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Environmental and socio-economic performance of different tillage systems in maize grain production: Application of Life Cycle Assessment and Multi-Criteria Decision Making

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A B S T R A C T

The growing need for additional production due to high global food demand should be supplied through sustainable intensification of agriculture. In Poland, conventional tillage with deep full ploughing is still the most common practice, however, it may harm the environment and natural resources. Therefore, this study aimed to evaluate the sustainability of no tillage (NT), reduced tillage (RT) and conventional tillage (CT) in grain maize monoculture based on economic, environmental, and social aspects. Based on the outcomes of long-term field experiments conducted at the Agricultural Experimental Station in Grabów (Mazowieckie Voivodship), life cycle assessment (LCA) and fuzzy analytic hierarchy process (FAHP) were applied to evaluate tillage systems and calculate the criteria weights. Results showed better performance for CT on economic and social criteria while NT and RT had better performances on environmental criteria. The final evaluation illustrated the greatest overall performance for CT followed by RT and NT. Findings emphasized that, in order to achieve a comprehensive view, it is necessary to study the impact of main criteria weights and annual yield variation conditions on the overall performance of alternatives. Sensitivity analysis was conducted combining five weights sets and two production scenarios conditions. The results showed that, except for the environmental criteria, in all other cases CT had the best performance. Moreover, it was illustrated that yield had a significant impact on the overall performance of the tillage systems. The results of final ranking introduced NT with the best performance in a year with the lowest level of grain yield, while on the contrary, under favorable conditions for maximum grain yield, CT was ranked first. According to the obtained results, it is concluded that expectations of climate change leading to increased yield variability may play an important role in the development of conservation tillage systems (RT and NT) in the studied area in Poland.

1. Introduction

Due to high global food demand and restricted arable land, additional production should be supplied through sustainable intensification. In recent decades, sustainability is one of the main challenges in agriculture. To achieve sustainability goals, the compatibility between environmental, economic and social aspects is necessary to be taken into consideration (Velten et al., 2015).

Maize as one of the major crops in European Union (EU-28) accounted for 21% of total cereal production in 2016. Almost 7% of total maize production in EU-28 came from Poland (Forti, 2017). In the last decade, the dynamic growth of cultivated area in Poland has been observed for maize, boosting from 733,000 ha to 1,200,000 ha (Statistics Poland, 2018, 2009).

In Poland, the most common practice in maize cultivation is conventional tillage with deep full ploughing (Księżak et al., 2018b). Despite the fact that conventional tillage (CT) has lots of benefits for

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Abbreviations

AD	Abiotic Depletion
AES	Agricultural Experimental Station
AHP	Analytic Hierarchy Process
AIJ	Aggregation of Individual Judgments
AP	Acidification Potential
CT	Conventional Tillage
EP	Eutrophication Potential
FAHP	Fuzzy Analytic Hierarchy Process
FU	Functional Unit
GHG	Greenhouse Gas
GP	Gross Product
GWP	Global Warming Potential
HY	High Yield
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LY	Low Yield
MCDA	Multiple-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
NT	No Tillage
OC	Operational Costs
ODP	Ozone Depletion Potential
POCP	Photochemical Oxidation Potential
QT	Quantitative
QL	Qualitative
RT	Reduced Tillage
SF	Supplementary File
TFN	Triangular Fuzzy Number

plants (e.g. good seed germination, incorporation of nutrients and better control over soil-borne diseases), it harms environment and natural resources (Hobbs et al., 2007). Tillage is the most energy-intensive operation in cropping systems (Sharma et al., 2011; Sefeedpari et al., 2012). Reduction in the intensity of tillage has several environmental advantages, such as carbon dioxide emissions reduction, carbon sequestration and soil structure improvement (Holland, 2004). No-tillage (NT) systems have less environmental impacts and production costs in comparison to CT systems, but on the other hand they may decrease the crop yield (De Vita et al., 2007). For this reason, farmers in Poland are reluctant to use NT systems (De Vita et al., 2007; Księżak et al., 2018b).

Tillage systems in maize cultivation are a theme of many research studies, however, they have been investigated only from economic (Archer et al., 2008; Sime et al., 2015) or environmental perspective (Bacenetti et al., 2015; Boone et al., 2016; Xue et al., 2014), and their social aspect has been ignored. Due to the fact that economic, environmental and social aspects are the sustainability dimensions, all these need to be considered in a sustainable production system. In previous studies, an inconsistency could be observed in the results of economic and environmental evaluations of different tillage systems. Sime et al. (2015) reported worse economic performance due to tillage simplifications, while contrary results were presented by Archer et al. (2008). Bacenetti et al. (2015) showed better environmental impacts due to simplification in tillage systems. Also, Xue et al. (2014) reported lower greenhouse gas emissions (GHG) for NT compared to CT. However, in the study conducted by Boone et al. (2016), no superiority was reported for reduced tillage systems in comparison to the CT. The reason was the lower yields in those tillage systems.

Regarding the fact that the sustainable assessment needs a holistic evaluation and a multi-criteria decision making (MCDM) allows to consider multiple conflicting attributes, this paper aimed to assess the sustainability of different tillage systems in maize grain production by applying the MCDM method. There are numerous studies on the application of MCDM for evaluating different agricultural systems (Cobuloglu and Büyüktahtakın, 2015; Gupta et al., 2000; Ramírez-García et al., 2015), however, tillage operation has been targeted in a lower number of studies. Some studies evaluated soil tillage practices by MCDM methods (Levy et al., 2000; Torbert et al., 2009), but only few of them considered all three (economic, environmental and social) sustainability aspects (Craheix et al., 2016; Król et al., 2018). For instance, Levy et al. (2000) evaluated the soil tillage practices by applying Web-HIPRE (hierarchical preference analysis software) based on the surface and groundwater criteria. While Torbert et al. (2009) conducted a study to assess different tillage systems in sorghum and wheat production using a fuzzy multi-attributive decision-making (MADM) approach based on the yield, N uptake and economic criteria. Craheix et al. (2016) studied the economic, social and environmental aspects of sustainability using a multi-criteria assessment for different cropping systems. The impacts of tillage operation intensity and crop rotations were assessed using a multi-criteria model. Also Król et al. (2018) considered environmental, financial and socio-economic criteria in a sustainability assessment of different tillage systems in maize monoculture in Poland. In that study, the preference ranking organization method for enrichment evaluations (PROMETHEE) was applied to aggregate the evaluations.

Among various MCDM methods, analytic hierarchy process (AHP) is one of the most powerful and widely used MCDM techniques (Büyüközkan and Karabulut, 2018). The AHP is a method for organizing complex decisions based on a set of pairwise comparisons (Srisawat and Payakpate, 2016). Despite many advantages of AHP methodology, it partially reflects human thinking in some cases of uncertainty, whereas the fuzzy theory represents natural preferences and judgments (Wang et al., 2009). In fuzzy AHP (FAHP) methodology, uncertainties due to different experts' opinion are reflected by the fuzzy membership functions (Houshyar et al., 2014). The fuzzy logic application in AHP methodology was observed in several agricultural research. The GIS-based FAHP method was applied in evaluation of land suitability for different agricultural products such as barley (Hamzeh et al., 2014) and bioenergy plants (Rodríguez et al., 2017). Seyedmohammadi et al. (2018) evaluated the criteria weights through FAHP methodology. Moreover, this methodology was applied to evaluate four irrigation projects based on technical, managerial, environmental, economic and social indicators (Montazar et al. (2013).

