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ENVIRONMENTAL EFFICIENCY OF ROOT CROP CULTIVATION[1]

Key words: efficiency, sugar beets, potatoes, carbon footprint, SBM-DEA

ABSTRACT. In this study environmental efficiency of main root crop (sugar beets and potatoes) cultivation in Poland is evaluated. Survey data from 62 sugar beet and 74 potato farms in the years 2016 and 2017 were used for analysis. To assess efficiency, the slack based Data Envelopment Analysis model (SBM-DEA) was used, where greenhouse gas emissions were assumed as undesirable output. The reasons for inefficiency in cultivation were explained using the fractional regression model (FRM), with habitat and organizational conditions as independent variables. Differences in the structure of greenhouse gas emissions from the crops under study were indicated as a result of differences in technology used at each farm. The estimated average carbon footprint on the analysed farms for sugar beet cultivation was 0.057 (±0.042) kg CO_2e/kg and 0.13 (±0.17) kg CO_2e/kg for potato cultivation. The obtained results indicate that effective farms growing sugar beet emit, on average, 14.5% less greenhouse gases, achieving a slightly higher yield. In potato cultivation, this reduction is 15.3% with a 27% increase in yield. It has been shown that weather conditions and the economic size of farms can significantly affect the environmental efficiency of both analysed crops.

INTRODUCTION

Sustainable agriculture should secure the food needs of a globally growing population and reduce the negative impact on the environment by rationalizing the use of inputs, such as mineral fertilizers as well as fuel and plant protection products. The quantitative assessment of environmental efficiency in plant production helps determine the potential for reducing the impact of agriculture on the environment, by indicating the reasons for ineffectiveness in relation to the yield obtained [Esteve 2012]. There are many ways to measure eco-efficiency using indicators, parametric or non-parametric methods [Żyłowski 2019]. The most commonly used non-parametric method for determining efficiency is the DEA (Data Envelopment Analysis) method, based on linear programming, which allows to classify production units as effective or ineffective and measuring the distance between them as relative efficiency, determined by the best observed practices. In connection with the observed climate changes, an important indicator of the environmental impact is the

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carbon footprint, understood as a balance of greenhouse gas emissions per unit of obtained product [Pandey et al. 2011]. The approach combining Life Cycle Assessment (LCA) and DEA (assessing relative efficiency) is widely used to evaluate the potential for reducing the environmental impact of plant production [Picazo-Tadeo et al. 2011, Pang et al. 2016, Żyłowski 2019]. One possible way of incorporating undesirable results in the DEA method is to use a model based on slacks [Pishgar-Komleh et al. 2020], described by Kaoru Tone [2003]. The impact of habitat and structural variables on crop efficiency can be analysed using regression methods. Due to the fact that the determined efficiency values are in the range [0; 1], it is expedient to use the fractional regression model, described, among others, by Esmeralda Ramalho et al. [2011].

Currently, potato cultivation in Poland covers approx. 300 thousand ha, and the average yield obtained are at a level of 25 t/ha. The area of sugar beet cultivation is about 240 thousand ha, and the average yield obtained is about 60 t/ha [GUS 2019]. Compared to the 1990s, the position of root crops in the crop structure has changed significantly; potatoes have lost their use as a fodder plant and their cultivation area has decreased by about 80%, while in the case of sugar beet cultivation the area decrease is about 40% [Czakowski 2015]. The aim of the study is to assess the environmental efficiency of sugar beets and potatoes, based on the example of selected farms.

MATERIAL AND METHODS

The data used in the study comes from surveys of farms in Poland conducted as part of the LCAgri project, for the purpose of determining the carbon footprint of crops. The pooled data from the 2015/2016 and 2016/2017 seasons were used in the analyses. The farms belonged to the Polish FADN system with production types (TF8): plant cultivation (C), dairy cattle (D) and pigs (P), and three economic size classes (ES6): small (EUR 8-25 thousand), medium (EUR 25-100 thousand), large (EUR 100-500 thousand). Preliminary data selection was carried out taking yield and cultivation area into account. Potato-growing farms with an area of less than 0.3 ha and yield less than 10 t/ha, and sugar beet yielding less than 30t/ha, were rejected. The *dbscan* procedure [Hahsler et al. 2019] was then used to detect outliers, using a multi-dimensional data density algorithm. Finally, 62 units growing sugar beet and 74 potato farms were used for further analysis. Meteorological data: (average spring temperature (III-V) in °C, average summer temperature (VI-VIII) in °C, total spring rainfall (III-V) in mm, total summer rainfall (VI-VIII) in mm were gathered from the EOBS network [Cornes et al. 2018]. Soil bonitation classes were aggregated into three levels: good (I-III), medium (IV) and poor (V, VI).

