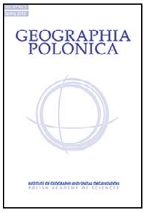

Geographia Polonica
2024, Volume 97, Issue 1, pp. 65-90
https://doi.org/10.7163/GPol.0269

INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION
POLISH ACADEMY OF SCIENCES
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THE POTENTIAL OF POLISH FORESTS TO PROVIDE ECOSYSTEM SERVICES

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Abstract

Polish forests differ in their potential to provide ecosystem services (ES), but it is unclear how and to what extent. We assessed the potential of 35 forest habitat types to provide 17 key ES and showed that the montane mesic broadleaved forest has a high potential to provide the largest number of key forest services (14 out of 17), which gives it the status of a multi-service hotspot. The highest overall potential was found in the forests of mountain regions, slightly lower in the postglacial northern regions, and the lowest in the central lowland regions.

Key words

Ecosystem service potential • ecosystem service hotspots • ecosystem service bundles • sustainable forest management • forest habitat types • forest regions • State Forests • nationwide scale • Poland

Introduction

In Poland, forests constitute the most structurally and functionally complex terrestrial ecosystems. The multi-layered structure of vegetation, the presence of trees of various ages and health conditions result in the creation of numerous microhabitats occupied by various organisms (Puchalski & Prusinkiewicz, 1990). From the legal point of view, a forest in Poland is a piece of land ≥ 0.10 ha covered with forest vegetation or temporarily deprived of it (Polish Forest Act, Art. 3). Forests understood in this way constitute 29.8% of Poland's area, of which public forests – 80.7% and private forests – 19.3% (BDL, 2022). The average growing stock density amounts to 261 m^3/ha (BDL, 2022) and is much higher than that calculated for the whole of Europe (169 m^3/ha) (Forest Europe, 2020).

Forest ecosystems provide many benefits to people that shape our well-being. Ecosystem services (ES) are all the contributions that ecosystems (i.e., living systems) make to human well-being (TEEB, 2010; Haines-Young & Potschin, 2018) understood as the combination of feeling good and functioning well (Ruggeri et al., 2020), both in the physical, mental and spiritual dimensions. The Common International Classification of Ecosystem Services (CICES) includes three main ES sections: provisioning, regulating, and cultural (Haines-Young & Potschin, 2018). Provisioning services cover all outputs of living systems suitable for consumption, processing or energy production. Regulating services are the ways in which living organisms mediate or moderate the surrounding environment, and, as a result, maintain or improve human health, safety or comfort, while cultural services are the creation of conditions (environmental settings, locations or situations) for interaction with nature, resulting in maintaining or improving the quality of people's lives.

Among forest provisioning services, wood is the most important for the economy (Forest Europe, 2020; Lovrić et al., 2020). Wood is used as a construction and furniture material in the form of solid wood or is processed into wood-based products (e.g., paper) or energy. Forests are also a rich source of non-wood forest products, such as food and materials. For personal use or to generate income people harvest forest fruits, mushrooms, seeds, herbal plants and spices, tree juices, honey, and game (Lovrić et al., 2020). Forests are also a place of work and a source of income for people engaged in logging and nature conservation. Thus, both forest resource extraction and conservation activities contribute to economic development and poverty reduction (Adams et al., 2004; Agrawal et al., 2013; FAO, 2020).

As an essential habitat for many species, forests support the maintenance and protection of biodiversity (Mori et al., 2016; FAO, 2020). As part of the regulating services, forests capture carbon dioxide from the atmosphere, contributing to regulating the global carbon cycle and mitigating climate change. They also moderate the climate on a local scale by reducing the difference between maximum and minimum air temperature and limiting wind speed. Trees ionize the air, release antibacterial substances, provide shade on sunny and hot days, and create a microclimate that positively stimulates human respiratory and circulatory systems. They can also be an effective barrier to noise, unpleasant smells, and sights, while also acting as a natural filter of pollution. Forest ecosystems maintain and protect soil and regulate water circulation, preventing land degradation and desertification and reducing the risk of natural disasters such as droughts, floods, and landslides (Brockerhoff et al., 2017). For example, the root systems of trees stabilize the ground and limit water and wind erosion (Pawlik, 2013) while the moss layer of coniferous forests can store large amounts of water, significantly reducing the volume and intensity of surface runoff (Hu et al., 2023).

Forest ecosystems also provide many cultural services, providing conditions for multiple interactions supporting health and overall well-being (Brockerhoff et al., 2017). Due to their high aesthetic, recreational and scientific value, forests are a popular place for relaxation, sports and ecological education. They are a research ground for scientists, an inspiration for artists, and a meeting place with history and cultural heritage, as numerous remnants of the past are best preserved under tree canopy (Affek et al., 2022).