According to the literature review, most of the previous studies focused on one or two aspects such as economic or environmental, however, we believe that considering all dimensions of sustainability will give a more comprehensive view to the policy makers and researchers. To the best of our knowledge no similar study has been conducted for different tillage systems in maize grain production. Therefore, we conducted a sustainability assessment for CT, RT and NT, by applying the FAHP algorithm to integrate and aggregate the results of multi-criteria assessments, and also to decrease the uncertainties (due to different opinions and preferences in the social assessments). Since developed countries are faced with the global challenges related to mitigation of environmental pollution, following Castellini et al. (2012), Falcone et al. (2016) and Ren et al. (2015) we decided to integrate life cycle assessment (LCA) and MCDM methods. Therefore, environmental assessments were done using LCA. The novelty of this study is in the integration of different techniques (LCA, fuzzy logic and MCDM methods). Also, we considered the most important criteria in our study, which leads to a more holistic result. Moreover, sensitivity analysis was applied to study the impact of climatic conditions and weighting scenario on final ranking.

2. Materials and methods

This study aimed to evaluate and compare the sustainability of three tillage systems in maize monoculture including no-tillage (NT), reduced tillage (RT) and conventional tillage (CT). This study has been carried out through the methodological framework presented in Fig. 1.

The main steps of the multi-criteria assessment were as follows: (1) description of alternatives – three tillage systems in maize monoculture production; (2) specifying the main criteria (economic, environment and social indicators) and sub-criteria in each main-criterion; (3) evaluation of alternatives based on selected main criteria and sub-criteria by using FAHP methodology and (4) final ranking of tillage systems.

2.1. Field experimental design

Evaluation of three tillage systems was done based on a field experiment. The experiment was conducted at the Agricultural Experimental Station (AES) of the Institute of Soil Science and Plant Cultivation – State Research Institute, in Grabów, the Mazowieckie voivodeship (located at 51°23′N and 21°38′E), Poland, in the period of 2013–2017. The field experiment was established in 2004 on grey brown podsolic soil formed from light loam.

The experiment included three tillage systems of maize monoculture cultivation with four replications. The experimental field was planned in a long strip design with the mirror image of the treatment. Each plot was 180 m^2 at the set-up, while 14 m^2 at harvest. Three types of tillage systems used were: (1) NT, (2) RT and (3) CT. Seed rate for all plots was 30 kg ha^{-1}. The soil under NT treatment was undisturbed. The RT included tillage by grubber (conducted twice). The CT consisted of ploughing, tillage by aggregate and harrow or cultivator. All detailed information about the types and the times of operations are presented in Table S1 in *Supplementary File* (*SF*). To control weeds, herbicides were used. All plots received fertilisation doses of 140 kg N ha^{-1} (70 + 70), 80 kg P_2O_5 ha^{-1} and 125 kg K_2O ha^{-1}. After the harvest operation, residues were shredded and left on the soil surface for NT plots, while turned under with RT and CT treatment.

2.2. Indicators for sustainability assessment

The choice of indicators is the key aspect for evaluation of agricultural business performance (Santiago-Brown et al., 2015). To assess the sustainability of different tillage systems, economic, environmental and social indicators were applied as the main criteria. For each main criterion, several sub-criteria were defined, which can be seen in Table 1.

2.2.1. Economic criteria

It was assumed that the sustainable agriculture is not economically viable if it is not profitable, subsidy independent, and has low economic efficiency index (Colomb et al., 2013; Craheix et al., 2016; Loyce et al., 2012). Thus, profitability (gross margin), economic independence and economic efficiency were specified as the economic sub-criteria. All economic indices were calculated by using Eqs. (1)–(3) as follows (Craheix et al., 2016):

$$GM = GP - OC \quad \text{Eq.(1)}$$

$$EI = \left(\frac{GM}{DS}\right) \times 100\% \quad \text{Eq.(2)}$$

$$EE = \left(\frac{GM}{OC}\right) \times 100\% \quad \text{Eq.(3)}$$

where: GM denotes gross margin (€ ha^{-1}), GP is gross product (€ ha^{-1}), OC shows operational costs (€ ha^{-1}), EI represents economic

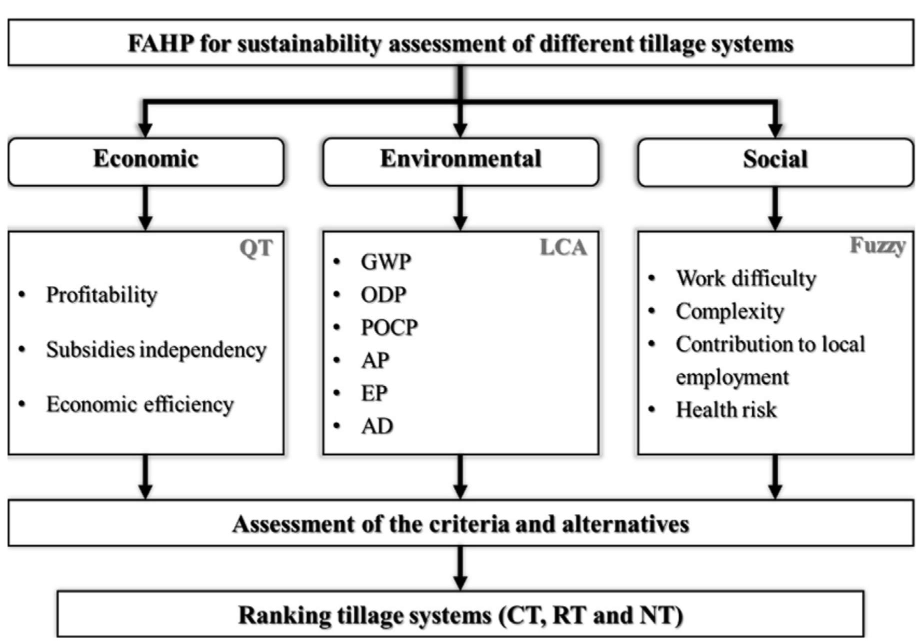

Fig. 1. Framework of FAHP for sustainability assessment of different tillage systems. Methodology for evaluation of sub-criteria was based on quantitative and calculated data (QT); life cycle assessment (LCA) and fuzzy data (fuzzy).

Table 1
Assessment methods for economic, environmental and social criteria evaluation.

