based on results from experimental fields, and (3) difficulty level evaluated based on experts' opinions and AHP methodology during the next stage. It was assumed that sustainable agriculture should result in an employment potential increase (defined as annual labour time), while a reduction of complexity and work difficulty level is desirable.

STEP 4. SUSTAINABILITY ASSESSMENT OF ANALYZED FERTILIZATION APPLICATION METHODS. The AHP method has been applied for a difficulty level evaluation (one of the social indicators) of the DP method in relation to SB, and for criteria weight evaluation. The expertise was based on a questionnaire among 27 respondents: scientists (10), agricultural advisers (9) and farmers (8). A detailed description of the expert group as well as sample survey questions are presented in [Król-Badziak, Księżak 2019]. In the framework of the questionnaire, the respondents assessed which fertilization application method is more difficult (related to higher requirements for specialized knowledge and specific machineries) and how much. The criteria and subcriteria weights were evaluated based on pairwise comparisons, assessing the level of importance of one criteria over another. The evaluation scale used in pairwise comparisons was based on the fundamental scale of Thomas L. Saaty [1994], from equal difficulty and importance ("1"), through slightly higher ("3"), significantly higher ("5"), much higher ("7") to absolutely higher difficulty and importance ("9"). Based on the data obtained within the questionnaires, a set of pairwise comparison matrices were constructed, for which the priority vector is calculated via the eigenvector method [Saaty 1994, Ong et al. 2020]. The consistency ratio (CR) was indicated under each pairwise comparison matrice based on Thomas L. Saaty [1994]. According to Thomas L. Saaty [1994], a CR of 0.1 or less is acceptable, while in some studies 0.2 is an acceptable consistency level [Pauer et al.

2016], therefore these judgments where CR was above 0.2 were not included in the study. The individuals' opinions were aggregated into a group choice based on the geometric mean of final outcomes [Saaty 2008]. In the next step, economic, environmental and social indicators were normalized (the linear sum normalization technique). Then, the final ranking is obtained using a generalized utility measure of the alternative via a weighted sum of criteria weights and the alternatives preference vector [Saaty 1994]. The fertilization application method (alternative) with the highest ranking is determined as the best solution among the alternatives.

RESEARCH RESULTS

The sustainability assessment was carried out separately for two production years. It was assumed that the first year of the experiment (2017) represents a situation, whereby the implementation of DP does not affect the yield, while the second year (2018) is considered as a situation in which an increase in farming efficiency is achieved as a result of yield increase. This is particularly apparent in the experiment with silage maize cultivation (Table 1).

The conducted analysis showed that the economic assessment depends on the yield level achieved. In the first year of the experiment, yields were lower in DP with the application of mineral and natural fertilizers than in SB by 3% and 9%, respectively. The yield decrease within DP resulted in lower economic performance through the reduction of GM, EI and EE in relation to SB. In the second year of research (2018), higher yield was obtained in DP (by 27% in mineral fertilization and 13% in natural fertilization) in relation to SB, which resulted in an increase of value for economic indicators (GM, EI and EE) (Table 2).

In the first year of the experiment, when slight differences in yielding (3%) in silage maize cultivation occured, the values of environmental indicators slightly differ between analysed fertilization application methods (by 5-9%). On the other hand, in grain maize cultivation, where slurry was injected directly into soil higher values of GWP, EP and AP, indicators were obtained in comparision to SB. However, when, in 2018, the productivity of maize with the DP method increased in relation to SB, a better environmental performance was obtained under the deep fertilizer placement method (Table 2). The obtained differences in the environmental evaluation between the analyzed practices are mainly caused by the yield level achieved.

In silage maize cultivation, the contribution to local employment (h/ha) influenced by types and numbers of agricultural operations applied, was higher in DP by 3% in 2017 and lower by 21% in 2018 in relation to SB. Due to the higher number of agricultural operations applied, and, consequently, higher number of machinery and equipment required, SB was defined as a more complex practice than DP due to additional pre-sowing cultivation (2017, 2018) and ploughing (2018). In maize cultivation, where slurry was injected directly into the soil, the workload was extended by about 2 hours in relation to SB. This resulted from dividing the slurry dose into three parts, while in SB it was applied once. SB was defined as more complex than DP, since, despite a lower number of agricultural operations, it requires more machinery. In the survey, DP was described as more difficult, and, therefore, requiring more specialized knowledge and machinery than SB.

