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ORIGINAL PAPER

How unit costs of conducting forestry vary with the natural and economic conditions of forests in eastern Poland

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ABSTRACT

Knowledge of costs, their structure, and change dynamics are the basis for decision making by forest managers. Furthermore, an understanding of the factors affecting the expenses borne by forest holdings influences forest resource management and is of importance in improving the profitability of silviculture. The objective of this study was to understand the relationships between unit costs of forest management and the attributes of forest districts distinguished on the basis of natural and economic conditions (*e.g.*, forest site type, compatibility between stand species composition and forest site type, silvicultural system, and fragmentation of forest complexes, etc.). This was accomplished using unit costs of forest management in 82 forest districts belonging to the Regional Directorates of State Forests in Białystok, Krosno, and Lublin (eastern Poland) in the years 2005-2009 and 2015-2019. Based on regression analyses, the main forestry activities significantly affecting costs were found to be forest regeneration, tending, protection, investment in infrastructure, as well as timber harvesting and skidding costs. Regeneration costs increased with the degree of management difficulty, while the costs of forest tending were significantly higher in districts managing mountain sites, especially those with fir-beech stands. Outlays on forest protection were significantly greater where the clearcutting system was used and in forest districts with compact forest complexes. Significantly greater bunching and extraction costs were reported by forest districts in mountain areas, where selection silvicultural systems predominated. Cost optimization of forest management can improve the net income of forest holdings, especially in the face of increasing 'ecologisation' pressures in forestry and the mounting opportunity costs of nature conservation and biodiversity protection in forests.

KEY WORDS

economics of forestry, principal activity costs, costs analysis, natural factors, economic factors

Introduction

The economic efficiency of forest management is affected not only by biogeographic conditions, including soil type, site mosaic, forest assemblages, orography, and terrain, but also by the legal regulations, silvicultural prescriptions, forestry principles, and forest management planning requirements used in individual countries. In a free market, the manner of awarding contracts to forestry

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contractors, as well as the competitiveness, innovativeness, and technological developments of the forest sector, determine the cost of forestry operations. While innovation has allowed some costs to remain relatively stable, other costs have been increasing (Harikrishnan *et al.*, 2019). Of no little consequence for the net income of forest districts is the 'ecologisation' of forestry, as well as requirements to protect the natural environment and biodiversity, which impose considerable constraints on forest management (Kożuch and Adamowicz, 2016; Pohjanmies *et al.*, 2017). There have been increased outlays for nature conservation and to support social functions of forests, such as recreation and environmental and forest education (Allemann *et al.*, 2015; Gołos and Kaliszewski, 2016). Furthermore, mounting pressures from different stakeholders on the forest environment (Uhde *et al.*, 2015) have increased costs, for example to carry out forest certification and maintain Natura 2000 sites (Van Deusen *et al.*, 2010; Pastur *et al.*, 2019).

In recent decades, problems of stand incompatibility (tree species on inappropriate sites) have become evident. These stands tend to break up at a younger age, which is expected to gradually worsen due to climate change and extreme weather (strong winds and droughts), resulting in increased costs to forest management. Currently, the greatest challenges facing forest managers are to adapt stands to the consequences of climate change and to implement 'close-to-nature', multifunctional forest practices (Povellato *et al.*, 2007; Roessiger *et al.*, 2011; Löf *et al.*, 2019; Gejdoš and Michajlova, 2022). While responsibilities to address these issues have been steadily rising, forest managers are also under mounting pressure to pursue social and environmental functions of forests, at the same time as the costs of forest operations have been rising and revenues from timber production declining (Merlo and Briales, 2000). According to Adamowicz *et al.* (2016) and Młynarski *et al.* (2021), forest holdings will face further responsibilities associated with managing forests for non-timber production functions. Because of these pressures, alternative sources of forest income are needed, including environmental products, to increase the financing potential of forestry, while pursuing cost optimization in forest management (Muttilainen and Vilco, 2022).