Main criteria	Sub-criteria	Unit	Type[a]	Direction	Description
Economic	Profitability	€ ha^{-1}	QT	MAX	Calculated using Eq. (1)
	Subsidy independency	%	QT	MAX	Calculated using Eq. (2)
	Economic efficiency	%	QT	MAX	Calculated using Eq. (3)
Environmental	GWP	kg CO_2 eq kg^{-1}	QT	MIN	All environmental impacts were calculated based on LCIA methodology (CML-IA baseline) using SimaPro 8.5.2.0 software
	ODP	kg CFC-11 eq kg^{-1}	QT	MIN	
	POCP	kg C_2H_4 eq kg^{-1}	QT	MIN	
	AP	kg SO_2 eq kg^{-1}	QT	MIN	
	EP	kg PO_4 eq kg^{-1}	QT	MIN	
	AD	MJ kg^{-1}	QT	MIN	
Social	Contribution to local employment	h ha^{-1}	QT	MAX	___
	Work difficulty	___	QL	MIN	Determined using questionnaires and FAHP methodology
	Complexity of implementation	___	QL	MIN	Determined using questionnaires and FAHP methodology
	Health risk	g ha^{-1}	QT	MIN	___

[a] QT and QL are quantitative and qualitative data, respectively.

independence (%), DS denotes direct subsidies (€ ha^{-1}), and EE is economic efficiency (%).

In order to extract the impact of weather conditions on maize yield and have the same conditions for all the treatments, economic evaluation of alternatives was done for each particular year (2013–2017). To calculate income, grain yield was multiplied with the mean annual price (Statistics Poland) (€ ha^{-1}). Total income was calculated by adding the subsidies (the single area payment, greening payments and additional payment) to the farm income. Gross product (GP) considers maize grain yield, grain price and subsidies. Operational costs (OC) included seeds, plant protection products, fertilisers, labour, fuel, maintenance and outsourcing costs (sowing, harvesting and grain drying). Regarding the fact that fixed costs (such as agricultural taxes) are not related to a specific tillage system, they were not included in calculations. Data related to input consumption (seeds, fertilisers, plant protection product use) as well as obtained yield level were collected from long-term experiment. Machinery use, labour and fuel consumption were estimated based on data provided by Agricultural Advisory Centres and literature. The prices for agricultural inputs were obtained from commercial offers, literature and data provided by Agricultural Advisory Centres. Details about data sources for economic indicators evaluation can be found in Table S2 in SF.

2.2.2. Environmental criteria

Since the environmental impact of agricultural operation is a wide range concept, it is difficult to find a recognized and unique method for environmental evaluation. To determine and compare the environmental impacts of three tillage systems, LCA was applied which is the most common method for environmental assessment. A fundamental step for any LCA study is defining a functional unit (FU). Some LCA studies used a land-based FU (Houshyar and Grundmann, 2017), while others used a mass-based FU related to maize crop production (e.g. Bacenetti et al., 2015; Boone et al., 2016). In studies comparing different cropping systems (with different amount of yield), the mass-based FU (e.g. 1 kg) is recommended. Therefore, in this study FU was defined as 1 kg of maize grain at standard water content required for storage (15%). System boundary was defined from cradle to farm gate (Bacenetti et al., 2016; Boone et al., 2016). Three tillage systems were evaluated and compared along the whole life cycle of the maize production regarding different farm operations including tillage, fertilisation, sowing, plant protection application, harvesting, transporting and drying. Due to the complexity of study, different data sources were combined (see Table S3 in SF). The inventory for different tillage systems is presented in Table S4 and Table S5 in SF. Data regarding the yield level, inputs usage (seeds, fertilisers, plant protection product and etc.) were collected from a long-term experiment. Data associated with the fuel consumption, lifetime, weight and the use of machinery were estimated based on the data provided by Agricultural Advisory Centres, tractor specifications and literature. Data on nitrous oxide emissions (direct and indirect N_2O emissions) were estimated according to IPCC (De Klein et al., 2006). Due to the fact that after the harvest operation the straw was left on the field, the annual amount of N in crop residues returned to the soil was included in N_2O emissions calculations. The emissions associated with the production of inputs were obtained from Ecoinvent 3.4 database (Wernet et al., 2016). Changes in the overall soil carbon content were not considered. Life Cycle Impact Assessment (LCIA) quantifies emissions and environmental burdens with respect to different environmental impact categories along the whole life cycle of a product (Castellini et al., 2012). LCIA was carried out based on CML-IA baseline method using SimaPro 8.5.2.0 software (Goedkoop et al., 2016). Impact categories applied in this study were global warming potential (GWP), ozone layer depletion potential (ODP), photochemical oxidation (POCP), acidification potential (AP), eutrophication potential (EP), and abiotic depletion, fossil fuels (AD).

2.2.3. Social criteria

Sustainable agriculture should be socially acceptable for the society and producers. According to the literature (Colomb et al., 2013; Craheix et al., 2016; Hanegraaf and Biewinga, 1998; Sadok et al., 2009), four social criteria were selected for assessing three tillage systems. Three criteria including "work difficulty", "complexity of implementation", and "health risk" are the social criteria which are important for producers, while "contribution to local development" is important for society. "Work difficulty" corresponds to the level of difficulty related to other agricultural operations (such as seed sowing, weeds control and fertilisation) and higher requirement for specialized knowledge and specific machineries as a result of applying different tillage systems in maize production. "Complexity of implementation" regards the operations' interdependencies and the number of machineries and equipment required. "Health risk" corresponds to the amount of active ingredient content in plant protection products (g ha^{-1}). "Contribution to local employment" corresponds to annual labour requirement (h ha^{-1}). More detailed description of selected social indicators can be found in Section S4 in SF.

The data sources for social indicators evaluation are presented in Table S6 in SF. "Contribution to local employment" and "health risk" were calculated based on experimental field data and data provided by the Agricultural Advisory Centre. "Work difficulty" and "complexity of implementation" of tillage systems were evaluated based on producers' opinions. These two criteria are subjective so there will be a difference in their evaluation according to respondents' skills and educational level.

2.3. Fuzzy analytic hierarchy process (FAHP)

The uncertainties play an important role in modelling (Hu et al., 2018). The uncertainty is a part of many natural systems and there is a growing need for reducing the uncertainties to increase the reliability (He et al., 2018; Zhou et al., 2019). To study the uncertainties, many methods can be applied including sensitivity analysis, first-order error analysis (FOEA) and the Monte Carlo (MC) method (Shen et al., 2008). Furthermore, various optimization methods may be used to reflect the uncertainties, such as: stochastic analytical approach (Guo et al., 2018), Markov stochastic process (Hu et al., 2018), interval parameter programming (IPP), stochastic mathematical programming (SMP) and fuzzy linear programming (FLP) (Li et al., 2018; Zhou et al., 2016).

The lack of uncertainty analysis in decision support processes reduces the robustness of the final results (Chen et al., 2018). There is a large number of multiple criteria decision analysis (MCDA) approaches with uncertain attribute evaluations, such as: probabilities, decision weights, explicit risk measures, fuzzy numbers, and scenarios. A review of MCDA for uncertain decision problems can be found in (Durbach and Stewart, 2012). In a fuzzy MCDM, fuzzy sets and numbers are applied to model the uncertainty elements of a decision making (DM) process.