Greenhouse gas emissions (GHG) in cultivation were calculated as the sum of carbon dioxide and nitrous oxide emissions expressed in a CO_2 equivalent [kg CO_2e/ha], according to the IPCC guideline [IPCC 2006]. Emission factors of the means of production used (mineral fertilizers, plant protection products, fuel and seeds) were adopted after the Biograce project [Neeft 2011]. The content of nitrogen in natural fertilizers was estimated in accordance with Agricultural Production Standards at: 5 kg N/t manure and 4 kg N/t slurry [CDR 2018]. Crop carbon footprint [Zheng, Han 2018] CF (kg CO_2e/kg) is calculated as:

$CF = GHG/Y$

where: *GHG* – greenhouse gas emissions in kg CO_2e/ha, *Y* – yield in kg/ha.

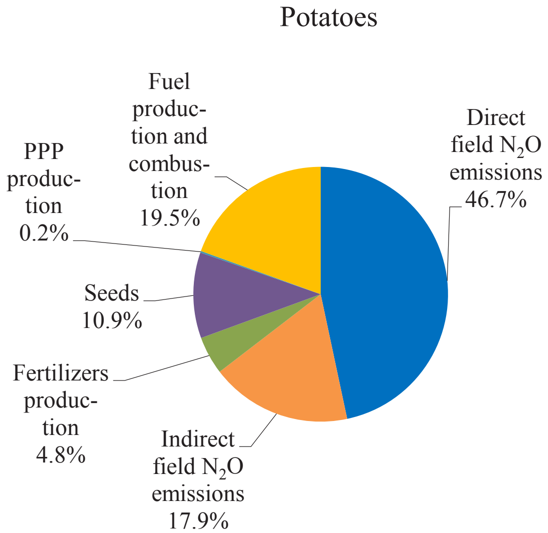
The work uses a slack-based, non-radial, non-oriented DEA model with undesirable output (greenhouse gas emissions) SBM-DEA [Tone 2003]. The model considers: inputs, desirable outputs and undesirable results. A detailed description of the model can be found in works of Karou Tone [2001, 2003] and William Cooper et al. [2007]. In the model: the sum of the pure component from NPK mineral fertilizers (kg), plant protection products (PPP) (kg), fuel (l), manure (t) and seeds (kg) were used as input variables, yield (t) as the desired output while greenhouse gas emissions (kg CO_2e) as an undesirable output. All data refer to 1 ha of cultivation area. The *deaR* package was used for calculations [Coll-Serrano et al. 2018].

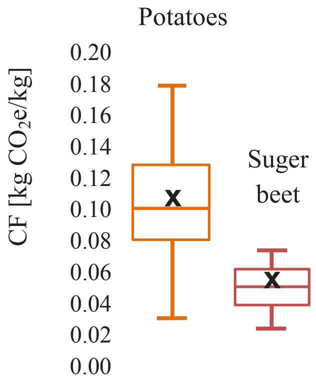
The impact of weather conditions (average temperatures and precipitation sums), soil (aggregated bonitation classes), structure (type and economic size of the farm) as well as cultivation season (variable year) on the efficiency of plant cultivation were assessed using the fractional regression model, as described by Leslie Papke and Jeffrey Wooldridge [1996] and in the work of Esmeralda Ramalho et al. [2011]. This method assumes the distribution of the dependent variable in the form of any continuous function $0 \leq G \leq 1$. By default, the following distribution functions are used: logistic (logit), normal (probit), Fisher-Tippet (loglog, cloglog) and Cauchy (cauchit). Using the RESET and P-test tests, the appropriate specification of the functional form of the dependent variable is selected. In addition, the average marginal effect has been calculated, determining the impact of changes in the tested parameters on the efficiency score (explained variable). The *frm* package was used for calculations [Ramalho 2015].

