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Data envelopment analysis models for the assessment of efficiency of sustainable forest management in Poland

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Abstract

The aim of the presented research was to analyse the efficiency of forest management as an approach to promote sustainable multifunctional forestry. A total of 17 Regional Directorates of State Forests (RDSFs) in Poland were studied with the use of data envelopment analysis (DEA). This method has been proposed and tested using criteria and indicators (C&Is) as inputs and outputs of the created models. The research process was divided into two stages: first, we analysed the efficiency of simple DEA models and models with additional variables, which allowed us to determine the major models providing the best combination of efficiency evaluation criteria. Second, we used these models to assess the efficiency of sustainable management of forests by RDSFs. According to our results, RDSFs were found to be highly efficient in converting resources into production and nonmarket results. Nevertheless, the implementation of sustainable development principles requires further actions, in order to fulfil all ecological, economic, and social functions in a more effective way. They are connected with the necessity to increase the areas of both protective forests and promotional forest complexes. Thus, the results of this study might be a valuable source of information for the planning process of forestry services at the strategic and operational levels.

Key words

data envelopment analysis (DEA), efficiency, Regional Directorates of State Forests (RDSFs), sustainable forest management

Introduction

According to the definition adopted in 1993 at the Ministerial Conference on the Protection of Forests in Europe in Helsinki, sustainable forest management stands for 'the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national and global levels' (MCPFE 1993). The ecological (protective) function of forests is demonstrated by their positive impact on the climate, composition of the atmosphere, and the water cycle in forest

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ecosystems; by the prevention of floods, erosion, landslides, and steppe-formation; and by the creation of conditions for the conservation of biodiversity and genetic variability. The economic (productive) function of forests refers to their ability to continuously produce timber, wood pulp, and bioenergy, whereas the social function is associated with the formation of conditions favourable for public health, creation of recreational sites and labour market, and finally, improvement of environmental awareness and culture of society (Vogt 2010; Kozioł and Matras 2011). Therefore, forests are designed to fulfil any combination of functions; however, 'none of these alone can be considered as being significantly more important than the others' (FAO 2004). These functions are often mutually exclusive; hence, management of forests in a way that ensures their sustainability is a major challenge.

Many organizations and individuals use criteria and indicators (C&Is) to monitor and estimate the ecological, economic, and social sustainability of forest management. The actual set of C&Is consists of 6 criteria and 45 associated indicators (34 quantitative indicators + 11 qualitative indicators). Following areas cover the 6 criteria: C1 – maintenance and appropriate enhancement of forest resources and their contribution to global carbon cycles; C2 – maintenance of forest ecosystem's health and vitality; C3 – maintenance and encouragement of productive functions of forests; C4 – maintenance, conservation, and appropriate enhancement of biological diversity in forest ecosystems; C5 – maintenance and appropriate enhancement of protective functions in forest management; and C6 – maintenance of other socioeconomic functions and conditions (MCPFE 2015). But, interpreting so many collected data can be cumbersome (Wijewardana 2008). Therefore, integrating them into a single efficiency score may help practitioners of C&I evaluate and compare cases.

Data envelopment analysis (DEA) is a well-known linear programming (LP) method that provides single efficiency score (Ullah et al. 2016). This method is commonly used in many fields, such as education (Mikušová 2015), banking (Tsolas and Charles 2015), health care (Ferrier and Trivitt 2013), agriculture (Toma et al. 2015), and industry (Sueyoshi and Goto 2012; Limaei 2013). It is useful in situations where the conventional methods of efficiency measurement, based on the analysis of costs and revenues, and based on productivity indicators are difficult to apply, due to the nonmarket character of the information (Šporčić et al. 2009). Therefore, the DEA method has demonstrated to be an appropriate and powerful tool to determine the relative efficiencies of forest districts that undertake not only business activity but also nonproduction activity (Kao et al. 1993; Şafak et al. 2014; Šporčić and Landekić 2014; Młynarski and Prędki 2016b; Młynarski and Kaliszewski 2017). However, there are currently no DEA studies that explore the efficiency of simultaneous fulfilment of all ecological, economic, and social functions to demonstrate that forest management is sustainable.

The aim of this study was to propose and develop alternative approach to measure the efficiency of sustainable forest management based on DEA method. We performed the analysis using 17 Regional Directorates of State Forests (RDSFs) in Poland as an example. To ensure the quality of research, we identified a suitable combination of variables with the use of a procedure deriving from the methodology proposed by Jitthavech (2016).

Methodology

DEA method is a nonparametric, linear programming-based method that assesses the relative efficiency of a set of similar units, the so-called decision-making units (DMUs). The procedure in this method consists of building a model that is described by the same number and type of inputs and outputs for all considered DMUs (Gierulski and Kaczmarska 2012). Solving the linear decision-making task, related to the tested unit, makes it possible to determine its ability to achieve the minimum possible input values for given outputs (for input-oriented DEA models) or the maximum possible output values for given inputs (for output-oriented DEA models) (Gutiérrez and Lozano 2013). Too high inputs or too low outputs are the evidence of a waste of material, human, and financial resources.

DEA method allows for an analysis of multidimensional processes in forestry, because a number of inputs and outputs can be used simultaneously. Moreover, the lack of input and output prioritizing and the lack of determination of functional dependency between these two is an advantage of this method (Tsai et al. 2016). But, the obtained results are dependent on the limitations of the method, which include sensitivity to values that significantly differ from the others and a change in the number of examined units, as well as the need to maintain the proportions whereby the number of the examined units will be 3–5 times bigger than the number of inputs and outputs (Hollingsworth 2016).