Timber production and forest management require a long-term approach to understand how forestry investments bring about financial returns. Some forest management expenses borne by landowners may be treated as a cost to preserve forest productivity, even though they may not provide direct financial benefits (Finley *et al.*, 2006; Parzych *et al.*, 2019). Timber production in traditionally managed stands may involve very long time horizons over which considerable changes in timber prices and management costs can occur, generating uncertainty in the expected return on investment. In a study by Cubbage (2004), returns from natural stands were much less than from plantations. Numerous researchers have analysed the economic efficiency of multifunctional forestry implemented under different management scenarios (Bosted and Mattsson, 2006). Others have evaluated forest investments at given interest rates under different natural and economic conditions, using the internal rate of return (IRR) (Mei, 2019). Analytical techniques, including discounted cash flows (DCF) and net present value (NPV), can help forecast financial results to guide investment decisions in forestry (Callaghan *et al.*, 2019). Equally important is knowledge about the costs of forest management, including their structure and change dynamics. Information about costs is the basis for decision making by forest managers, and knowledge of costs is indispensable for determining financial results. Costs provide an objective description of economic activity and are also a measure of the efficiency of forestry managers (Nowak, 2018). In contrast to revenues, forest management costs are borne by forest holdings far in advance of income from those forests, affecting their liquidity; costs are also more readily controllable, and so should be optimized. In analyzing the unit costs of forest district operations (both principal and administrative activities), it was assumed that disproportionate costs of basic silvicultural procedures in forest districts are linked to differences in timber production and work intensity, which depend on natural and economic conditions (Kocel *et al.*, 2012). For these reasons, the relationship between forest management and its biological and geographical determinants has attracted considerable scrutiny.

Many authors identify the need for improved systems of economic and financial assessment of forest districts because of their complex natural conditions and wood production factors (Hanewinkel *et al.*, 2014; Adamowicz *et al.*, 2017; Młynarski *et al.*, 2021). Such analyses should include costs, as they have a major effect on the economic performance of forest holdings. However, costs can be difficult to predict because wood production is technically, organizationally, and environmentally complicated. Given this complex set of factors and determinants, cost analysis forms the most central aspect of an economic assessment of the profitability of forest management. In most cases, analyses of the impact on costs of just a single independent variable have been carried out, but in this study the impact of several factors on costs is simultaneously evaluated. Control of cost effectiveness as well as the general costs of forest holdings during the decades-long cycle of timber production is of great significance due to the need to maintain financial liquidity and to carry out statutory tasks.

The present study evaluates the effects of selected natural and economic factors on the unit costs of the most important forestry tasks in forest districts within the Regional Directorates of State Forests (RDSF) in Białystok, Krosno, and Lublin in the years 2005-2009 and 2015-2019. Relationships between unit costs for these principal forestry activities and the natural and economic conditions of the forest districts are described. The effects of natural and economic factors on forest district costs are far from clear and gave rise to the following research question: Are there statistically significant relationships between unit costs of principal activities (in particular, the costs of forest protection, fire protection, infrastructure, forest regeneration, forest tending, agrotechnical drainage, felling and processing, bunching and extraction) and forest site type (FST), compatibility between stand species composition and forest site type, actual tree species composition, silvicultural system, timber harvesting intensity, fragmentation of forest complexes, and management difficulty?

Materials and Methods

Source materials. In order to appropriately manage the state-owned properties they are in charge of, forest district managers need to carry out forestry in an economically viable manner and are required to maintain full accounting records. SFNFH (State Forests National Forest Holding) technical and economic datasets are generated using a harmonized accounting policy, a chart of accounts, and the State Forest Information System (Rozporządzenie, 1994; Zarządzenie, 2020). The analysis carried out for this study considers net costs in 82 forest districts within the RDSF Białystok, Krosno, and Lublin. Costs and effects of natural and economic factors on those costs were compared for two periods, 2005-2009 (in the case of the Kołaczyce Forest District established in 2008, the period was 2008-2009) and 2015-2019. These periods differ in the degree of technological advancement and mechanization of forestry, as well as wages. Furthermore, views on environmental protection and social forest functions evolved considerably between these periods.

Costs were adjusted based on inflation using the Consumer Price Index (CPI) published by the Statistics Poland (2022). Costs were converted from PLN (Polish currency) to EUR (average euro exchange rate from mid-2022) according to the rates of the Narodowy Bank Polski (NBP, 2022).

Empirical data were derived from reports generated using the State Forest Information System: (1) LPIR-1 reports on planned and actual activities conducted by forest districts, both in terms of costs and activity levels, by cost center, including: 5102 – forest cultivation, 5104 – forest protection, 5105 – fire protection, 5106 – maintenance of infrastructure in forests, 511 – timber harvesting and skidding and revenues from timber sales, 516 – balance of payments with the Forest Fund, (2) LPIO-9 reports on harvesting and timber sales, (3) LPIR-4 reports on state-owned land managed by the State Forests within the RDSF Białystok, Krosno, and Lublin, (4) BLP-344 report 'Management difficulty indices for the organizational units of the State Forests: Methodology adjustment and updated results' from 2010, (5) forest management plans for the Białystok, Krosno, and Lublin Forest Districts, (6) annual plans on the activity of State Forests, and (7) financial and economic reports.