Table 2. Evaluation of economic, environmental and social criteria in maize cultivation according to analysed fertilizer application methods

Criteria	Mineral fertilization in silage maize cultivation (AES in Grabów)				Natural fertilization in grain maize cultivation (AES in Werbkowice)			
	2017		2018		2017		2018	
	DP	SB	DP	SB	DP	SB	DP	SB
Economic criteria								
GM [PLN/ha]	3,921.9	4,062.1	7,130.5	5,240.8	2,411.5	2,934.8	3,816.0	3,321.1
EI [%]	508.5	526.6	929.2	683.0	312.6	380.5	497.3	432.8
EE [%]	181.2	184.5	393.0	267.2	103.8	134.9	151.1	138.3
Environmental criteria								
GWP [kg CO_2 eq/kg]	5.3×10^{-2}	5.6×10^{-2}	3.4×10^{-2}	4.7×10^{-2}	2.5×10^{-1}	2.2×10^{-1}	2.0×10^{-1}	2.2×10^{-1}
AP [kg SO_2 eq/kg]	2.2×10^{-4}	2.2×10^{-4}	1.4×10^{-4}	1.9×10^{-4}	7.7×10^{-4}	6.2×10^{-4}	6.0×10^{-4}	6.1×10^{-4}
EP [kg PO_4 eq/kg]	9.8×10^{-5}	8.9×10^{-5}	6.2×10^{-5}	7.7×10^{-5}	3.7×10^{-4}	3.3×10^{-4}	2.9×10^{-4}	3.2×10^{-4}
Social criteria								
Employment [h/ha]	9.8	9.5	7.8	9.9	12.3	9.6	11.9	9.7
Complexity	19.0	21.0	21.0	25.0	21.0	23.0	20.0	24.0
Difficulty [%]	73.5	26.5	73.5	26.5	73.5	26.5	73.5	26.5

Source: own study

After the consistency tests, 17, 13 and 22 out of 27 filled questionnaires were taken into account in the evaluation of criteria weights for main sustainability dimensions, economic and social subcriteria, respectively. According to the respondents, the economic dimension was the most important, while the environmental and social efficiency dimensions had lower priority (Figure 1). Among the economic subcriteria, GM was defined as the most important, while within social subcriteria, difficulty had the highest priority. The weights of environmental subcriteria were based on Serenella Sala et al. [2018], where GWP was defined as the most important criteria in comparison to the other ones.

The conducted assessment of overall sustainability shows that, in the first year of the experiment (2017), SB was determined to be preferred as compared to DP in maize cultivation with mineral and natural fertilizers (Figure 2). On the other hand, with regard to the second year of the experiment (2018), it was indicated that DP can become an efficient alternative to SB. In maize silage cultivation, the DP of mineral fertilizers shows better economic, environmental and overall performance in relation to SB. However, SB was most preferred over DP in terms of selected social criteria. In grain maize, the practice where slurry was injected directly into the soil, better economic and environmental performance was obtained than in SB, however the overall performance for both practices was similar due to the significant advantage of SB in terms of social performance.

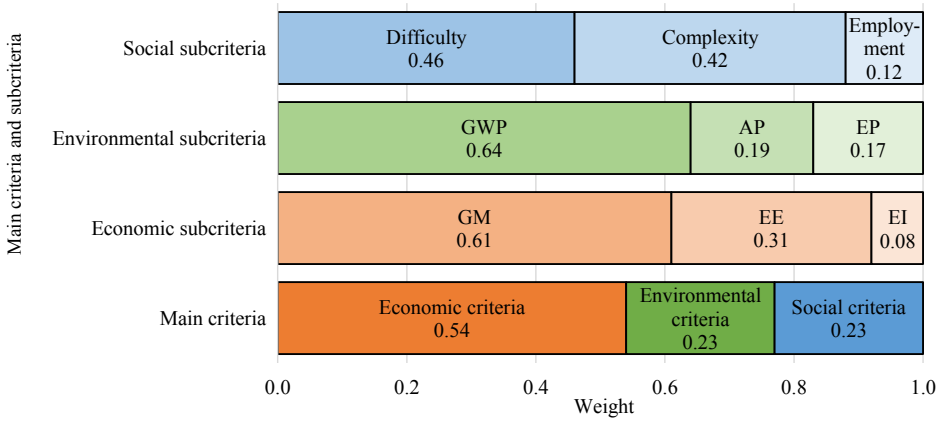

Figure 1. The relative importance (weights) for main sustainability criteria, and economic, environmental and social subcriteria according to the mean opinion of scientists, agricultural advisers and farmers using the AHP method

Source: own study, environmental criteria based on [Sala et al. 2018]