One of the most important parts of ES assessment is the presentation of their differentiation between types of ecosystems and in space. Local case studies clearly show that forests, even those directly adjacent to each other, differ significantly in their ability to provide services, for example, due to the diversity of habitats and management methods (Affek et al., 2020; Matuszkiewicz et al., 2021; Kruczkowska et al., 2023).

ES can be considered from the demand side, actual use, and the potential of ecosystems to provide them (supply side) (Villamagna et al., 2013). Demand for ES refers to what society and the economy need from nature, while ES use shows the actual, current flow of services. Potential, in turn, is the capacity of ecosystems to provide services and can be determined regardless of whether people use a given service or not.

Forests are multifunctional ecosystems, so they can provide many different services at the same time. When considering various services simultaneously, the term *ecosystem service bundle* is used, defined as a set of ES that occur together in space or time (Raudsepp-Hearne et al., 2010). Linkages between services may result from shared conditions that affect one or more services at the same time (e.g., presence of specific plant species, land use change, hydrological change), and/or direct interactions between services (e.g., dependence on the same ecological processes). Determining the links between ES is crucial for the proper management of forest ecosystems and the sustainable use of the services they provide (Bennett et al., 2009).

Thus, the demand for reliable and comprehensive recognition of ES is growing. Currently, however, appropriate indicators are often missing from standard monitoring and reporting frameworks (Jenkins & Schaap, 2018). Proper identification of services and recognition of the multifunctionality of forests can help, among others: in developing forest management that is more sustainable and beneficial to society and the environment. This is important because the processes that are the main causes of biodiversity loss (e.g., habitat transformation, overexploitation of natural resources, expansion of invasive alien species, climate change) are accelerating, resulting in the degradation of many ecosystems and the reduction of their ES potential (Kowalska et al., 2019).

Forest ecosystems in Poland differ in terms of their potential to provide ES, but it is unclear in what way and how much. We aimed to: (1) assess the potential of different forest types in Poland to provide key ES, (2) indicate ES hotspots, bundles of ES, and similarities between forest ecosystems in terms of their potential to provide ES, and (3) provide recommendations for sustainable forest management from the ES perspective.

Methods

Ecosystem service potential

We assumed that ES potential is the ability of an ecosystem to generate an ecosystem service at the highest yield or use level that does not negatively affect the condition of the ecosystem (future supply of the same or other ES from that ecosystem) (United Nations, 2021). Due to the nationwide scale of the study, we also assumed that current management and uses specific to a given forest fragment, resulting from local law or protection status, will not be taken into account when estimating the potential. This means, for instance, that the potential for providing mushrooms or berries will be non-zero for forests in nature reserves, even though they cannot be harvested there by law. This understanding of potential corresponds to the definition of *potential supply* included in The System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA) (United Nations, 2021). We assessed forest potential based on multiple structural and functional characteristics of forest ecosystems, in line with the European guidelines for the ES assessment (Maes et al., 2018).

Ecosystem services and their indicators

We selected 17 key forest ES for the assessment, including, among others, timber, forest fruits, mushrooms, global and local climate regulation, air purification, pollination, habitat maintenance, and providing an environmental setting for recreation, health regeneration, and education (Tab. 1). Services from each of the three sections of CICES V5.1 were included. Depending on the nature of the service and available data, the potential of a given service is described using one or two indicators. Since some services are provided by the same ecosystem component and are therefore closely related, they were considered together in this work and described by the same indicator. This applies, for example, to mushrooms as a provisioning service and mushroom picking as a cultural service, which involves creating conditions for interaction with the forest.

The indicator values refer to forests managed by the National Forest Holding "State Forests" (including those under strict protection in nature reserves), which constitute 77% of public forests and 62% of all Polish forests. The basic unit of analysis for most indicators was the forest sub-compartment (Pol. *wydzielenie leśne*), the smallest spatial unit in forest management in Poland. The indicators were constructed primarily using data on the characteristics of the forest stand and habitat, which were obtained from the Forest Data Bank (www.bdl.lasy.gov.pl) – an online platform providing spatial information on forests managed by National Forest Holding. Another frequently used resource were thematic layers developed based on satellite data, mainly within the European Copernicus program (land.copernicus.eu). In the absence of appropriate nationwide data, the potential was estimated based on expert assessment and information from the literature. The raw values of each indicator were translated into a five-level potential scale common to all services. The highest raw values were assigned the maximum rank value (5) and the lowest raw values were assigned the minimum rank value (1). In this way, the extent of the scale refers to the values recorded for individual forest types throughout the country. By assumption, no monetary value was assigned to the potential values obtained in this way.