Due to the fact that comparison process has a fuzzy nature, it is difficult for the decision makers to identify their preferences. Therefore, it is more convenient to make a decision based on linguistic judgments rather than crisp value logic (Wang et al., 2009). Fuzzy logic is considered as a part of the computational intelligence (Morar et al., 2018; Sefeedpari et al., 2014, 2015). Fuzzy logic approach was introduced by Zadeh (1965). FAHP is a kind of MCDM method that combines AHP and fuzzy logic. The FAHP was firstly presented by Van Laarhoven and Pedrycz (1983), in order to reflect experts' uncertainties and deal with the subjectivity and vagueness in the alternatives selection of the judgments (Houshyar et al., 2014; Hsieh et al., 2004). Furthermore, Buckley and Uppuluri (1987) extended AHP method by applying the geometric mean method for fuzzy weights calculations.

In this study, FAHP method was applied for social assessment (evaluation of work difficulty and complexity) of different tillage systems based on farmers' and experts' opinions. Also, FAHP was applied for determining the sub-criteria weights. The major reason for application of fuzzy set theory is that, there are no crisp boundaries to define objects that belong to the classes or not (Bellman and Zadeh, 1970). Furthermore, while a panel of experts is involved in a DM process and the linguistic scales are used, the application of fuzzy numbers is very important (Bottani and Rizzi, 2006). However, besides several advantages, on account of diversity of defuzzification methods, unstable results may be obtained by FAHP (Wang et al., 2009).

The triangular fuzzy numbers (TFNs) were applied in this study as a membership function. According to Kwiesielewicz (1998), Van Laarhoven and Pedrycz (1983) a TFN may be expressed as follows:

$$\tilde{a} = (l_a, m_a, u_a) \qquad \text{Eq.(4)}$$

where l_a, m_a, u_a, are lower, modal and upper values of a fuzzy number $\tilde{a}$, with $l_a \le m_a \le u_a$.

The judgment's degree of fuzziness is expressed by parameter δ, where $\delta = m - l = u - m$ (Kamvysi et al., 2014; Promentilla et al., 2008). The value of δ defines the suitable judgment's degree of fuzziness, $\delta = 0$ implies a non-fuzzy number, $\delta = 1$ indicates moderate fuzziness, while $\delta = 2$ means significant fuzziness (Kamvysi et al., 2014). Choice of δ value varied between researches, Kamvysi et al. (2014) used $\delta = 1$, while Hsieh et al. (2004) applied $\delta = 2$. Since Zhu et al. (1999) suggested $0.5 < \delta < 1$ as a proper term, following Kamvysi et al. (2014) we decided to apply δ as equal to 1. The linguistic scale used in the FAHP and corresponding TFNs are presented in Table S7 in SF. The comparison matrices on the basis of the mean opinion of 18 respondents by using the geometric mean are presented in Tables S8−S12.

The procedure of FAHP method can be summarized in the following steps:

Step 1. Construction of pairwise comparison matrices $\tilde{A}$ among social criteria and alternatives (Hsieh et al., 2004):

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{2n} & \cdots & 1 \end{bmatrix} \qquad \text{Eq.(5)}$$

Step 2. Determining the fuzzy geometric mean of each criterion (Buckley and Uppuluri, 1987; Hsieh et al., 2004):

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \cdots \tilde{a}_{in})^{\frac{1}{n}} \qquad \text{Eq.(6)}$$

where $\tilde{a}_{in}$ is the value of fuzzy comparison of criterion i to criterion n.

Step 3. Determining the fuzzy weights for each criterion (Buckley and Uppuluri, 1987; Hsieh et al., 2004):

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \cdots \oplus \tilde{r}_n)^{-1} \qquad \text{Eq.(7)}$$

where $\tilde{r}_i$ is a geometric mean of fuzzy comparison of criterion i to each criterion.

Step 4. Defuzzification of TFNs by application of the formula (Yager, 1981; Bottani and Rizzi, 2006):

$$\frac{Lw_i + 2Mw_i + Uw_i}{4} \qquad \text{Eq.(8)}$$

where Lw_i, Mw_i and Uw_i are the lower, mean and upper values of the fuzzy weight of the *i criterion*, respectively.

2.4. Criteria weights for decision making

The main criteria as well as the economic and social sub-criteria' weights were estimated based on group decision making process and FAHP methodology. The FAHP was carried out on the basis of the mean opinion of 18 respondents. The calculated inconsistency index for each individual should be less than 0.1 (Saaty, 1994, 2008). In this study the group decision making process was applied, since the individual opinions may differ between respondents. The individual opinions may be combined into group judgments by Aggregation of Individual Judgments (AIJ) method based on a geometric mean. The elements of aggregated comparison matrix $\widehat{A}_g$ may be described by the following formula: $(a_{i,j})_g = \sqrt[N]{\prod_{n=1}^{N} (a_{i,j})_{Ind\_n}}$, where $(a_{i,j})_{Ind_n}$is the judgment of the individual n (Forman and Peniwati, 1998; Parra-Lopez et al., 2007).

Regarding to the fact that there is much disagreement about the importance of environmental impact categories, we used the weighting set for the environmental indicators provided by Sala et al. (2018). The provided weighting set is based on panel-weighting method. It also takes into account the aspects of the robustness of the results. More detailed information about the applied weights and the common weighting approaches for environmental indicators can be found in Section S6 in SF.

2.5. Sensitivity or scenario based analysis

An essential component of FAHP decision-making models is a sensitivity analysis that shows the robustness of the final ranking in different conditions. There is a strong relation between the final alternatives evaluation and the main criteria weights, where even a small change in a value of criteria priorities may affect the final ranking (Balusa and Gorai, 2019). Many authors considered the sensitivity analysis in multi-criteria evaluation (See *Section S7* in *SF* for more details). In this study, two types of sensitivity analyses were performed by applying i) different weights sets for the main criteria and ii) the two states of nature scenarios. To have a deeper analysis and wider assessments, five cases (five viewpoints) were considered for the weights of each main criterion (economic (wec), environmental (wen) and social (ws)). Following Ren et al. (2015), the subsequent weight sets were examined: equal importance of sustainability dimensions (Case 1), one dominant sustainability dimension with the remaining of equal importance (Cases 2–4). Additionally, we considered a case where both economic and environmental criteria have an equal importance and greater than social criterion (the weights was 40% for each criterion). More specifically, we assumed the Case 1 as the most common viewpoint (the equality viewpoint), where all the economic, environmental and social criteria have the same importance. Case 2 is the producers' viewpoint where the economic criterion has the greatest weight. In the ecologists' viewpoint (Case 3) the environmental criterion has the greatest weight. From the society's point of view (Case 4) it is the social criterion that has the greatest importance and weight. Finally, based on a viewpoint that concerns both economic and environmental aspects of a production system (Case 5), economic and environmental criteria have the highest weights. All the classification and weights can be found in Table 2.