This study used forest districts grouped into their most homogenous categories as described by Kożuch and Marzęda (2021). Forest districts were assigned to natural and economic categories based on cluster analysis using the k-means method:

- Four forest site types (coniferous, broad-leaved, upland, and mountain) were identified based on soil moisture, fertility, and elevation;
- Forest district stand species composition was classified based on the relative volumes of the major forest tree species: Scots pine *Pinus sylvestris* L., Norway spruce *Picea abies* L. H.Karst., Silver fir *Abies alba* Mill., European beech *Fagus sylvatica* L., and oaks *Quercus* L.;
- Compatibility of tree species with forest site type occupied allowed forest districts to be divided into three categories: compatible, partially compatible, and incompatible;
- Forest districts were classified in terms of management difficulty (Kocel *et al*., 2010, 2012);
- The degree of fragmentation of forest complexes in forest districts was classified based on a concentration indicator;
- Forest districts were also classified into homogeneous groups based on silvicultural (felling) systems predominantly used: clearcutting (I), mixed systems (II), and those with predominantly selective cutting (III);
- The intensity of harvesting operations in forest districts was categorized based on the volume of timber harvested (m^3/ha) in the two time periods.

COMPUTATION OF UNIT COSTS. The study considered costs for all major activities taking place in forest districts, which are the subject of financial and economic planning and which are subsequently verified in the districts' financial reports. Unit costs were calculated using records of expenditures for each of the seven principal forestry activities in forest districts within the RDSF Białystok, Krosno, and Lublin (Table 1). The principal activities were groups of operations that formed the major components of forest management, ranging from regeneration activities to timber harvesting and skidding. Costs were determined according to Płotkowski (1996) as direct financial outlays without markups, such as indirect administration or management costs. This makes it possible to compare costs between organizational entities. Activities for which unit costs were calculated for forest districts in the RDSF Białystok, Krosno, and Lublin are shown in Table 1.

METHODS. Single factor analyses of the effects of independent qualitative variables (FST, tree species composition, etc.) on the quantitative dependent variable (costs) in the 82 forest districts were conducted using linear regression separately for each period. Reference values

Table 1.
Principal forestry activities for which unit costs were calculated

Principal forestry activity costs	Components
Forest protection costs (EUR/forest area in forest district [ha])	obtaining prognostic materials, limiting pests (insects, fungi), protecting the forest against ungulate damage, protecting biodiversity, nature protection (protection of nature reserves and plant and animal species of concern)
Fire protection costs (EUR/forest district area [ha])	fire prevention (maintenance of the observation and alarm network, landing sites, specialized firefighting equipment), water access points, rescue procedures
Infrastructure costs (EUR/forest district area [ha])	maintenance and repair of forest roads, viaducts (economic depreciation), and information and educational infrastructure facilities
Forest regeneration costs (forest renewal) (EUR/treatment area [ha])	mechanical, manual site preparation, costs of acquiring seedlings/seeds, direct seeding, planting (hand and machine), artificial regeneration, supplementary regeneration, site preparation for natural regeneration, afforestation
Forest tending costs (EUR/area of care treatment [ha])	soil cultivation and weed control (mowing), early cleaning, late cleaning
Agrotechnical drainage costs (EUR/treatment area [ha])	removal of branches, felling waste, preparation of the ground for forest renewal, earthworks, water drainage
Timber harvesting and skidding costs (EUR/volume of harvested/skidded wood [m^3])	felling, delimbing, bucking, cut-to-length system or another system, forwarding, skidding and moving timber from stump to road

serving as the basis for comparison were selected following the logic of analyses. The applied model is given by:

$$Y = \sum_{i=1}^{k} \beta_i X_i + \varepsilon$$

where:

Y – dependent variable (costs),

X_i – independent variables (FST, etc.),

β – model parameters,

ε – random error, with its assumed distribution being $\varepsilon \sim N(0,\sigma^2)$.

The β parameters show the effects of independent variables on Y (costs):

$\beta>1$ denotes a stimulant, i.e., a factor increasing costs,

$\beta<1$ denotes a destimulant, i.e., a factor causing costs to decrease (Weisberg, 2014).

Values of p less than 0.05 indicated significant relationships. The coefficient of determination (R^2) indicates the proportion (percentage) of the variation in the dependent variable explained by the independent variable. Analyses was done using R software, version 4.1.2 (R Core Team, 2021).

Results

Relationships between unit costs and forest management conditions. Statistically significant relationships between natural and economic conditions and costs were found, but not always in both periods. For example, in 2005-2009, a statistically significant relationship was found between the costs of the principal forestry activities and the intensity of timber harvesting – forest districts in the 'intensive (high)' category incurred costs that were on average 31.00 EUR/ha greater compared with the 'very high' category. In comparison, in 2015-2019, each cubic meter of timber harvested increased principal activity costs on average by 16.51 EUR/ha. Principal activity costs were affected by species composition of stands: in forest districts composed predominantly of pine stands, principal activity costs were significantly higher by on average 39.43 EUR/ha, compared to districts with predominantly pine and spruce stands (Tables 2 and 3). Moreover, there were no statistically significant relationships between principal activity costs and other forest district categorisations.