The efficiency of forest management units results directly from the accepted input and output variables. The quantitative indicators reflecting six criteria of sustainable forest management can be used as input and output variables in the DEA model. The indicators related to resources and condition of forests managed by the investigated units should be introduced as inputs in the DEA model, whereas the indicators representing the ecological, business, and social activities of the units should be applied as outputs. To ensure the discriminatory power of the DEA model, a reduction of the long list of indicators may be required. Therefore, it is recommended to include some statistical and econometrical methods as a criterion for inputs and outputs selection in the DEA model (Serrano-Cinca et al. 2002; Pastor et al. 2002; Masternak-Janus and Rybaczewska-Błażejowska 2017). One of the many proposals is a selection procedure developed by Jitthavech (2016), which consists of comparing the efficiency of total DEA models with reduced DEA models and applying statistical tools to assess the significance of a variable. The aim of this procedure is to eliminate those variables that have the least influence on the set of efficient DMUs. To provide the appropriate combination of variables for the study of the efficiency of sustainable forest management, an approach based on the aforementioned procedure is proposed in this article. It consists of the following steps:

1. Classification of the variables into two sets: S_1 for the variables that should be incorporated in the DEA model and S_2 for the variables that are candidates.
2. Determination of the efficiency of RDSFs with the application of the reduced DEA model, using a set of mandatory variables as inputs and outputs.
3. Determination of the efficiency of RDSFs with the application of the total DEA model containing additional candidate variables.
4. Performing the McNemar test to eliminate candidate variables based on the number of efficient DMUs. This stage consists of testing the null hypothesis that the number of efficient DMUs in the reduced model and the full model are equal.

In order to calculate the efficiency scores, one of the many DEA models may be applied. The BCC model – first introduced by Banker, Charnes, and Cooper (Banker et al. 1984) – was chosen as a tool for the efficiency assessment of RDSFs in Poland. This model takes into account variable returns to scale (VRS), and it is presented either in input- or output-oriented form. An assumption of VRS is that an increase in the inputs does not result in a proportional change in the outputs. It can be expected that not all RDSFs operate at an optimal scale; therefore, the BCC model is useful (Lozano et al. 2009). In this case study, an output-oriented approach was selected, indicating that the maximization of forest functions at a given level of inputs is prioritized. The output-oriented BCC model assuming VRS can be formulated as follows:

$$min\theta_o \tag{1}$$

$$\sum_{j=1}^{J} y_{rj}\lambda_j \geq y_{ro} \qquad r = 1, \ldots, R \tag{2}$$

$$\sum_{j=1}^{J} x_{nj}\lambda_j \leq x_{no}\theta_o \qquad n = 1, \ldots, N \tag{3}$$

$$\sum_{j=1}^{J} \lambda_j = 1 \tag{4}$$

$$\lambda_j \geq 0 \tag{5}$$

where:
θ_o – efficiency score of the tested DMU,
J – number of DMUs,
j – 1,…, J index of DMUs,
0 – index of DMU being tested,
y_{rj} – amount of r-th output of j-th DMU,
y_{ro} – amount of r-th output of the tested DMU,
R – number of outputs produced by the DMUs,
r – 1,…, R index on outputs produced,
x_{nj} – amount of n-th input of j-th DMU,
x_{no} – amount of n-th input of the tested DMU,
N – number of inputs consumed by the DMUs,

n – 1,…, N index on inputs consumed,
l_j – weight coefficients (participation of j-th DMU for the goal of the tested DMU).

In order to evaluate the efficiency of forest management in Poland and the level of its sustainability, a set of quantitative indicators was selected. The indicators were developed according to the criteria of sustainable forest management (C1–C6) and considering the Polish forestry legislation, including the Act of 28 September 1991 on Forests (1991). One important consideration in determining the indicators was the availability of statistical data from the Central Statistical Office of Poland (CSO) and the State Forests National Forest Holding (SFNFH). The other indicators, however, if accessible, can be similarly used in the DEA method.

In view of the above, the following set of input variables was selected:
x_1 – forest area [in thousands of ha],
x_2 – growing stock per 1 ha [in m^3],
x_3 – average age of tree stands [in years],
x_4 – average defoliation (monitored species of trees: pine, spruce, fir, beech, oak, birch, alder) [in %],
x_5 – tree stands aged over 20 years damaged to various degrees by selected abiotic and anthropogenic factors (disturbances in water relations, low and high temperature, wind, immission, forest fires, snow, and hail) [in ha],
x_6 – tree stands subject to protection against biotic factors (insects plagues, animals, and parasitic fungi) [in ha],
x_7 – deciduous tree stands [in %],
x_8 – coniferous tree stands [in %],
x_9 – seed tree stands and seed orchards [ha].

The set of accepted output variables is as follows:
y_1 – timber harvesting [in thousands of m^3],
y_2 – protective forests [in thousands of ha],
y_3 – average paid employment [in persons],
y_4 – promotional forest complexes (PFCs) [in thousands of ha].

Table 1 provides the values of all the variables adopted for the calculations.