In this study, the effect of annual yield variation on the performance of different tillage systems was also assessed. It was assumed that many parameters such as weather conditions influence maize yield (Boone et al., 2016). This assessment helps to have a better view about the different tillage systems and to identify the impact of exogenous parameters such as weather conditions on the final results. This dimension can be taken into account as a separate sub-criterion in the form of risk parameters (standard deviation of yield and income). However, we studied this impact by considering two production scenarios including i) LY, low yield scenario and ii) HY, high yield scenario. These scenarios can represent poor and favorable weather conditions, respectively. Years 2015, 2016 were selected as LY and HY scenarios. The grain maize yield for different tillage systems varied from 1.01 to 3.34 t ha^{-1} for LY scenario, whilst for HY scenario yields ranged between 10.19 and 14.08 t ha^{-1}). During the cultivation season (from April to October) the sum of precipitation in HY scenario was higher than in LY scenario by 13%. It should be highlighted that, in LY scenario, drought duration was a critical factor as during some months the precipitation sum did not exceed 35 mm, while the mean temperature did not differ between the two scenarios.

3. Results and discussion

3.1. Economic assessment

Table 3 shows the results of the comparison of tillage systems based on profitability, subsidy independence and economic efficiency sub-criteria. Average gross product and production costs (2013–2017) of the different tillage systems are presented in Table S13 in SF. As it can be seen, CT had the highest levels for all economic sub-criteria, followed by RT and NT. CT was the most profitable tillage system, with 355.30 € ha^{-1}, followed by RT, with 266.45 € ha^{-1} and NT with 237.14 € ha^{-1}. The costs for CT were higher than in NT and RT due to more intensive tillage that results in higher costs of labour, fuel consumption, use of own machinery and higher costs related to outsourcing on account of higher yield and consequently higher grain drying costs. However, despite the reduction of costs in NT, gross margin is reduced due to lower gross product as a result of lower yields. Results obtained from experimental field showed the highest average yield level (for 2013–2017) for CT (8.93 t ha^{-1}) followed by RT (8.21 t ha^{-1}) while NT had the lowest yield (7.34 t ha^{-1}). However, within the analysed timeframe, NT achieved the highest yield level in 2015 and 2017. In previous studies, there is an inconsistency in a comparative yield evaluation within tillage systems. Lu and Liao (2017) observed no significant yield difference in NT, RT and CT while, Jat et al. (2013), Parihar et al. (2016), Seddaiu et al. (2016), Sekutowski (2009) and Sime et al. (2015) reported a significant impact of tillage systems on yield. Our results were similar to the ones obtained by Giuliano et al. (2016), Seddaiu et al. (2016) and Sekutowski (2009), where concluded simplification in tillage management reduces maize grain yield. Smith and Chalk (2020) noticed that in generally, CT obtained higher yield than NT, however the yield advantage is reducing while N fertiliser rate is increasing. Nonetheless, in some studies higher yield was seen in NT system in comparison to CT (Jat et al., 2013; Parihar et al., 2016).

Results of the economic assessment were similar to the results obtained by Sime et al. (2015) which reported that replacing CT by conservation tillage systems reduces gross margin as well as income. Księżak et al., 2018a highlighted that the amount of changes depends on the analysed period and location. In contrary to our results, higher net returns were reported for NT system in comparison to CT in some studies (Archer et al., 2008; Jat et al., 2013; Lu and Liao, 2017; Parihar et al., 2016). Furthermore, in few studies RT had the higher net income in comparison to CT (Gathala et al., 2015; Jat et al., 2013). These various results can be explained by diversity in climate and soil conditions as well as field management variation.

3.2. Environmental assessment

Results of environmental impacts for different tillage systems are shown in Table 3. The best environmental performances (lowest environmental impacts) for almost all evaluated impact categories (except ODP) were obtained for RT followed by NT, while the CT obtained the worst environmental performance for all evaluated impact categories. As it can be seen, there was a big difference between environmental impacts for CT and conservation tillage systems (NT and RT), however, the differences for RT and NT were less than 4%. The environmental impact of RT was slightly lower

Table 2
Weights of main criteria based on different perspectives.

	Weights of main criteria		
	Economic criterion (w_{ec})	environmental criterion (w_{en})	social criterion (w_s)
Case 1	0.33	0.33	0.33
Case 2	0.50	0.25	0.25
Case 3	0.25	0.50	0.25
Case 4	0.25	0.25	0.50
Case 5	0.40	0.40	0.20

Table 3
The results of economic, environmental and social indicators evaluation for different tillage systems (mean from 2013 to 2017).

Items	Unit	NT	RT	CT
Economic indicators				
Profitability	€ ha^{-1} $year^{-1}$	237.14	266.45	355.30
Subsidies independency	%	107.14	120.38	160.52
Economic efficiency	%	23.34	23.98	31.65
Environmental indicators				
GWP	kg $CO_{2\ eq}$ kg^{-1}	0.59	0.57	0.85
ODP	kg CFC-11 $_{eq}$ kg^{-1}	2.79×10^{-8}	2.83×10^{-8}	4.70×10^{-8}
POCP	kg $C_2H_{4\ eq}$ kg^{-1}	1.00×10^{-4}	9.64×10^{-5}	1.27×10^{-4}
AP	kg $SO_{2\ eq}$ kg^{-1}	2.26×10^{-3}	2.21×10^{-3}	3.02×10^{-3}
EP	kg PO_4^{-} $_{eq}$ kg^{-1}	8.88×10^{-4}	8.60×10^{-4}	1.37×10^{-3}
AD	MJ kg^{-1}	3.98	3.91	5.63
Social indicators				
Contribution to local employment	h ha^{-1}	7.47	9.52	10.80
Health risk	g ha^{-1}	2217.45	2217.45	849.45
Work difficulty	–	0.52	0.29	0.19
Complexity	–	0.10	0.24	0.67

than in NT (except ODP impact category) in spite of tillage simplification. This unexpected worst environmental performance in NT results from lower yield. For RT, higher environmental impact is achieved for ODP than in NT due to substantial tillage contribution (8%) in total emission.

In comparison to our study, Bacenetti et al. (2015) reported a slight reduction of the environmental burdens by simplification of field operations in maize silage production. However, Boone et al. (2016) reported slight differences (less than 6%) between environmental impacts of NT, RT and CT in maize grain production, except freshwater eutrophication impact category.

The evaluated GWP ranged from 0.57 kg $CO_{2\ eq}$ for RT, through 0.59 kg $CO_{2\ eq}$ for NT to 0.85 kg $CO_{2\ eq}$ for CT per 1 kg of maize grain. Although environmental impact assessment of maize grain production was considered in several studies, a comparison of the results is rather difficult due to different LCIA methodology (Bacenetti et al., 2016; Boone et al., 2016; Noya et al., 2015), system boundaries (Goglio et al., 2012; Noya et al., 2015) and functional units applied (Goglio et al., 2012). The achieved results of GHG emissions are close to those obtained in literature. Żyłowski et al. (2018) reported that the total GHG emissions per 1 kg of maize grain ranges from 0.23 to 0.78 kg $CO_{2\ eq}$. Noya et al. (2015) showed that GHG emissions from maize grain cultivation vary between 0.37 and 0.63 kg $CO_{2\ eq}$ per 1 kg depending on the maize class. Results obtained by Zhang et al. (2017) reported GHG emissions of maize production as 0.48 kg $CO_{2\ eq}$ per 1 kg.