Forest protection costs were affected by the silvicultural system. Forest districts with predominantly 'mixed' systems reported lower direct forest protection costs (on average by 15.13 EUR/ha in 2005-2009) compared to districts that mostly used clearcutting. In both periods, protection costs were significantly affected by the fragmentation of forest complexes. In districts with highly compact forest complexes, protection costs were higher on average by 5.92 EUR/ha than in districts characterized by substantial fragmentation. Forest protection costs were also increased by the volume of harvested timber – on average by 1.20 EUR/ha per each cubic meter of timber (2015-2019). In comparison, fire protection costs were not significantly related to qualitative features, either in 2005-2009 or 2015-2019. In addition, infrastructure costs depended on silvicultural system and the volume of harvested timber, especially in 2015-2019. In both periods, forest regeneration costs were related to the level of management difficulty. In forest districts belonging to the 'difficult' category, regeneration costs were 196.70 EUR/ha less than in districts rated 'very difficult.' Forest districts in the 'easy' category, that is, stands managed in the most favorable locations, had regeneration costs on average 241.90 EUR/ha lower than in the 'very difficult' category. In 2015-2019 regeneration costs in the 'difficult' forest districts were on average lower by 262.82 EUR/ha *vs.* 'very difficult' districts.

Forest tending costs depended on timber harvesting, as well as on forest site type. Thus, forest districts managing fir and beech stands located in the mountains and foothills experienced higher costs compared with those managing pine stands. In turn, agrotechnical drainage costs were dependent on stand compatibility with forest habitat type; these costs were also affected by tree species composition and the intensity of silvicultural operations (Tables 2 and 3).

Timber harvesting and skidding costs depended on the forest site, the compatibility of stands with forest sites, and with tree species composition. Moreover, harvesting and skidding costs were affected by silvicultural system, as forest districts belonging to the 'mixed' category reported costs that were on average higher by 0.64 EUR/m^3 compared with districts where clearcutting was more common (Tables 2 and 3).

Values of the coefficient of determination, R^2, indicated that a considerable proportion of the variation in the dependent variable (i.e., costs) was explained by the independent variables adopted in the models. This dependence was especially strong for expenditures on principal activities (66.3%), fire protection (65.9%), forest tending (88.6%), and timber harvesting and skidding (82.6%). Lower R^2 values were obtained for forest protection costs both in 2005-2009 and 2015-2019 (22.7% and 48.5%, respectively). Lower coefficients of determination were also found for infrastructure (32.4% and 48.1%) and forest regeneration expenditures (36.5% and 47.1%) (Table 4).

Discussion

The optimisation of forest management expenditures is at this time crucial due to the deteriorating financial status of forest districts. Forest management that does not cover its costs can put

Table 2.

Relationships between type of forest district cost in 2005-2009 and natural and economic factors (qualitative characteristics)

		Principal forestry activity [EUR/ha]	Forest protection costs [EUR/ha]	Fire protection costs [EUR/ha]	Infrastructure costs [EUR/ha]	Forest regeneration costs [EUR/ha]	Forest tending costs [EUR/ha]	Agrotechnical drainage costs [EUR/ha]	Timber harvesting and skidding [EUR/m^3]
Forests	lowland (broadleaved)	ref.‡							
Site	lowland (coniferous)	–19.66	11.90	0.60	–2.06	–153.15	–40.33	–107.35	–0.53
Types	lowland (mixed)	–4.84	–5.04	0.34	–1.72	–26.00	–44.77	–138.16	–2.18
(FST)	upland	11.35	5.79	–0.86	0.54	18.43	7.05	51.54	–0.97
	mountain	10.00	0.75	–1.29	0.37	215.09	52.00*	97.97	2.93
Stand compliance	compatible	ref.							
with forest	partially compatible	–9.23	4.73	–0.03	–1.00	–40.39	–20.67	57.47	0.40
habitat types	incompatible	–9.95	5.70	–0.52	1.55	–41.56	–11.55	83.87*	–0.23
Tree species	pine	ref.							
composition	pine and spruce	–19.41	–0.57	–0.46	–2.44	19.35	–18.80	178.89*	–0.19
	pine and oak	–13.62	7.88	–0.32	–0.80	–115.11	12.58	–11.69	0.40
	fir and beech	–3.35	–2.09	–0.11	2.06	–95.36	56.84	–151.46	7.54*
Silvicultural	clear cutting	ref.							
system (timber	mixed	4.50	–15.13*	–0.57	–1.20	32.76	7.02	–0.09	0.10*
harvesting and	indirect (selective)	–0.86	–10.69	–0.60	–1.09	–82.70	–28.69	–100.72	–1.00
regenerating)									
Fragmentation	scattered	ref.							
of forest	compact	10.52	1.69*	–0.52	–0.86	–116.15	9.09	5.19	0.29
complexes	tightly compact	15.62	5.25	–0.75	–0.40	–54.12	22.42	19.78	1.03
Management	very difficult	ref.							
difficulty	difficult	–8.20	–0.66	–0.32	–0.46	–196.69*	–5.33	–25.14	–0.95
level	easy	–13.27	–6.91	–0.54	–0.95	–241.92*	–2.90	0.46	0.45
	very easy	–18.80	–13.70	–0.80	–1.09	99.43	13.84	12.81	–0.85
Timber	very high	ref.							
harvesting	high	30.99*	–6.76	0.14	–0.03	59.79	22.39*	129.47*	–0.59
(2005-2009)	medium	–19.72	–0.20	0.03	–0.32	64.69	4.93	–6.56	–1.00