RESULTS AND DISCUSSION

The estimated carbon footprint of potato and sugar beet cultivation is 0.13 (±0.17) and 0.057 (±0.042) kg CO_2e/kg, respectively (Figure 1). The obtained carbon footprint of potato cultivation in the analysed farms did not differ significantly from that obtained in the research carried out in the Czech Republic, and was 12% lower than their estimate of 0.145 kg CO_2e/kg [Moudrý et al. 2013]. The CF estimated in the present study was higher than that obtained in Dutch conditions, where, depending on the purpose and method of growing potatoes (seed, table, starch or organic), the obtained results were: 0.115, 0.077, 0.071, 0.082 kg CO_2e/kg, respectively. The main reason for that is obtaining higher yield due to the use of irrigation [Haverkort, Hillier 2011]. John Tzilivakis et al. [2005] estimated the CF of sugar beet cultivation in Great Britain at 0.024 kg CO_2e/kg, and it was 58% lower than the one obtained in this paper. In Polish conditions, the estimation of the carbon footprint of sugar beet cultivation was carried out by Marek Hryniewicz et al., who received the result of 0.097 kg CO_2e/kg [Hryniewicz et al. 2015], which means that the estimated carbon footprint is 70% higher than that specified on the analysed farms. These differences most likely result from the fact that the analyses were made on the basis of averaged data for adopted scenarios (standard technologies) [Tzilivakis et al. 2005] or only coming from one cultivated field [Hryniewicz et al. 2015], while the presented results are based on the actual consumption of means of production and the yield obtained from several dozen existing farms. A greater dispersion of the calculated carbon footprint for potato cultivation (cv = 131.2%) than for sugar beet (cv = 74.8%) may be caused by the occurrence of more diverse potato cultivation, when considering the technology used, than in the case of sugar beet.

Due to the greater use of manure by potato-growing farms, in comparison with sugar beet (on average 3 times more per 1 ha) and by using ~70% less mineral fertilizer, there are differences in the structure of greenhouse gas emissions of the analysed root crops (Figure 1). A larger share of direct and indirect N_2O emissions from soil is observed, reaching 65% in potato cultivation, with a smaller (six times) share of emissions from mineral fertilizer production. Due to differences in methodology for estimating emissions in sugar beet cultivation, mainly in the approach to estimating emissions from manure, the structure of emissions obtained in this study differs from that obtained by Marek Hryniewicz et al. [2015], where the share of emissions from animal husbandry and manure storage was set at 30%, and emissions from soil at 20%.





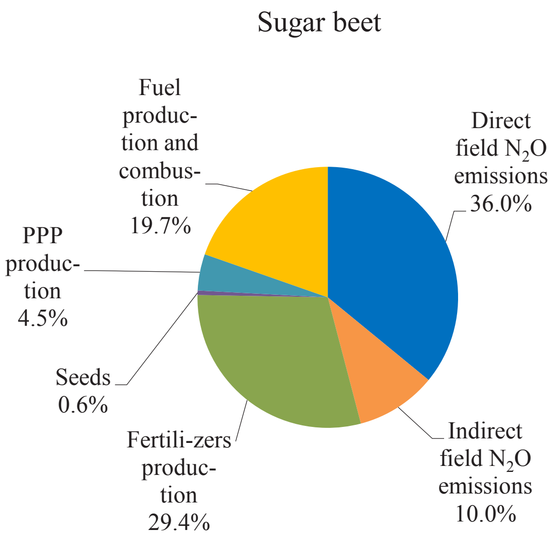


Figure 1. Carbon footprint and structure of greenhouse gas emissions in sugar beet and potato cultivation

Source: own study

Table 1. Inputs, yield and greenhouse gas emissions (GHG) for efficient (Ef = 1) and inefficient (Ef < 1) units in relation to 1 ha of crop

Specification	Sugar beets			Potatoes		
	Ef = 1	Ef < 1	difference* [%]	Ef = 1	Ef < 1	difference* [%]
NPK [kg]	233.8	343.3	-46.8	144.2	196.9	-36.5
Fuel [l]	121.9	137.6	-12.9	130.3	145.7	-11.8
PPP [kg]	6.3	9.0	-41.7	4.8	6.2	-28.3
Seeds [kg]	4.0	4.3	-5.5	2,227.0	2,496.0	-12.1
Manure [t]	5.9	6.2	-4.3	18.3	20.3	-10.9
Yield [t]	67.9	64.8	4.6	36.2	26.3	27.3
GHG [kg CO_2e]	2,786.0	3,189.0	-14.5	2,415.5	2,786.0	-15.3

* The difference column is calculated as the difference between the average values for efficient and inefficient units divided by the average for efficient units and expressed as a percentage. A negative difference means less resource consumption and a carbon footprint of efficient units
Source: own study