In addition to mass based FU, land based FU was applied for environmental assessment. Table S14 in SF shows the environmental impacts per cultivation area. While land based FU was applied, the best environmental performances (lowest environmental impacts) for all evaluated impact categories were obtained for NT. As it can be seen, the differences between environmental impacts of RT and CT were less than 2%. RT had the worst environmental performance (except for ODP) in spite of lower emissions related to tillage due to higher emissions related to yield drying process. It is caused by higher amount of evaporated water as a result of higher grain moisture content in RT than in CT. GWP ranged from 3836 kg $CO_{2\ eq}$ for NT, through 3982 kg $CO_{2\ eq}$ for CT to 4032 kg $CO_{2\ eq}$ for RT per 1 ha. These results were in agreement with the results obtained by similar studies. Żyłowski et al. (2018) reported that the total GHG emissions for maize grain production varied between 1178 and 4636 kg $CO_{2\ eq}$ per 1 ha. Zhang et al. (2017) reported GHG emissions of maize production as 4052 kg $CO_{2\ eq}$ per 1 ha. In comparison to our study, Ma et al. (2012) determined lower GHG emissions in maize monoculture with similar fertilisation dose, which ranges from 2528 kg $CO_{2\ eq}$ to 3143 kg $CO_{2\ eq}$ per 1 ha. The differences may be due to different system boundary. In our study we considered the grain drying process, while other authors did not determine it in their calculations.

Evaluation of environmental impacts based on two functional units showed that, although application of NT system in comparison to CT led to less environmental impacts per hectare, due to a big reduction in grain yield, NT system had greater environmental impacts per kg grain (except 2015 and 2017 year). Despite the fact that in most of the studied years (with the exception of 2015) NT had greater environmental impact per kg grain than CT, CT had the greatest average environmental impacts for years 2013–2017. It was due to the fact that much higher emissions were determined for CT than in NT in 2015 (because of low yield), while in the remaining years the differences were lower.

3.3. Social assessment

The results of social assessment for different tillage systems are presented in Table 3. CT was the highest rated tillage system based on all social sub-criteria except for complexity indicator.

While CT was reported as the most complex system, NT was selected as a system with the least complexity. According to obtained results, contribution to local employment (h ha^{-1}) will decrease due to shifting from CT to RT and NT by 12% and 31%, respectively due to avoidance or reduction of workload required for tillage. The CT which involved ploughing, required the highest workload for tillage (3.80 h ha^{-1}) and, consequently, the highest amount of total working time (10.80 h ha^{-1}). Our results were in agreement with those obtained by Craheix et al. (2016), Gathala et al. (2015), Giuliano et al. (2016), and Šarauskis et al. (2014) who illustrated that RT and NT, reduce the labour demand. According to Craheix et al. (2016) research, higher labour requirement has a positive effect on local employment. However, according to some studies, labour demand reduction may be desirable in creating the possibility of carrying out other agricultural operations that are important at the time of autumn tillage (Šarauskis et al., 2014).

Due to higher application of biocides in NT and RT systems, the higher health risk values were determined for these tillage systems in comparison to the CT system. These results were in agreement with the Craheix et al. (2016) finding that also indicated negative impact of simplified tillage systems on the criteria related to health risk due to higher phytosanitary products use. Xue et al. (2014) noted that theoretically lower requirement for pesticides is observed within CT systems due to reduction of weeds by moldboard or field cultivator. The NT was defined as the most difficult tillage system with greater difficulty for farmers (to seed placement, plant protection, fertilisation placement and problem with volunteer plants) and higher requirement for specialized knowledge and specific machineries. The CT was determined as the most complex system with greater difficulty for farmers related to the number of operations required (subsequently the number of machineries and equipment required) due to more intensive tillage.

3.4. Criteria weights

Fig. 2 shows the criteria weights evaluation according to pairwise comparisons. In other words, the weights are the priority or importance value of each criteria in comparison to the other ones regarding the opinions of farmers, decision makers and specialists. According to respondents, economic issues had the greatest priority, while the social and environmental efficiency were less important. As it is seen, in the economic main criterion, profitability had the largest priority, followed by economic efficiency and subsides independency. Between the social sub-criteria, work difficulty was the most important criteria and health risk, complexity of implementation, and contribution to local employment were in the next places (Fig. 2). As discussed previously, the applied weights for environmental indicators were based on Sala et al. (2018). As it is seen, GWP, followed by AD, have the greatest importance while the priority of ODP, AP, EP and POCP is much lower.

3.5. Final ranking

After evaluating three tillage systems based on economic, social and environmental sub-criteria and weighting the sub-criteria by using FAHP, the results were aggregated and ranked. The relative comparison of tillage systems regarding to the sub-criteria and the main criteria are presented in Figs. 3 and 4 respectively. These figures show the priority of each alternative in comparison to the other alternatives regarding to a sub-criterion and a main criterion. As mentioned above in Table 1, there were a number of criteria to be maximized while the rest of criteria had to be minimized. In order to make the results comparable, the values obtained were normalized so that the same non-negative results were produced. The new values were considered as an indication of performance. In Fig. 3, performance of the alternatives for each sub-criterion is shown in percentages summing up to 100%. In environmental impact categories, CT had the least relative performance, which means that this alternative had the greatest environmental impact in comparison to the other alternatives. As it has been discussed in detail in Sections 3.1 to 3.3, CT had the best economic performance while RT and NT showed the best performance for the environmental sub-criteria (the least environmental impacts). In the social criterion, CT showed the best performance for almost all sub-criteria except complexity, where the best performance was seen for NT.

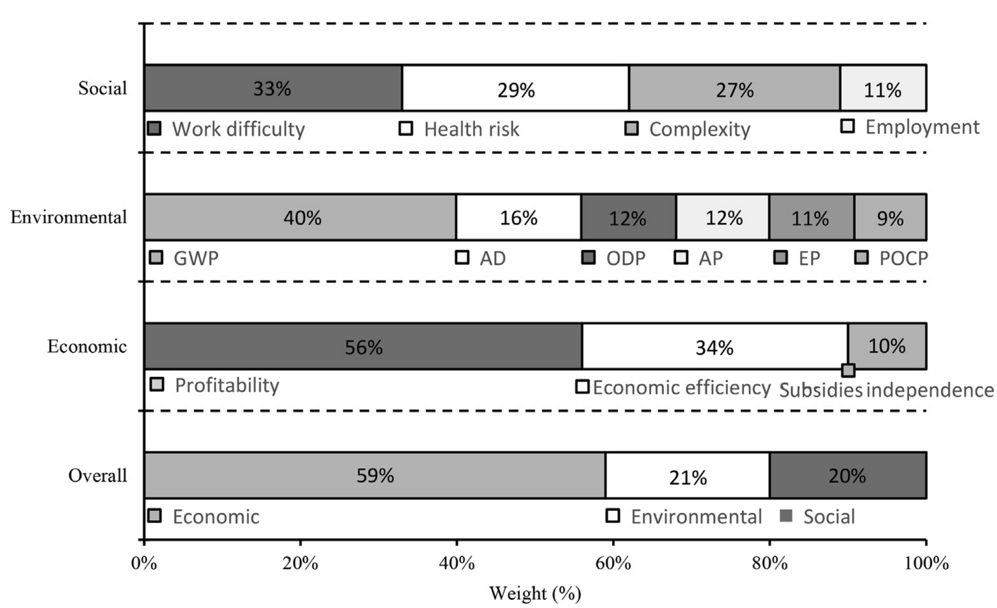

Fig. 2. The relative importance (weights) for sub-criteria and main criteria according to pairwise comparisons.