* statistically significant (p<0.05)
‡ ref. - reference level

Table 3.

Relationships between type of forest district cost in 2015-2019 and natural and economic factors (qualitative characteristics)

		Principal forestry activity [EUR/ha]	Forest protection costs [EUR/ha]	Fire protection costs [EUR/ha]	Infrastructure costs [EUR/ha]	Forest regeneration costs [EUR/ha]	Forest tending costs [EUR/ha]	Agrotechnical drainage costs [EUR/ha]	Timber harvesting and skidding [EUR/m^3]
Forests Site Types (FST)	lowland (broadleaved)	ref.‡							
	lowland (coniferous)	–18.22	–5.46	0.54	0.32	–128.22	–7.82	4.14	–0.81
	lowland (mixed)	–5.84	–5.80	0.56	5.87	–205.20	13.08	98.19	–0.52
	upland	–13.44	–0.95	–0.63	–6.53	–178.32	14.76	21.65	–0.09
	mountain	29.71	2.34	–0.58	–3.17	27.98	49.36*	171.94	3.53*
Stand compliance with forest habitat types	compatible	ref.							
	partially compatible	–8.72	–2.85	0.12	–1.51	–63.59	0.12	–0.97	0.15
	incompatible	–2.24	1.39	–0.07	4.60	12.30	–3.31	–38.43	–0.76*
Tree species composition	pine	ref.							
	pine and spruce	–39.43*	–5.19	–0.75	–7.77	–160.03	–16.15	110.05	–0.63
	pine and oak	–19.09	–3.63	–0.24	–4.24	16.39	–13.56	5.82	–0.71
	fir and beech	14.81	–1.92	–0.46	14.25	–179.92	80.34*	4.80	2.51*
Silvicultural system (timber harvesting and regenerating)	clear cutting	ref.							
	mixed	7.74	–0.19*	0.29	6.40	183.94	9.18	–4.53	0.64*
	indirect (selective)	8.06	–2.44	–0.12	9.94*	149.14	11.96	–32.73	0.26
Fragmentation of forest complexes	scattered	ref.							
	compact	–0.15	2.70	–0.17	0.83	26.13	–3.56	–57.91	–0.05
	tightly compact	1.22	5.92*	–0.32	3.46	163.85	–12.42	–99.09	–0.75
Management difficulty level	very difficult	ref.							
	difficult	13.05	–7.83	–0.41	1.15	–262.82*	5.70	41.13	0.68
	easy	18.56	7.10	–0.37	5.43	–250.16	2.24	–2.51	0.92
	very easy	30.13	5.48	0.34	28.43	105.72	10.69	6.48	0.12
Timber harvesting (2015-2019)	very high	ref.							
	high	–16.51	–1.20*	2.44	–1.9*	45.75	21.28	19.33*	–0.29*
	medium	–21.77	0.76	–0.02	0.66	55.74	–2.66	–1.73	–0.02

* statistically significant (p<0.05)
‡ ref. - reference level

Table 4.
Model fit (R^2) in two time periods for different types of forest district costs

Years	Principal forestry activity [EUR/ha]	Forest protection costs [EUR/ha]	Fire protection costs [EUR/ha]	Infrastructure costs [EUR/ha]	Forest regeneration costs [EUR/ha]	Forest tending costs [EUR/ha]	Agrotechnical drainage costs [EUR/ha]	Timber harvesting and skidding costs [EUR/m^3]
				[%]				
2005-2009	41.9	22.7	48.0	32.4	36.5	57.8	47.8	67.6
2015-2019	66.3	48.5	65.9	48.1	47.1	88.6	30.0	82.6

at risk the long-term provision of some ecosystem services (Bont *et al.*, 2022). In this study, the intensity of timber harvesting exerted the greatest effect on forest district revenues. The sale of timber provides approximately 90% of total revenues, and so the volume of expenditures made by individual forest districts depends on that factor (assuming a constant cost to revenue ratio). In forest districts with large areas of pine stands, unit costs were generally lower than in districts with pine and spruce stands (such as the Browsk, Białowieża, and Hajnówka Forest Districts). In the latter districts, timber harvesting was reduced to achieve certain nature conservation objectives.