The averaged efficiency scores determined by the non-oriented, non-radial SBM-DEA model, assuming variable scale effects are 0.75 (±0.21) and 0.51 (±0.27) for sugar beet and the potato, respectively. Analyses indicate that, in the case of sugar beet cultivation, 35% of production units are effective (22/62), while in the case of the potato this ratio is 20% (15/74). In the case of sugar beet cultivation, most farms operate below the optimal production scale (38/62), unlike in the case of potato cultivation, where 30 production units operate above the optimal production scale and 27 below. Table 1 presents a summary of the inputs used and the yield and greenhouse gas emissions between effective and inefficient farms. The results of the DEA analysis indicate lower consumption inputs (in the range of 4.3 to 46.8%) with a 4.6% higher yield in the case of sugar beet cultivation. Efficient

Table 2. Specification test for selecting the FRM model (p-values) for technical efficiency in sugar beet cultivation

Specification	logit	probit	loglog	cloglog	cauchit
RESET test	0.039**	0.032**	0.044**	0.033**	0.161
P test:					
logit	-	0.028**	0.092*	0.013**	0.479
probit	0.048**	-	0.084*	0.017**	0.493
loglog	0.027**	0.016**	-	0.008***	0.377
cloglog	0.079*	0.058*	0.130	-	0.584
cauchit	0.010**	0.007***	0.020**	0.004***	-

*, **, *** – denote test statistics which are significant at 10, 5 and 1% (respectively)

Source: own study

units, in the context of the DEA method, achieve an average 27% higher yield in potato cultivation with lower greenhouse gas emissions (15.3%) and consumption of inputs.

RESET and P-test results showed that only the *cauchit* model was not rejected at a 10% significance level, which allows it to be used to explain crop efficiency for both plants tested (Table 2 and 3). The determined model coefficients and average marginal effects indicate that the weather had a significant impact on the achieved efficiency of cultivating

Table 3. Specification test for selecting the FRM model (p-values) for technical efficiency in potato cultivation

Specification	logit	probit	loglog	cloglog	cauchit
RESET test	0.073*	0.064*	0.053*	0.072*	0.144
P test:					
logit	-	0.728	0.080*	0.073*	0.311
probit	0.641	-	0.089*	0.048**	0.306
loglog	0.029**	0.038**	-	0.030**	0.210
cloglog	0.143	0.106	0.152	-	0.754
cauchit	0.758	0.834	0.159	0.374	-

*, **, *** – denote test statistics which are significant at 10, 5 and 1% (respectively)

Source: own study

Table 4. Estimation results of the *cauchit* FRM model for technical efficiency together with average partial effects (sugar beet cultivation)

Specification	Model coefficient				Average Partial Effect			
	value	st. error	p-value		value	st. error	p-value	
constant	23.883	6.999	0.001	***	-	-	-	-
area	-0.080	0.027	0.003	***	-0.012	0.004	0.002	***
spring_temp	1.072	0.609	0.078	*	0.155	0.084	0.064	*
spring_precip	-0.002	0.006	0.793	-	0.000	0.001	0.792	-
summer_temp	-1.722	0.579	0.003	***	-0.250	0.073	0.001	***
summer_precip	0.001	0.004	0.765	-	0.000	0.001	0.766	-
type=D	-1.332	0.479	0.005	***	-0.193	0.064	0.002	***
type=P	-0.205	0.593	0.730	-	-0.030	0.086	0.730	-
econ_class=big	0.943	0.491	0.055	*	0.137	0.068	0.043	**
intercrop=yes	-0.903	0.780	0.247	-	-0.131	0.115	0.253	-
soil=good	-0.437	0.339	0.198	-	-0.063	0.046	0.168	-
year =2017	-0.097	0.245	0.692	-	-0.014	0.035	0.690	-
$R^2 = 0.350$								

*, **, *** – denote test statistics which are significant at 10, 5 and 1% (respectively)

Source: own study

both root crops (Table 4 and 5). The analysis implies a positive effect of the average spring temperature on the cultivation efficiency for both analysed crops. In the case of potato cultivation, a positive impact on the efficiency of the sum of spring precipitation was also shown. The obtained results indicate a negative impact of high temperature in the summer on the efficiency score for both analysed crops.

Large farms (in terms of economy class) are cultivated more efficiently, which is probably related to a better use of agricultural inputs [GUS 2017]. The adopted soil quality index (aggregated bonitation classes) did not significantly differentiate the environmental efficiency score of both root crops, which may be due to the fact that the data were collected at a level of cultivation on the farm, not taking the diversity of soil quality in individual fields into account. This may also indicate the decisive role of cultivation technology. In the case of sugar beet cultivation, farms with a field crop (C) profile are more effective.