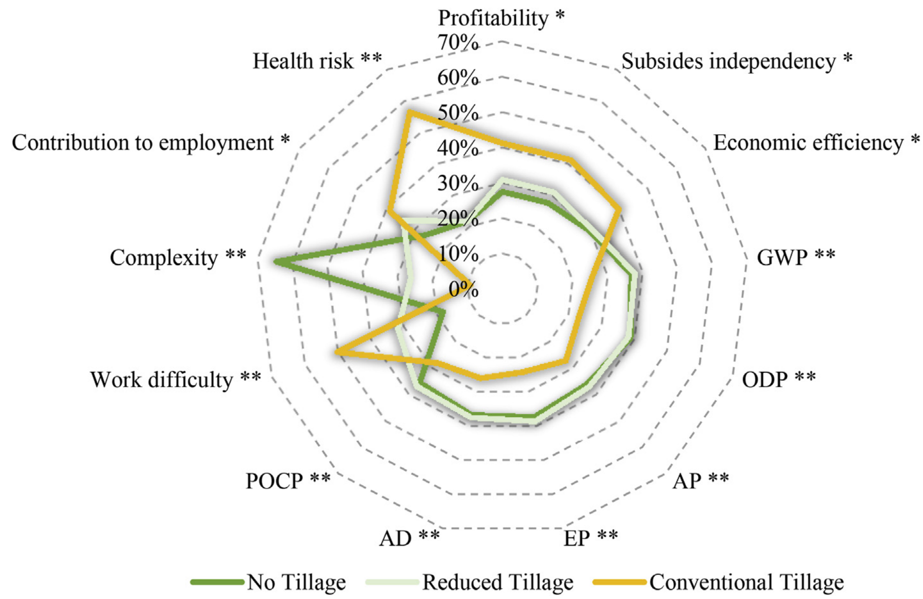

Fig. 3. Relative comparison of three tillage systems based on different sub-criteria.* and ** are the criteria which aimed to be maximized and minimized, respectively. Values have been normalized and the greater values indicate the better performance.

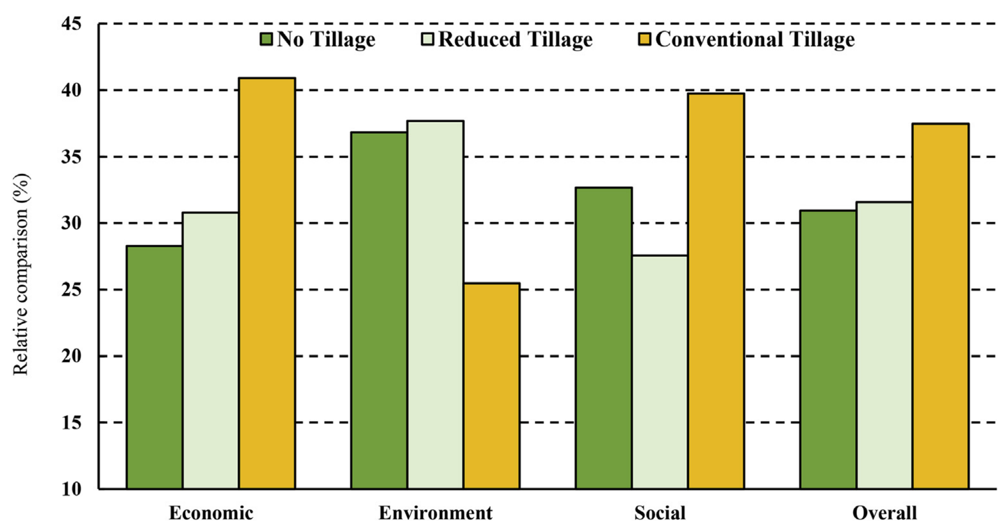

Fig. 4. Relative comparison of three tillage systems based on economic, environmental, social criteria. The overall column is final ranking of three tillage systems. Values have been normalized and the greater values indicate the better performance.

The results of relative comparison of three tillage systems based on economic, environmental and social criteria showed that CT had the greatest performance in economic and social criteria while the lowest performance was reported for this tillage system regarding the environmental aspect (Fig. 4). Comparison of NT and RT showed that from the economic and environmental point of view RT performed better, while from the social perspective NT had better performance. Our results were similar to the results obtained by Craheix et al. (2016) who reported the best social performance for CT, whilst regarding the environmental aspect the best options were NT and RT. The final rank using MCDA allowed to pinpoint the most sustainable tillage system in maize grain monoculture in accordance with the studied criteria. The overall evaluation shows that the CT was the most sustainable alternative (Fig. 4).

Considering limitations of current study, for further research more regional studies need to be conducted and also a broader assessment may be needed for a full evaluation. Various parameters like climatic conditions and soil N_2O emission may affect the results of sustainability assessment which were neglected in our study. Also, it is recommended to conduct similar assessment for different crops or different crop rotations. Extending the expert group would help to include more various points of view (e.g. economists and farmers) to the sustainability assessment. Furthermore, climate change impact may affect the sustainability assessment of maize. Projected climate change impact may be investigated by regional climate models (RCM) approaches (Zhou et al., 2018). The environmental and sustainability assessment may be also improved by the use of tools that can be adaptable to local conditions (Lovarelli et al., 2017). Moreover, the effect of tillage systems on soil carbon stocks may be considered in order to increase the assessment precision (Bacenetti et al., 2015). Additionally, with respect to the fact that soil-borne N_2O emissions may increase under conservation tillage, while it also can reduce nitrate leaching, it is suggested to consider N_2O emissions in future studies (Krauss et al., 2017; Prechsl et al., 2017).

3.6. Sensitivity or scenario based analysis

3.6.1. Weighting cases for main criteria

A sensitivity analysis was performed by assessing different weighting cases for the main criteria to test ranking stability, and the final ranking differs according to the weights assigned by different cases (Fig. 5). Regarding the sustainable point of view described by Case 1, where all dimensions are equally important, the best performance was obtained for the CT followed by NT and RT. In Case 2 (with the biggest focus on economic aspects) and in Case 5 (with the high weights assigned to the economic and environmental criteria), the CT was the most sustainable alternative while RT was the second choice. From the environmental viewpoint (Case 3), the ranking was changed and NT was ranked first, followed by RT and CT. In this case, environmental aspect had the highest importance. Considering Case 4 with the high weights assigned to social criteria, the CT was the most sustainable alternative, followed by NT, and RT.