The main forest protection expenditures were for tree protection from damage by ungulates (approximately 57%), fire protection (16%), insect pest control (15%), and direct nature conservation costs (approximately 11%). The use of the clearcutting system increased forest protection expenditures. Forest districts predominantly using 'mixed' felling systems had lower direct forest protection costs compared with those using clearcutting, with similar results reported in Czechia (Pulkrab *et al.*, 2011). Cost differences due to silvicultural system are likely attributable to the lower resistance of stands established after clearcutting to damage from abiotic and biotic factors. Forest protection costs were strongly affected by the greater need to protect seedlings and saplings from ungulates, a factor that forest owners should take into account when considering financial risks with different approaches to forestry (Clasen *et al.*, 2011). Protection from ungulates significantly contributed to costs, which was highest in the RDSF Białystok at 3,833,669.81 EUR/year (accounting for 62% of overall forest protection costs of 6,166,583.80 EUR/year). In forest districts with high ungulate levels, the protected area and protection costs increased proportionately with the area of newly established stands. Furthermore, the highest forest protection unit costs were in forest districts belonging to the highly compact forest complexes. Compact forest complexes are often found on poor sites, which have many single-species stands, usually even-aged, and are often sites of outbreaks of pest insects and fungal pathogens. Severely damaging events constitute both an environmental and economic disaster to forests that increase forest management costs. As coniferous stands tend to be at greater risk of severe events, the costs of their protection are more likely to rise. However, neither in 2005-2009 nor in 2015-2019 were fire protection costs significantly related to any of the qualitative features that were evaluated. The highest median fire protection cost was found for lowland coniferous sites, while protection costs decreased with increasing proportions of broadleaved forests stands.

Infrastructure costs in the study area amounted to 87,874,457.54 EUR/year, of which forest road maintenance accounted for 80% and the maintenance of tourist and recreational infrastructure for 7.5% (in the case of the RDSF Białystok, recreational infrastructure cost was as much as 14% of the total). Investment in road construction is more justified in areas where regular thinning is planned (Ryan *et al.*, 2004). However, Knoke *et al.* (2001) noted that the costs of maintaining roads and infrastructure in forests managed using continuous cover forestry were similar to those in forests managed with rotation-based forestry *(i.e.*, a clearcutting system) (Purser *et al.*, 2015). Findings here are similar, but they show that infrastructure costs depend on the harvesting and regeneration systems used. Forest districts categorised as mainly using selective forestry had higher infrastructure maintenance costs than those employing mostly clearcutting, with the difference being 9.94 EUR/ha. This was probably associated with greater total road lengths producing higher costs of road maintenance for the selection system. Moreover, road maintenance costs are also related to harvest volumes, with each cubic meter of timber increasing infrastructure costs by 1.90 EUR/ha. Higher volumes of harvested timber with clearcutting thus increased costs of road repair, while clearcutting's higher revenues from timber sales enabled more extensive investments in infrastructure than did selection forestry.

The median regeneration cost was greatest for mountain forest districts, lower in upland districts, and lowest in districts managing coniferous lowland sites. Moreover, regeneration costs were affected by management difficulty, with forest districts in the 'difficult' category having regeneration costs lower than districts considered 'very difficult' and forest districts in the 'easy' category (located on the most favourable sites) having regeneration costs on average 241.92 EUR/ha less than the 'very difficult' category. Glura and Moliński (2003) reported higher regeneration costs for fresh mixed broadleaved forest sites compared with mixed coniferous and fresh coniferous forest sites, one reason being that higher planting densities lead to poorer financial results, as also shown in the modelling study conducted by Hyytiäinen *et al.* (2005). Moreover, planting 10,000 seedlings/ha was unprofitable due to the high initial investment, which was not compensated for by higher revenues from timber sales. Regeneration systems significantly impact the final financial costs and revenues of stands. Previous research on natural and artificial regeneration of pine stands and stands with dominant pine in Poland (Nowa Dęba Forest District) reveal that natural regeneration is cost effective on fresh coniferous forest sites, fresh mixed coniferous forest sites, and moist mixed forest sites. In contrast, the high costs of tending and corrective procedures on fresh mixed broadleaved forest sites produced negative economic results for natural regeneration (Długosiewicz *et al.*, 2019). The choice of regeneration system is of economic significance at low discount rates; the use of genetically modified plant material makes planting preferable (Simonsen, 2013). In Finland, at an interest rate of 1%, artificial regeneration by planting or sowing and high site preparation costs produced the highest net present values. According to Hyytiäinen *et al.* (2006), natural regeneration is preferred at high discount rates. Natural regeneration has lower material and labour costs and becomes the preferred form of regeneration at an interest rate of 3% and higher. Natural regeneration may lead to continuous tree cover, but also carries a greater risk of failure, so it is important to select the most suitable sites for this type of regeneration (Crouzeilles *et al.*, 2020).