Table 1. Inputs and outputs used in the analysis of the efficiency of sustainable forest management (2015 as a base year)

Regional Directorates	Input variables									Output variables			
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	y_1	y_2	y_3	y_3
Białystok	573.8	278	63	22.8	1,005	3,408.2	28.8	69.5	21,714.2	2,987.9	346.6	2,017	179.8
Gdańsk	284.6	269	68	20.8	938	1,193.8	33.4	62.2	12,062.3	1,545.7	123.5	982	59.7
Katowice	596.9	246	60	23.0	17,242	4,193.8	29.0	66.2	14,526.9	3,238.2	503.2	2,241	39.9
Kraków	167.9	309	76	20.5	78	1,626.4	40.8	53.7	5,610.8	913.6	154.1	714	36.6
Krosno	400.6	303	74	21.9	842	3,878.0	40.8	52.3	10,022.4	1,886.2	346.1	1,536	99.1
Lublin	396.9	270	65	22.7	1,159	11,457.3	36.1	60.8	13,953.9	2,056.2	181.4	1,356	31.6
Łódź	282.8	256	64	20.9	828	6,497.8	23.7	74.6	9,107.9	1,290.5	156.1	939	59.2
Olsztyn	570.0	280	61	21.8	440	2,014.7	32.3	65.2	23,474.3	3,152.1	164.1	1,913	85.5
Piła	337.2	261	58	19.1	32	1,849.0	13.7	85.1	6,501.6	1,976.0	97.4	1,017	56.1
Poznań	407.9	253	60	22.8	3,648	1,856.5	25.4	70.8	10,390.8	2,113.1	237.0	1,463	77.1
Radom	309.0	267	66	22.2	484	8,869.8	23.6	74.7	7,319.3	1,773.0	197.2	1,199	107.3
Szczecin	639.6	278	59	18.7	6,623	1,644.3	24.6	71.9	15,193.4	3,832.8	355.0	2,100	104.4
Szczecinek	570.8	254	59	17.9	126	7,792.9	30.5	68.2	12,751.1	3,418.8	177.5	1,878	56.5
Toruń	421.7	255	63	21.4	3,846	2,669.7	16.0	82.0	14,295.9	2,070.4	200.3	1,358	109.3
Warszawa	183.3	256	62	23.0	737	1,384.8	25.6	72.9	4,617.8	995.1	72.6	760	48.6
Wrocław	526.8	271	64	22.5	9,766	4,318.0	30.0	61.5	11,147.2	3,114.1	363.0	2,247	65.2
Zielona Góra	424.9	235	56	21.4	697	1,700.9	15.0	82.1	5,630.2	2,044.5	136.8	1,286	32.1

Source: CSO 2016; Directorate General of the State Forests 2016; SFNFH 2016.

In a DEA study of sustainable forest management, all outputs related to the ecological, business, and social functions are relevant. Therefore, models with the following specifications were distinguished related to the output variables:

- model 1—timber harvesting (y_1),
- model 2—protective forests (y_2),
- model 3—average paid employment (y_3),
- model 4—PFCs (y_4).

Input and output variables were introduced into the models one after another to analyse their impact on results of efficiency. This approach made it possible to limit the number of variables to the number of tested DMUs and, above all, inputs and outputs that the influence the most in maintaining the efficiency were selected. In addition, it seems that designing models with numerous combinations of inputs and outputs is a good solution for the process of estimating efficiency (Gierulski 2009).

Results

The procedure of selecting variables for the DEA model begins with the determination of two sets: S_1 for the mandatory variables and S_2 for the candidate variables. While taking decisions regarding the choice of variables that have to be incorporated in the analysis, experience and expertise should be applied. In this study, the output variables included in four subsequent DEA models are members of the subsequent subsets of S_{11}–S_{14}. All output variables depend on the forest area (x_1); therefore, variable x_1 was introduced into subsets of S_{11}–S_{14}. Consequently, the models 1–4 consisting of one input and one output were created. All the other variables are candidates for selection in these models, and thus, they are to be grouped in the subsets of S_{21}–S_{24}. In the next stage, in each of the four generated models, 17 tasks of LP were solved with the use of the Solver tool in Excel program. Then, the models were extended with input and output candidate variables, and then, their efficiency was calculated. Finally, DMUs in simple DEA models (the so-called reduced models) and DMUs in models with additional candidate variables (the so-called full models) were classified as efficient and inefficient DMUs. The number of efficient DMUs was denoted by M_{it} in reduced model and M_{full} in full model. The decision to include a variable in the next stage of the research was undertaken based on the McNemar test (Jitthavech 2016). In summary, the model with a variable significantly influencing the efficiency results must be considered as a basis for further comparisons and the whole procedure, based on the addition of the candidate variables and evaluating their impact on the efficiency, should be repeated. Based on this approach, a range of models presented in Table 2 was created.

For example, model 1 (x_1, y_1) was extended with the subsequently added input and output candidate variables, thereby creating the models of 1.1–1.11 (Tab. 2). Efficiency scores obtained in the new models did not differ significantly from the scores obtained in model 1. Therefore, the p-values of the test statistic Q_{it} ($M_{full} - M_{it}$), which has a χ^2 distribution with one degree of freedom, indicated that the null hypothesis H_0: $M_{it} = M_{full}$ at the significance level $\alpha = 0.01$ should not be rejected, and thus, the candidate variables can be discarded from S_2. This means that the candidate variables do not carry any important information about the variable y_1 (timber harvesting), and its values are best explained by the variable x_1 (forest area). Similarly, no significant changes in efficiency were recorded in the models 2.1–2.11 in relation to model 2 (x_1, y_2), as well as in the models 4.1–4.11 in relation to model 4 (x_1, y_4). The variable x_1 (forest area) can explain both the values of the variable y_2 (protective forests) and the values of the variable y_4 (PFCs) in the best way. The remaining variables do not provide any vital information, and variable x_1 will be their representative.