Table 5. Estimation results of the cauchit FRM model for technical efficiency together with average partial effects (potato cultivation)

Specification	Model coefficient				Average Partial Effect			
	value	st. error	p-value		value	st. error	p-value	
Constant	8.023	1.847	0.065	*	-	-	-	-
Area	-0.010	-0.599	0.549		-0.003	0.004	0.549	
spring_temp	1.780	3.125	0.002	***	0.461	0.124	0.000	***
spring_precip	0.012	2.030	0.042	**	0.003	0.001	0.030	**
summer_temp	-1.486	-3.088	0.002	***	-0.385	0.107	0.000	***
summer_ precip	0.003	1.169	0.243	-	0.001	0.001	0.232	-
type=D	0.473	1.457	0.145	-	0.123	0.080	0.126	-
type=P	0.220	0.605	0.545		0.057	0.093	0.541	-
econ_ class=big	0.980	2.636	0.008	***	0.254	0.090	0.005	***
econ_ class=medium	0.918	3.904	0.000	***	0.238	0.052	0.000	***
intercrop=yes	-0.613	-1.370	0.171	-	-0.159	0.114	0.162	-
soil=good	0.338	0.936	0.349	-	0.088	0.093	0.346	-
soil=medium	0.081	0.286	0.775	-	0.021	0.073	0.775	-
year=2017	-0.229	-0.954	0.340	-	-0.059	0.061	0.333	-
$R^2 = 0.292$								

*, **, *** – denote test statistics which are significant at 10, 5 and 1% (respectively)

Source: own study

CONCLUSIONS

In the analysed set, farms defined as efficient constituted a higher percentage in the case of sugar beet cultivation, sharing 35% of the total number than in the case of potato cultivation, where it was 20%. It has been shown that inefficient farms emit, on average, about 15% more greenhouse gases, which is a result of using more inputs. It was pointed out that improving the efficiency of cultivation is mainly possible by reducing mineral fertilization and fuel used.

Differences in the structure of emissions between analysed crop cultivation are mainly due to the use of manure for potato cultivation (on average 3 times more per 1ha) and the greater use of mineral fertilizers in sugar beet cultivation. The conducted analyses indicate a significant impact of weather conditions on crop efficiency. A warmer spring is conducive to greater efficiency, while an increase of average summer temperature has a negative impact in this regard. For both root crops, the economic size of the farm increases crop cultivation efficiency. A lack of significant impact of soil quality on achieved efficiency may indicate a decisive role of cultivation technologies used.

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EFEKTYWNOŚĆ ŚRODOWISKOWA UPRAWY ROŚLIN OKOPOWYCH

Słowa kluczowe: efektywność, buraki cukrowe, ziemniaki, ślad węglowy, SBM-DEA

ABSTRAKT

W artykule oceniono efektywność środowiskową uprawy dwóch głównych roślin okopowych w Polsce: buraków cukrowych i ziemniaków. Analizie poddano dane ankietowe pozyskane z 62 gospodarstw, w których uprawiano buraki cukrowe oraz z 74 gospodarstw uprawiających ziemniaki w latach 2016 i 2017. Do oceny efektywności środowiskowej użyto modelu SBM-DEA, w którym jako niepożądany efekt środowiskowy uwzględniono wielkość emisji gazów cieplarnianych. Przyczyny nieefektywności w uprawie objaśniono wykorzystując model regresji dla zmiennej frakcyjnej (*fractional regression model*), używając jako zmiennych niezależnych wskaźników siedliskowych i określających warunki organizacyjne gospodarstwa. Wskazano na różnice w strukturze emisji gazów cieplarnianych uprawy badanych roślin, wynikające ze stosowanych technologii. Oszacowany średni ślad węglowy w analizowanych gospodarstwach dla uprawy buraków cukrowych wyniósł 0,057 (±0,042) kg CO_2e/kg i 0,13 (±0,17) kg CO_2e/kg dla uprawy ziemniaków. Otrzymane wyniki wskazują, że gospodarstwa efektywne uprawiające buraki cukrowe emitują średnio o 14,5% mniej gazów cieplarnianych, osiągając nieznacznie wyższy plon. W uprawie ziemniaków różnica ta wynosiła 15,3%, przy plonie wyższym o 27%. Wykazano, że przebieg warunków pogodowych oraz wielkość ekonomiczna gospodarstw mogą istotnie wpływać na efektywność środowiskową uprawy obu analizowanych roślin.

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