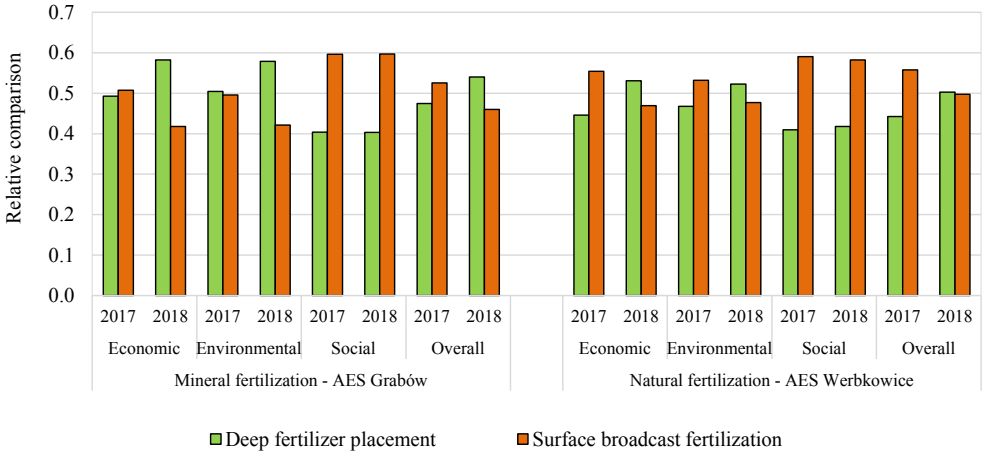

Figure 2. Comparative assessment of the deep fertilizer placement (DP) and surface broadcast application (SB) method with regard to the economic, environmental, social and overall sustainability assessment

Source: own study

The literature indicates that fertilizer deep placement is one of the most efficient fertilization application methods [Agyin-Birikoran et al. 2020]. Despite the fact that localized fertilization does not result in a significant yield increase, it should be recommended due to its lower environmental impact [Stanisławska-Glubiak, Korzeniowska 2010]. Tomasz Piechota et al. [2014] showed that row liquid manure injection in maize did not influence emergence, and achieved yields were similar to those obtained with mineral fertilization. Moreover, the new technology of deep fertilization can reduce costs since it performs

tillage, fertilization and sowing simultaneously [Fujii et al. 2015]. In agricultural systems, there are numerous practices that result in a reduction of NH_3 emissions, such as manure acidification, the use of ammonium nitrate, controlled release fertilizers. The deep placement of manure and mineral fertilizers is one of them [Ti et al. 2019]. Deep placement fertilization is seen as an environmentally friendly farming method, which, along with the slow release of fertilizer, maintains the effect of fertilization over a longer period [Fujii et al. 2015]. It has also been found that the deep placement of fertilizers reduces surface runoff, leaching, volatilization and denitrification, and limits the loss of nitrogen and increases nitrogen use efficiency that lead to a nitrogen rate reduction [Bautista et al. 2001].

CONCLUSIONS

The proposed method enabled the assessment of sustainability of the deep fertilizer placement method considering the evaluated priority (weights) of selected criteria based on the mean opinion of scientists, agricultural advisers and farmers. To achieve this goal, the results of the economic, environmental (LCA) and social assessment were incorporated into the multi-criteria analysis (AHP).

The obtained results show that the introduction of practices with the application of deep fertilization obtained a significantly better sustainability performance only where a productivity increase was achieved. However, in the case of a maintained productivity level or a decrease of it, reasonableness of introducing this practice is questionable. It should be underlined that the practice with the surface broadcast application of fertilizers (SB) shows better social performance when compared to the deep placement method (DP). Based on expert opinions, DP was defined as a more difficult fertilizer application method, when compared to SB, due to a higher requirement of specialized knowledge and machinery. It is suggested that if existing social barriers are abolished thanks to educational and training activities, this would greatly contribute to an increase in popularity of deep fertilizer placement methods, which lead to positive environmental effects.

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EFEKTYWNOŚĆ WGŁĘBNEGO STOSOWANIA NAWOZÓW W UPRAWIE KUKURYDZY W ASPEKCIE KRYTERIÓW ZRÓWNOWAŻONEGO ROZWOJU

Słowa kluczowe: kukurydza, nawożenie, ocena zrównoważenia, proces analitycznej hierarchizacji, ocena cyklu życia

ABSTRAKT

Zrównoważenie technologii produkcji w rolnictwie jest coraz bardziej istotne w obliczu obserwowanej zmiany klimatu i konieczności ograniczenia negatywnego wpływu rolnictwa na środowiskowo. Celem pracy jest porównanie aspektów zrównoważenia uprawy kukurydzy z zastosowaniem praktyki wgłębnego i powierzchniowego nawożenia. Na podstawie wyników eksperymentów polowych i opinii ekspertów wyznaczono wartości wskaźników zrównoważenia (aspekt ekonomiczny, środowiskowy i społeczny). W ocenie porównawczej wykorzystano metodę AHP (procesu analitycznej hierarchizacji). Przeprowadzona analiza wykazała, że ocena ekonomiczna, środowiskowa oraz ogólna ocena zrównoważenia warunkowana jest osiągniętym poziomem plonowania. W pierwszym roku prowadzenia doświadczenia, gdy nie uzyskano wzrostu plonowania, praktyka nawożenia powierzchniowego uzyskała wyższą ocenę zrównoważenia w stosunku do praktyki wgłębnego nawożenia. Natomiast w drugim roku badań, gdy uzyskano wyższe plony z praktyką wgłębnego stosowania nawozów, wykazano, że ocena zrównoważenia tej metody nawożenia przewyższa praktykę powierzchniowej aplikacji nawozów mineralnych oraz że uzyskuje podobną ocenę w przypadku nawozów naturalnych.

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