Analysing the models 3.1–3.11, the largest number of efficient DMUs in comparison to model 3 (x_1, y_3) can be observed in model 3.6 (x_1, x_7, y_3). Furthermore, the null hypothesis can be rejected as the p-values of the test statistic Q_{it} were found to be 0.008. In view of this, extending model 3 with the variable x_7 is justified, and model 3.6 should be enriched with additional variables, thereby creating models of 3.6.1–3.6.10. Nevertheless, model 3.6 is the ultimate development in this procedure, as other variables added to the model did not cause any significant changes in the number of obtained efficient DMUs.

Considering the results of the models' specification search, RDSFs in Poland should evaluate the efficiency of sustainable forest management from the

Table 2. Efficiency scores obtained from the models with different combinations of variables and the *p*-values of the test statistic

	Model number																			
	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10	1.11	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7
Input variables	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1
		x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9					x_2	x_3	x_4	x_5	x_6	x_7	x_8
Output variables	y_1	y_1	y_1	y_1	y_1	y_1	y_1	y_1	y_1	y_1	y_1	y_1	y_2	y_2	y_2	y_2	y_2	y_2	y_2	y_2
										y_2	y_3	y_4								
Regional Directorates	Efficiency scores																			
	q_1	$q_{1.1}$	$q_{1.2}$	$q_{1.3}$	$q_{1.4}$	$q_{1.5}$	$q_{1.6}$	$q_{1.7}$	$q_{1.8}$	$q_{1.9}$	$q_{1.10}$	$q_{1.11}$	q_2	$q_{2.1}$	$q_{2.2}$	$q_{2.3}$	$q_{2.4}$	$q_{2.5}$	$q_{2.6}$	$q_{2.7}$
Białystok	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.89	0.91	1	0.72	0.72	0.72	0.72	0.99	0.78	0.72	0.72
Gdańsk	0.94	0.94	0.94	0.94	0.94	1	0.94	0.94	0.94	0.94	0.94	0.94	0.49	0.60	0.55	0.52	0.49	1	0.55	0.49
Katowice	0.91	1	0.91	0.91	0.91	0.91	0.91	0.94	0.91	1	1	0.91	1	1	1	1	1	1	1	1
Kraków	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Krosno	0.80	0.80	0.80	0.80	0.80	0.80	0.80	1	0.80	1	0.90	0.83	1	1	1	1	1	1	1	1
Lublin	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.53	0.55	0.56	0.53	0.53	0.53	0.53	0.53
Łódź	0.79	0.8	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.80	0.80	0.63	0.86	0.81	0.66	0.63	0.63	0.94	0.63
Olsztyn	0.92	0.92	0.92	0.92	0.92	0.93	0.92	0.94	0.92	0.92	0.93	0.93	0.34	0.34	0.34	0.37	0.65	0.47	0.34	0.34
Piła	1	1	1	1	1	1	1	1	1	1	1	1	0.33	0.39	1	1	1	0.41	1	0.33
Poznań	0.88	0.9	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.67	0.76	0.87	0.67	0.67	0.88	0.79	0.67
Radom	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1	0.73	0.86	0.84	0.73	0.77	0.73	1	0.73
Szczecin	1	1	1	1	1	1	1	1	1	1	1	1	0.71	0.71	0.86	1	0.88	1	0.89	0.71
Szczecinek	1	1	1	1	1	1	1	1	1	1	1	1	0.37	0.37	0.43	1	1	0.37	0.37	0.37
Toruń	0.83	0.83	0.83	0.83	0.83	0.83	0.87	0.83	0.83	0.83	0.83	0.87	0.55	0.61	0.60	0.59	0.55	0.61	1	0.55
Warszawa	0.98	1	1	0.98	0.98	1	1	0.98	1	0.98	0.99	1	0.44	1	1	0.44	0.44	1	1	0.44
Wrocław	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1	1	1	1	0.99	0.81	0.81	0.81	0.82	0.84	0.81	0.82	0.81
Zielona Góra	0.81	1	1	0.81	0.81	0.81	0.93	0.81	1	0.81	0.82	0.81	0.37	1	1	0.40	0.44	0.51	0.88	0.37
p-value of the test statistic Q_{it}	–	0.083	0.157	1	1	0.157	0.317	0.157	0.083	0.083	0.157	0.083	–	0.157	0.083	0.083	0.157	0.083	0.046	1