In forest districts characterized by 'intensive' timber harvesting, forest tending costs were higher on average by 22.38 EUR/ha than in districts with 'very intensive' harvesting. Tending costs of 'mountain' forest districts were approximately 52 EUR/ha greater than 'lowland (broadleaved)' forest districts. The lowest median tending cost was found for lowland forest districts, and tending costs increased with the proportion of broadleaved sites, upland sites (upland districts), and mountain sites. Similarly, Lysik (2007) found that forest tending costs increased with the proportion of upland and mountain sites. Glura and Moliński (2003) noted that site conditions strongly influenced costs of forest establishment, maintenance, and cultivation. Forest districts that were predominantly fir and beech stands in mountain and foothill regions reported costs that were on average 80.34 EUR/ha higher than districts managing pine stands. This difference is likely due to the ease of tending pine seedling and sapling stands established (usually by planting) after clearcutting, while multi-species and multi-generation stands in districts characterized by more complex species compositions are more difficult to tend.

In forest districts with a majority of stands classed as 'incompatible' with site type, agrotechnical drainage costs were on average 83.9 EUR/ha higher than in 'compatible' stands. Also 'pine and spruce' species composition increased agrotechnical drainage costs, on average by 178.89 EUR/ha, compared with 'pine' stands. Stands incompatible with site type can have higher silvicultural costs associated with stand conversion. The compatibility of stand species composition with forest site type is increasing in Polish State Forests.

The costs of timber harvesting (felling and delimbing) and skidding (bunching and extraction) are characterized by low dynamics, probably due to a large amount of machine harvesting. The advancing mechanization of forestry work in Poland has primarily been in timber harvesting and skidding. While in 2006 there were 21 harvesters in operation, by late 2011/early 2012, 351 harvesters and 485 forwarders were reported. By 2015, the number of harvesters had increased to 530 (Mederski *et al.*, 2016). Given the shortage of forestry workers and increasing wages, the mechanization of forestry (not only harvesting and skidding) is crucial for optimising forest management. Germain *et al.* (2019) estimated the average harvesting cost in the north-eastern USA at 24.67-93.68 USD/m^3. According to Oikari *et al.* (2010), there are considerable opportunities to increase timber harvesting cost effectiveness by improving harvesting conditions in stands, later harvesting, and by reducing costs in young stands by using techniques with the greatest potential. Unit costs of harvesting are higher and profits lower for low intensity harvesting and when smaller diameter logs are harvested (Pan *et al.*, 2008). The cost productivity of skidding increases with machine payload and is inversely proportional to distance (Jiroušek *et al.*, 2007). The costs to forest districts of harvesting fir/beech stands were on average higher than those of districts harvesting pine stands by 7.54 and 2.51 EUR/m^3 in 2005-2009 and 2015-2019, respectively. Districts in mountain areas reported higher costs compared with districts in lowland (broadleaved) areas, the difference amounting to 3.53 EUR/m^3. Furthermore, costs were influenced by silvicultural system, as the average cost to forest districts in the 'mixed' category was 0.64 EUR/m^3 greater than those districts where clearcutting was the most common silvicultural system.

Conclusions

The financial position of forest districts examined in this study was poorer in 2015-2019 than in 2005-2009. The largest increase in unit costs was for infrastructure and forest tending silvicultural treatments, regeneration, and forest protection. The least volatile costs were for activities whose level of mechanization is growing (in particular agrotechnical drainage costs, timber harvesting, and skidding). This suggests that financial savings may be achieved using innovative approaches and increased mechanization of forestry work.

The current results may assist decision making by those who manage forest resources and analyse the profitability of forestry operations. For instance, in forest districts where wood production is less important due to the higher cost of forest management, the information provided here may point to the need for alternative directions to diversify revenue streams.