Table 1. Key forest ecosystem services in Poland and indicators of potential[1]

Ecosystem service	Section	Indicator
Wood	P	timber that can be harvested annually, expressed in price-equivalent volume of pine wood [m^3/ha per year]
Forest fruits	P	abundance of blueberry fruit per hectare of forest [kg]
Mushrooms	P	ecological conditions favorable for the occurrence of edible mushrooms, traditionally harvested in Poland
Mushroom picking	C	
Game	P	number of red deer possible to be harvested per 10 km^2 of forest per year
Hunting	C	
Honey	P	size of food base for bees
Pollination	R	
Global climate regulation	R	(1) carbon stock in biomass [t/ha] (2) rate of carbon accumulation in biomass [t/ha per year]
Local climate regulation	R	leaf area index (LAI)
Air purification	R	
Soil erosion control	R	(1) coefficient of the protective role of forest vegetation (C) (2) difference in the amount of soil potentially eroded between a forest plot and a plot with bare soil [t/ha per year]
Flood control	R	water holding capacity of forest vegetation (trees and undergrowth)
Habitat maintenance	R	(1) number of undergrowth plant species per 400 m^2 (2) number of protected plant species in niche optimum
Science and education	C	
Recreation	C	vegetation and habitat conditions favorable for recreation
Health regeneration	C	combined effect of phytoncides (beneficial) and allergenic pollen (unfavorable) produced by trees

Explanation of abbreviations: P – provisioning services, R – regulating services, C – cultural services.

[1] A brief description of indicator construction and the data sources used is provided in the online Appendix https://rcin.org.pl/dlibra/publication/277247. A detailed description can be found in the peer-reviewed Polish-language report published by WWF (Affek et al., 2023).

Mature forests

Since the aim of the work was to show the potential of different types of forests, the indicator values were calculated for relatively mature forests that are already quite stable communities and have been proven to achieve the highest overall multi-service potential (Affek et al., 2020). We assumed that for Polish forests, a mature stand would be one that is over 80 years old (see Matuszkiewicz et al., 2021). Adopting a higher age threshold would significantly reduce the pool of forest sub-compartments and make the results not representative for many forest types.

Forest habitat types and mapping units

To determine the ES potential of forests, especially in the long term, it is necessary to focus on the ecosystem characteristics that are most stable and least dependent on current management. For this reason, the division of forest ecosystems into forest habitat types (Pol. *typy siedliskowe lasu*) was chosen, commonly used in Polish forestry for forest planning and management (Mroczkiewicz & Trampler, 1964). In this classification, individual types of forest habitat clearly differ in soil moisture and fertility, and therefore in production capacity and suitability for silviculture, which fits very well into the adopted potential approach (Fig. 1).

To map the potential of forest ecosystems on a nationwide scale, we selected the forest region (Pol. *kraina przyrodniczo-leśna*) as the basic mapping unit (Zielony & Kliczkowska, 2012). The division into forest regions results from the diversity of climatic conditions, which is reflected in the different forest-forming roles of beech, fir, and spruce and their usefulness in forest cultivation. The region delimitation was also influenced by the extent of the last glaciation, topography, and the division into natural landscapes (Richling & Dąbrowski, 1995) (Fig. 2). Lowland landscapes dominate in the Bałtycka, Mazursko-Podlaska, Wielkopolsko-Pomorska, and Mazowiecko-Podlaska forest regions. Landscapes of uplands and low mountains are most common in the regions: Śląska, Małopolska, Sudecka, and Karpacka. Whereas, landscapes of highlands and high mountains are abundant in the Sudecka and Karpacka regions, and also present in the Małopolska region. Landscapes of valleys and depressions are observed in all regions – they have the largest share in the area of the Wielkopolsko-Pomorska, Mazowiecko-Podlaska, and Bałtycka regions, and a small share in the Sudecka region (Zielony & Kliczkowska, 2012). As a result, the division into forest regions is closely related to the range of occurrence of individual forest habitat types and divides Poland into eight regions with different conditions for forest cultivation (Trampler et al., 1990; Zielony & Kliczkowska, 2012). Therefore, ES potential was estimated for forest habitat types both at the level of the entire country and within each of the eight individual regions. Similarly, the area-weighted average potential was calculated both for Poland and for each forest region.