	Model number																			
	2.8	2.9	2.10	2.11	3	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	3.10	3.11	3.6.1	3.6.2	3.6.3	3.6.4
Input variables	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1
	x_9					x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9				x_7	x_7	x_7	x_7
																	x_2	x_3	x_4	x_5
Output variables	y_2	y_2	y_2	y_2	y_3	y_3	y_3	y_3	y_3	y_3	y_3	y_3	y_3	y_3	y_3	y_3	y_3	y_3	y_3	y_3
		y_1	y_3	y_4										y_1	y_2	y_4				
Regional Directorates	Efficiency scores																			
	$q_{2.8}$	$q_{2.9}$	$q_{2.10}$	$q_{2.11}$	q_3	$q_{3.1}$	$q_{3.2}$	$q_{3.3}$	$q_{3.4}$	$q_{3.5}$	$q_{3.6}$	$q_{3.7}$	$q_{3.8}$	$q_{3.9}$	$q_{3.10}$	$q_{3.11}$	$q_{3.6.1}$	$q_{3.6.2}$	$q_{3.6.3}$	$q_{3.6.4}$
Białystok	0.72	0.89	0.90	1	0.90	0.90	0.90	0.90	1	0.92	0.91	0.90	0.90	0.91	0.90	1	0.91	0.91	0.91	1
Gdańsk	0.49	0.94	0.81	0.64	0.81	0.82	0.81	0.84	0.86	1	0.81	0.81	0.81	0.94	0.81	0.84	0.82	0.81	0.86	0.86
Katowice	1	1	1	1	0.99	1	1	0.99	1	1	1	0.99	0.99	1	1	0.99	1	1	1	1
Kraków	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Krosno	1	1	1	1	0.90	0.90	0.90	0.90	1	0.90	0.90	1	0.90	0.90	1	0.97	0.90	0,90	0.90	1
Lublin	0.53	0.88	0.80	0.53	0.80	0.80	0.80	0.80	0.88	0.80	0.80	0.80	0.80	0.88	0.80	0.80	0.80	0.80	0.80	0.89
Łódź	0.63	0.79	0.78	0.72	0.78	0.82	0.79	0.80	0.83	0.78	0.86	0.78	0.78	0.80	0.78	0.81	0.87	0.86	0.92	0.86
Olsztyn	0.34	0.92	0.85	0.48	0.85	0.85	0.87	0.86	0.99	0.97	0.85	0.85	0.85	0.93	0.85	0.88	0.85	0.87	0.86	0.99
Piła	0.51	1	0.71	0.49	0.71	0.72	1	1	1	0.80	1	0.71	0.80	1	0.71	0.73	1	1	1	1
Poznań	0.67	0.88	0.84	0.72	0.84	0.92	0.98	0.84	0.89	0.99	0.89	0.84	0.84	0.88	0.84	0,87	0.94	0.98	0.89	0.91
Radom	0.86	0.99	0.91	1	0.91	0.92	0.92	0.91	0.99	0.91	1	0.91	0.92	0.99	0.91	1	1	1	1	1
Szczecin	0.71	1	0.93	0.86	0.93	0.93	1	1	0.97	1	1	0.93	0.93	1	0.93	0.97	1	1	1	1
Szczecinek	0.40	1	0.84	0.44	0.84	0.84	0.93	1	1	0.84	0.84	0.84	0.84	1	0.84	0.84	0.84	0.93	1	1
Toruń	0.55	0.83	0.76	0.79	0.76	0.82	0.77	0.78	0.80	0.82	1	0.76	0.76	0.83	0.76	0.86	1	1	1	1
Warszawa	1	0.98	0.97	1	0.97	1	1	0.97	0.97	1	1	0.97	1	0.99	0.97	1	1	1	1	1
Wrocław	0.94	1	1	0.84	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Zielona Góra	0.88	0.81	0.71	0.37	0.71	1	1	0.73	0.82	0.86	1	0.71	1	0.82	0.71	0.71	1	1	1	1
p-value of the test statistic Q_{it}	0.317	0.046	0.317	0.083	-	0.083	0.025	0.083	0.046	0.046	0.008	0.317	0.157	0.046	0.157	0.083	1	1	0.317	0.083

	Model number																	
	3.6.5	3.6.6	3.6.7	3.6.8	3.6.9	3.6.10	4	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	4.10	4.11
Input variables	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_1
	x_7	x_7	x_7	x_7	x_7	x_7		x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9			
	x_6	x_8	x_9															
Output variables	y_3	y_3	y_3	y_3	y_3	y_3	y_4	y_4	y_4	y_4	y_4	y_4	y_4	y_4	y_4	y_4	y_4	y_4
				y_1	y_2	y_4										y_1	y_2	y_3
Regional Directorates	Efficiency scores																	
	$q_{3.6.5}$	$q_{3.6.6}$	$q_{3.6.7}$	$q_{3.6.8}$	$q_{3.6.9}$	$q_{3.6.10}$	q_4	$q_{4.1}$	$q_{4.2}$	$q_{4.3}$	$q_{4.4}$	$q_{4.5}$	$q_{4.6}$	$q_{4.7}$	$q_{4.8}$	$q_{4.9}$	$q_{4.10}$	$q_{4.11}$
Białystok	0.92	0.91	0.91	0.91	0.91	1	1	1	1	1	1	1	1	1	1	1	1	1
Gdańsk	1	0.81	0.81	0.94	0.81	0.84	0.62	0.62	0.62	0.80	0.62	1	0.62	0.72	0.62	0.94	0.64	0.84
Katowice	1	1	1	1	1	1	0.22	0.53	0.33	0.22	0.22	0.22	0.22	0.24	0.28	0.91	1	1
Kraków	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Krosno	0.90	1	0.90	0.90	1	0.97	0.75	0.75	0.75	0.81	0.75	0.79	0.75	1	0.82	0.83	1	0.97
Lublin	0.80	0.80	0.80	0.88	0.80	0.80	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.28	0.24	0.88	0.53	0.80
Łódź	0.86	0.86	0.86	0.86	0.94	0.86	0.62	0.79	0.66	0.78	0.62	0.64	0.64	0.62	0.62	0.80	0.72	0.81
Olsztyn	0.97	0.85	0.85	0.93	0.85	0.88	0.48	0.48	0.61	0.54	0.79	0.73	0.48	0.54	0.48	0.93	0.48	0.88
Piła	1	1	1	1	1	1	0.49	0.56	1	1	1	0.63	1	0.49	0.63	1	0.49	0.73
Poznań	0.99	0.89	0.89	0.89	0.90	0.89	0,57	0.79	0.79	0.57	0.57	0.79	0.58	0.59	0.63	0.88	0.72	0.87
Radom	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Szczecin	1	1	1	1	1	1	0.58	0.58	1	1	0.58	1	0.67	0.58	0.71	1	0.86	0.97
Szczecinek	0.84	0.84	0.84	1	0.84	0.84	0.32	0.54	0.56	1	0.83	0.32	0.32	0.33	0.42	1	0.44	0.84
Toruń	1	1	1	1	1	1	0.79	1	0.84	0.92	0.79	0.85	1	0.79	0.79	0.87	0.79	0.86
Warszawa	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Wrocław	1	1	1	1	1	1	0.39	0.41	0.39	0.40	0.39	0.39	0.39	0.46	0.52	0.99	0.84	1
Zielona Góra	1	1	1	1	1	1	0.23	1	1	0.27	0.23	0.35	0.37	0.23	0.46	0.81	0.37	0.71
p-value of the test statistic Q_{it}	0.317	0.317	1	0.317	0.317	0.317	-	0.157	0.083	0.083	0.317	0.157	0.157	0.317	1	0.083	0.157	0.157