Statistically significant relationships were found for regeneration costs, which depended on the level of difficulty of forest management, while tending costs were significantly higher in districts containing mountain sites, especially those with fir and beech stands. Forest protection costs increased significantly for the clearcutting system and for districts with compact forest complexes. Infrastructure costs rose with harvesting intensity. Timber harvesting and skidding costs were significantly lower on incompatible vs. compatible sites. Finally, significantly higher costs were observed in forest districts with mountain sites dominated by fir and beech stands and using a mixed silvicultural system.

It is important to continue research on the economic consequences of artificial and natural methods of forest regeneration, as well as on the frequency of tending procedures in forests. Another challenge is management of ungulate populations to reduce expenditures on forest protection.

Conflict of interests

The author declare no conflicts of interest.

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STRESZCZENIE

Koszty jednostkowe a uwarunkowania przyrodniczo-gospodarcze działalności nadleśnictw na terenie Polski Wschodniej

Na efektywność ekonomiczną gospodarki leśnej, poza uwarunkowaniami biogeograficznymi, wpływają koniunktura gospodarcza, regulacje prawne w zakresie leśnictwa, a także konkurencyjność i innowacyjność rynku usług leśnych. Znajomość kosztów, ich struktury i dynamiki zmian stanowi podstawę podejmowania decyzji przez kadrę kierowniczą nadleśnictw. Koszty są obiektywną kategorią związaną z działalnością gospodarczą, a zrozumienie czynników wpływających na wydatki ponoszone przez gospodarstwa leśne wpływa na proces gospodarowania zasobami leśnymi i ma znaczenie w poprawie opłacalności gospodarki. Celem badań była analiza wybranych kosztów jednostkowych gospodarki leśnej w 82 nadleśnictwach w RDLP Białystok, Krosno

i Lublin w latach 2005-2009 i 2015-2019. Okresy te różniły się stopniem zaawansowania technologicznego i mechanizacji prac leśnych oraz płacami w gospodarce i leśnictwie. Ponadto ewolucji uległy poglądy na ochronę przyrody i społeczne funkcje lasu. Podstawowym źródłem danych empirycznych był System Informatyczny Lasów Państwowych (SILP). W pracy opisano zależności między kosztami jednostkowymi działalności podstawowej (tab. 1) a kategoriami nadleśnictw wyróżnionymi na podstawie warunków przyrodniczych i ekonomicznych (m.in. typ siedliskowy lasu, zgodność składu gatunkowego drzewostanu z typem siedliskowym lasu, sposób zagospodarowania, fragmentacja kompleksów leśnych, wielkość pozyskania). Analizy regresji posłużyły do zidentyfikowania zmiennych niezależnych, które istotnie wpływały na koszty jednostkowe: działalności podstawowej, odnowienia, pielęgnacji i ochrony lasu, inwestycji, melioracji agrotechnicznych oraz koszty pozyskania i zrywki drewna. Stwierdzono statystycznie istotne zależności kosztów odnowienia lasu od stopnia trudności zagospodarowania, natomiast koszty pielęgnacji były istotnie wyższe w nadleśnictwach z dominacją siedlisk górskich, zwłaszcza w drzewostanach jodłowych i bukowych. Koszty ochrony lasu były wyższe w przypadku nadleśnictw z przewagą zrębowego sposobu zagospodarowania oraz nadleśnictw o zwartych kompleksach leśnych. Stwierdzono, że koszty infrastruktury rosły wraz z intensywnością pozyskania. Koszty pozyskania drewna i zrywki były niższe w przypadku nadleśnictw, w których zgodność składu gatunkowego drzewostanów z siedliskowym typem lasu była najniższa. Wyższe koszty pozyskania drewna zaobserwowano w nadleśnictwach gospodarujących na siedliskach górskich z przewagą drzewostanów jodłowych i bukowych, a także zagospodarowanych rębniami złożonymi (tab. 2, 3). Wartości współczynnika determinacji R^2 wykazały, że znaczny odsetek przyjętych zmiennych został wyjaśniony przez zastosowane w modelach zmienne objaśniające. Dotyczy to przede wszystkim kosztów działalności podstawowej, zabiegów pielęgnacyjnych oraz pozyskania i zrywki drewna (tab. 4). Poziom wybranych kosztów w badanych nadleśnictwach zależał od warunków przyrodniczo-gospodarczych. Niemniej prawdopodobnie coraz większy wpływ na gospodarkę leśną będą miały koszty alternatywne ochrony przyrody i realizacji społecznych funkcji lasu. Optymalizacja kosztów jest możliwa poprzez wykorzystanie nowych technologii i mechanizację prac leśnych. Warto analizować ekonomiczne aspekty odnowienia i pielęgnacji lasu. Kolejnym wyzwaniem jest aktywne zarządzanie populacjami zwierzyny łownej w kontekście obniżenia kosztów ochrony lasu.