To sum up, taking into consideration the economic, environmental and social dimensions, the CT system had the best overall results for the studied cases, except for Case 3. The obtained results (based on Case 1) were not in a good agreement with the results reported by Craheix et al. (2016) which showed RT as a tillage operation with the best performance. The results obtained by Craheix et al. (2016) showed that simplification in tillage system does not harm the cropping systems sustainability scores when diversified crop rotation is involved. However, when diversified crop rotation was not coupled with direct seeding, the lowest sustainability evaluation was achieved. Moreover, Archer et al. (2008) reported NT as a good option for replacing the CT system due to economic and environmental benefits. As we discussed previously, the higher performances were reported in our study for the CT in comparison to the NT and RT within economic dimension, which resulted from the greater maize grain yield in CT. This can be due to weather and soil conditions in the study area. Seddaiu et al. (2016) reported heavy constrains in maize productivity due to severe water stress that appears during the reproductive phases. De Vita et al. (2007) showed that in dry year conditions, greater grain yields were observed under NT system, while in wet year conditions CT system achieved greater yields. According to previous studies, the most likely reasons of lower yield and economic performance in NT and RT can be explained by the temporary waterlogging (Sime et al., 2015) and increased number of weeds (Sekutowski, 2009; Sime et al., 2015) which is compounded by monoculture.

3.6.2. Production scenarios - year to year variation

All the previous assessments and evaluations were based on the average value of criteria for 2013–2017 timeframe. In this section the results of a sensitivity analysis for two production scenarios (LY and HY scenarios) are reported. The obtained results showed that year to year variation affects the results of economic, environmental and social evaluations for different tillage systems as well as the final ranking (see Table S15 and Figs. S1–S3 in SF). In LY scenario, for economic and environmental criteria evaluation as well as for overall evaluation, NT obtained the first rank, whilst for social criteria CT was ranked first. In HY scenario, CT was the best tillage system. In both scenarios, RT was the second choice.

In a more detailed evaluation, based on the economic main criterion, HY and LY scenarios have impacts on economic sub-criteria mainly due to year to year yield, subsidies and prices variations. In case of LY scenarios, the best economic evaluation was obtained for NT, while in HY scenario CT system was the best. Yield reduction decreases economic evaluation due to lower output (production value) with almost unchanged input (costs).

Similar to previous studies conducted by Bacenetti et al. (2016) and Boone et al. (2016), our results showed that yield variability highly affects the environmental performance indirectly. Yield reduction increases the environmental impacts due to lower output in a production system with almost the same amount of inputs usage. However, yield increase causes N_2O emissions from soils due to higher N input from crop residues management.

When considering the social main criterion, year to year yield variations had impact on the contribution to local development and health risk sub-criteria. In case of the contribution to local development and health risk sub-criteria, CT had the best evaluation for LY and HY scenarios, while differences between the preferences of tillage systems were larger in HY scenario.

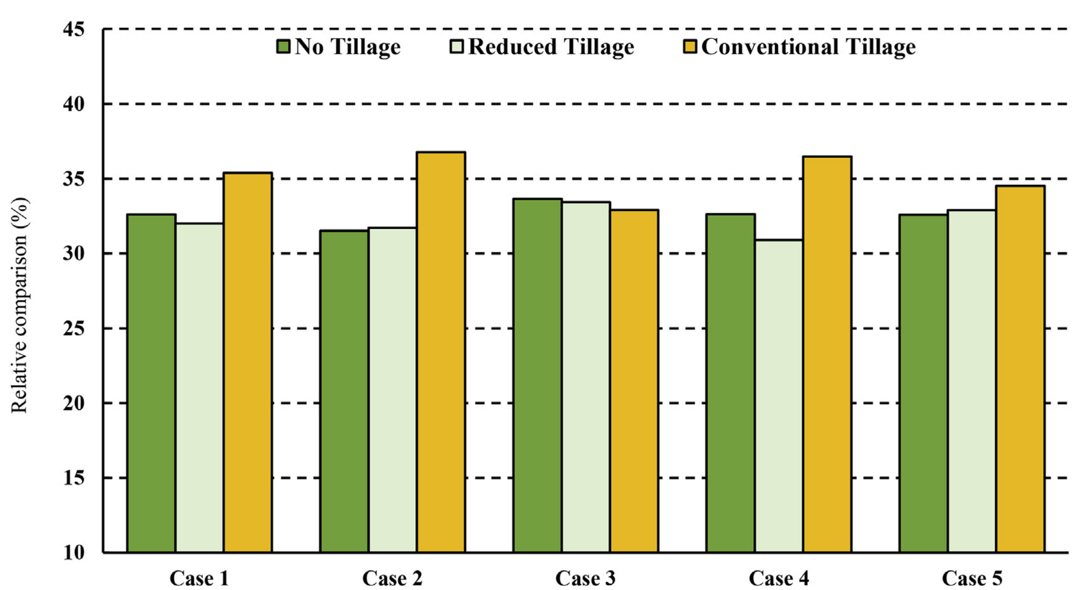

Fig. 5. Final ranking of three different tillage systems according to five weighting cases. Values have been normalized and the greater values indicate the better performance.

4. Conclusions

This paper evaluated the sustainability of different tillage systems (NT, RT and CT) for maize grain monoculture production based on data provided by long-term field experiment. Tillage is the most energy intensive operation in cropping systems and decreasing the intensity of tillage operation has some positive economic and environmental impacts while it may decrease the crop yield. Therefore, the sustainability (considering the economic, environmental and social aspects) of different tillage operations was evaluated by using a decision making process. To aim this goal, besides the economic and social analysis, LCA and FAHP methodologies were applied. The criteria weights were assigned using experts' opinions and the corresponding uncertainties were decreased using FAHP method and the fuzzy membership functions. Furthermore, the sensitivity analysis was conducted to show the changes in the final ranking of tillage systems due to changes in the main criteria weights and annual yield variation.

The results of relative comparison of three tillage systems based on environmental criterion showed the greater performance for RT and NT compared to CT, while CT had the best performance in the economic and social criteria. The obtained results revealed that the grain yield plays an important role (as a limiting factor) in the extension of conservation tillage systems (RT and NT) in Poland. Due to high impact of economic results, the overall evaluation showed that the CT was the most sustainable alternative, followed by RT and NT.

Sensitivity analysis showed that the final ranking of sustainability assessment depends on the conditions of the field experiments and choices made during the methodology implementation. The preference cases as well as the yearly yield variation affected the final evaluation. According to the sensitivity results for different weighting cases for the main criteria, the CT system had the greatest performance in four out of five cases, while the NT system was ranked first only in the case in which the environmental criterion had the highest importance compared to the other criteria. Sensitivity analysis results for different production scenarios showed that in high yield scenario, CT was ranked first, followed by RT, whilst in low yield scenario the ranking conversely changed.

CRediT authorship contribution statement

Aleksandra Król-Badziak: Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Seyyed Hassan Pishgar-Komleh:** Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - review & editing. **Stelios Rozakis:** Conceptualization, Writing - review & editing. **Jerzy Księżak:** Investigation, Resources, Data curation, Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.123792.

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