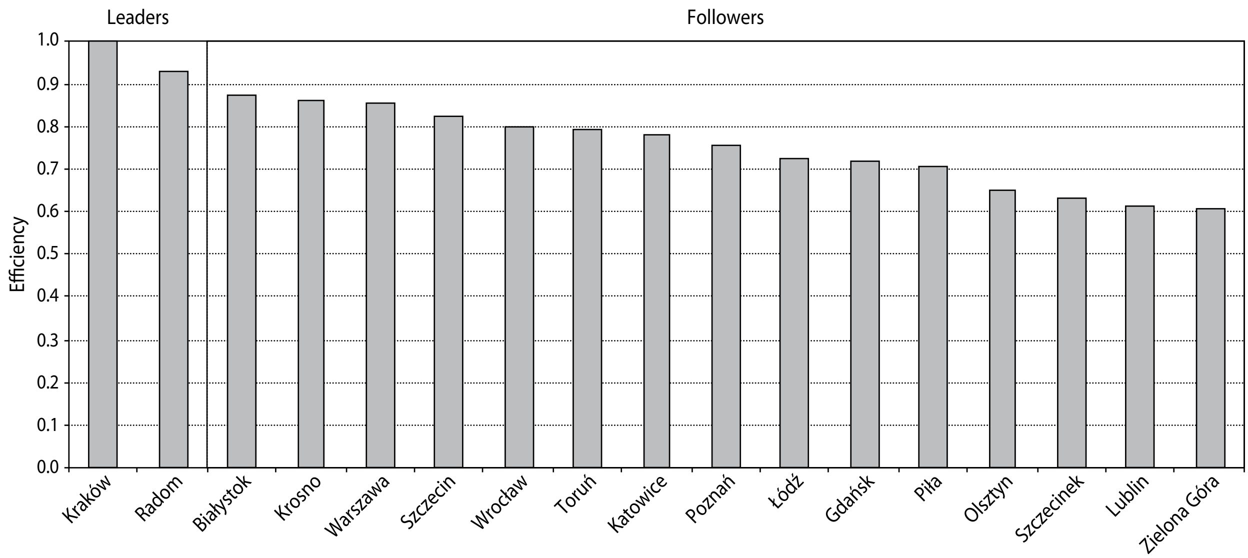

Figure 1. Ranking of the Regional Directorates of State Forests in terms of the efficiency of sustainable forest management

information obtained from model 1 (x_1, y_1), model 2 (x_1, y_2), model 3.6 (x_1, x_7, y_3), and model 4 (x_1, y_4). These models and their efficiency scores were highlighted in bold in Table 2. Calculating the average value of the efficiency scores specified in these models, a ranking of RDSFs can be created (Fig. 1), and they can be divided into two groups according to their effectiveness in converting their resources into results, which arise from the tasks posed by sustainable forest management:

Group I – efficiency leaders, having the efficiency score ≥ 0.9, that is, Kraków (1) and Radom (0.93).

Group II – efficiency followers, having the efficiency score within the range [0.6; 0.9), that is, Białystok (0.87), Krosno (0.86), Warszawa (0.85), Szczecin (0.82), Wrocław (0.80), Toruń (0.79), Katowice (0.78), Poznań (0.75), Łódź (0.72), Gdańsk (0.72), Piła (0.70), Olsztyn (0.65), Szczecinek (0.63), Lublin (0.61), and Zielona Góra (0.60).

None of the analysed RDSFs obtained the average score of efficiency lower than 0.6, and therefore, were not included both in the group of efficiency moderates, having the efficiency score within the range (0.3; 0.6) and efficiency laggards, having the efficiency score within the range (0; 0.3). The Directorate in Kraków was the only one to be fully effective in all four models considered, and thus, it had the efficiency score of 1 in the leaders group. Assuming that the average value of

Table 3. Inverse of efficiency scores of the Regional Directorates of State Forests

No.	Regional Directorates	Model 1	Model 2	Model 3.6	Model 4
		$1/q_1$	$1/q_2$	$1/q_{3.6}$	$1/q_4$
1	Białystok	1.1503	1.3986	1.1025	1
2	Gdańsk	1.0651	2.0274	1.2295	1.6056
3	Katowice	1.1043	1	1	4.5078
4	Kraków	1	1	1	1
5	Krosno	1.2553	1	1.1119	1.3356
6	Lublin	1.1405	1.8914	1.2479	4.1546
7	Łódź	1.2669	1.5946	1.1694	1.6050
8	Olsztyn	1.0830	2.9341	1.1746	2.0903
9	Piła	1	3.0150	1	2.0496
10	Poznań	1.1417	1.4851	1.1222	1.7430
11	Radom	1.0150	1.3723	1	1
12	Szczecin	1	1.4175	1	1.7226
13	Szczecinek	1	2.7169	1.1965	3.1662
14	Toruń	1.2066	1.8122	1	1.2645
15	Warszawa	1.0153	2.2984	1	1
16	Wrocław	1.0107	1.2318	1	2.5585
17	Zielona Góra	1.2316	2.6719	1	4.3267

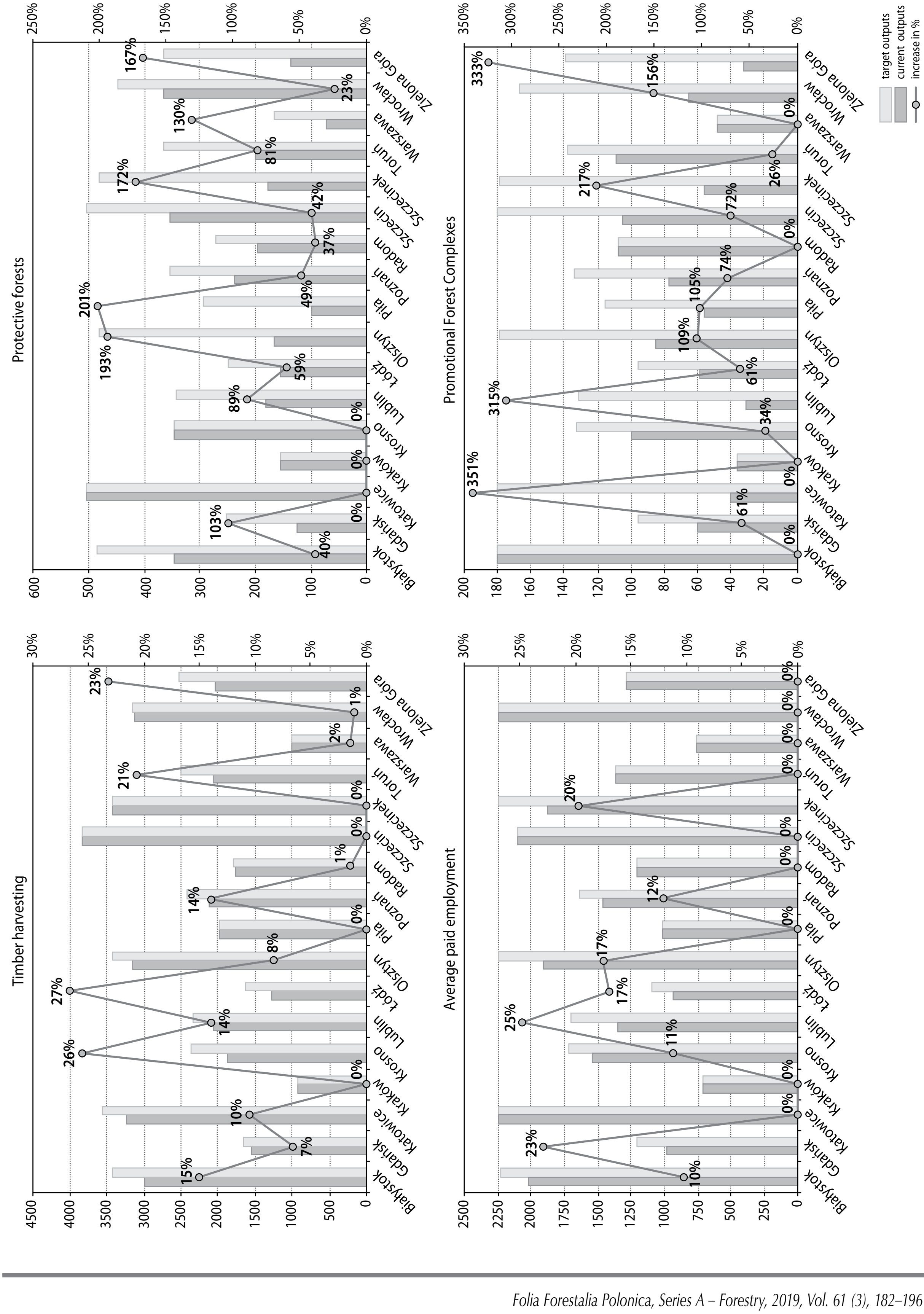

Figure 2. Current and target outputs of the Regional Directorates of State Forests

the efficiency score, which is lower than 0.3, qualifies the RDSF as efficiency laggards, none of the RDSFs was included in this group. Due to the very low score obtained in both models 2 and 4, the Directorate in Zielona Góra held the last place in the efficiency ranking. Its average efficiency score was found to be 0.60, which means that this unit produces, on an average, 0.40 too little outputs for the given inputs.

Based on the inverse of efficiency scores $1/q$ (Tab. 3), the target values of outputs for a given level of inputs can be established for the inefficient RDSFs (Fig. 2). For instance, for the Directorate in Zielona Góra, which had the lowest efficiency score, the optimum values of outputs were timber harvesting – 2518 thousands of m^3 (1.2316*2044.5 thousands of m^3), protective forests – 365.5 thousands of ha (2.6719*136.8 thousands of ha), average paid employment – 1286 (1*1286 persons), PFCs – 139 thousands of ha (4.3267*32.1 thousands of ha). To achieve efficiency, the Directorate in Zielona Góra ought to produce 23% more timber as well as it ought to increase the area of protective forests by 169% and PFCs by a huge 333%.

The highest potential increases are related to the area of protective forests and PFCs, which results from the fairly low efficiency scores of RDSFs obtained in models 2 and 4. Though the values for improvements are different depending on the Directorate and its efficiency level, on an average, the inefficient Directorates ought to increase the area of protective forests and PFCs by 82% and 113%, respectively.

Discussion and conclusions

The new approach toward forest management involves considerations for both production and nonproduction forest functions, in accordance with the concept of sustainability. This is connected with the simultaneous implementation of a number of, often contradictory and nonmarket, purposes. In this situation, the analysis and evaluation of the efficiency of the undertaken actions and utilizing resources is difficult but necessary. DEA method is a valuable alternative approach to assess the efficiency of sustainable forest management, which is proven by this study. It is indeed applicable in the comparative analysis as, by integrating several indicators into a single efficiency score, it provides information on the current level of efficiency of all considered DMUs. Moreover, by setting directions toward increasing the productivity, it helps in the decision-making process. Essentially, the application of many DEA models in analysis may be useful in improving the quality and management of available resources, especially that these models can take completely different economic, social, technical, and environmental criteria into account.

Due to its advantages, the DEA method has been used in forestry since the 1990s (Kao and Yang 1991; Kao et al. 1993), where it is applied to assess the performance of the various forestry organisational units. Thus, this method has been employed to model the operational process in many countries around the world, including Japan (Shiba 1997), the United States (LeBel and Stuart 1998), Finland (Viitala and Hänninen 1998), Denmark (Bogetoft et al. 2003), Croatia (Šporčić et al. 2009) and Turkey (Bayramoğlu and Toksoy 2017). In Poland, the DEA method was first introduced and used by Młynarski and Szybki (2016a, 2016b, 2017) for the evaluation and comparison of the financial and economic resources efficiency of forest districts. It should be emphasized, however, that the application of the DEA method using indicators reflecting the criteria of sustainable forest management at the level of forest management units, that is, RDSFs, is the first attempt of its kind in Poland and in the world.

In Poland, forests occupy 9215 thousand ha (as of 31 December 2015), which constitutes 29.5% of the country's total geographical area. The ownership structure is dominated by public forests (80.8%), and RDSFs manage 77.0% of the forest area (SFIC 2016). Based on the average efficiency scores determined by four adequately selected DEA models, it can be concluded that the efficiency of this management is quite high and RDSFs quite efficiently convert inputs to outputs resulting from the tasks of sustainable forest management. This is confirmed by the certification process started in 1996, which resulted in awarding certificates of good forest management by Forest Stewardship Council (FSC), in particular, the certificate issued by the organization called Societe Generale de Surveillance (SGS), which confirms that the management of forests in Poland is conducted with considerations for all forest functions: productive and non-productive. Currently, apart from the Directorate in Krosno and 3 forest districts of the Directorate in Białystok, all Directorates are certified by FSC (FSC Poland 2019), which clearly indicates that they are oriented towards forest management, which provides a balance at the ecological, economic, and social level.

Nevertheless, there are still challenges that need to be taken up for the optimal implementation of all forest functions. They are connected with the necessity to increase the forest areas and the economic efficiency of growing stock; the use of diverse species composition, often unfavourable in financial terms; as well as various technologies of regeneration, tending, protection, and forest exploitation. Particular attention should be paid to the forest stands threatened by collapse; reconstruction should be started appropriately early to avoid an ecological disaster. The construction and modernization of forest roads, ecological paths, tourist facilities, and greater communication and cooperation with the society is becoming necessary. DEA is the methodology that provides information on which areas need to be improved and how much work remains to be performed to become efficient.

In this study, DEA method was able to provide target outputs (i.e., in the forest functions such as timber harvesting, protective forests, average paid employment, and PFCs), proving it to be a powerful tool to enhance the decision-making process. In order to conduct a more effective policy of sustainable development, one needs to, first of all, increase the area of forests in which ecological and educational activity will be performed. It might lead to the development of local tourism and services, increase in the research work, as well as more considerable integration of the primary goals of the forest economy, that is, wood production and environmental protection.

The ability to establish proper efficiency guidelines by making right decisions based on the target outputs is of particular significance for sustainable forest management. If the selection process of variables is not reasonable and accurate, the ranking of DMUs based on efficiency scores, and thus, the target outputs could be unreliable and confusing. But, the selection procedure proposed in this study can identify significant variables with high accuracy, making it possible to obtain a reliable indicator for evaluating business and non-production activity of forestry units. Jitthavech (2016) identified relevant advantages that encourage the implementation of the procedure of eliminating candidate variables using the statistical test for hypothesis testing and based on the number of efficient DMUs.

Furthermore, the usefulness and reliability of research using the DEA method are highly dependent on the data assumed. Thus, employing a different set of inputs and outputs may lead to different results, including a different distribution of efficiency scores. Nevertheless, the fact remains that the business and non-production activity of RDSFs is best represented in this study using the statistical data published by the CSO and SFNFH.

Finally, we believe that additional research over a longer period of time is undoubtedly required to confirm the results obtained in this study. Therefore, a future prospective analysis with respect to the assessment of efficiency of sustainable forest management, regarding the varying temporal and spatial dimensions, has been planned, which will cover all forest districts, since measurements can be more precise at this level.

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