In our study, all results showing the ES potential are expressed per unit area (e.g., per 1 ha), both for forest types and for forest regions. Therefore, the size of the region or the total forest area in the region does not affect the value of the calculated potential.

Multi-service analysis

The obtained values of the potential of 35 forest habitat types to provide 17 key ES were used for multi-service analyses aimed at determining the relationships between services (e.g., defining ES bundles, Raudsepp-Hearne et al., 2010) and identifying multi-service hotspots, i.e., types of forest with high potential to provide many ES.

We compiled indicator values into two databases: (1) with the original raw values and (2) with rank values on a 1-5 scale. Missing values mean that the source data did not allow for a reliable estimate of the potential.

The raw indicator values after standardization were used to analyze the links between services. We applied hierarchical cluster analysis, which identifies groups (clusters) of similar objects, to identify ES bundles, while

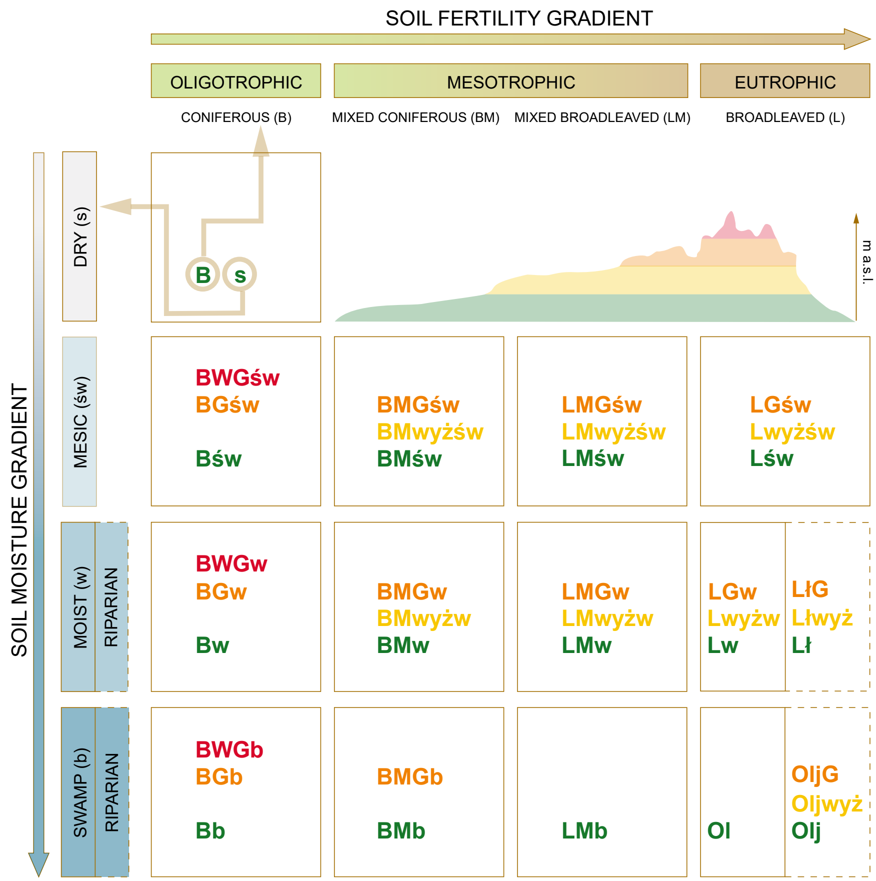

Figure 1. Forest habitat types on the gradients of soil moisture and fertility. The scheme includes lowland, upland (wyż), montane (G), and upper montane (WG) forest types

The abbreviations used here and further in the article are derived from the Polish names of habitat types and as such are commonly used in literature. Explanation of abbreviations see Table 2.
Source: Affek et al. (2023), modified.

the links between services were characterized based on the analysis of pairwise correlations between indicators. If the potential to provide a given service was determined using two indicators, we used the mean value in the analyses. Services described by the same indicator were considered together because, due to the adopted methodological solutions, they form close bundles by definition. The analysis of links between services was complemented by an analysis of the similarity between forest habitat types in relation to their ES potential. In the hierarchical cluster analysis used for this purpose, each service was entered separately. We used principal component analysis (PCA) to determine the factors that influenced the grouping of forest habitat types based on their ES potential. Calculations were performed in IBM SPSS Statistics 28 (IBM Corp., 2021) and PAST 4.03 (Hammer et al., 2001).

In turn, the ranks were used to calculate the aggregate potential of forest habitat types and identify multi-service hotspots. The adopted rank scale and the layout of the assessment matrix are based on the solutions

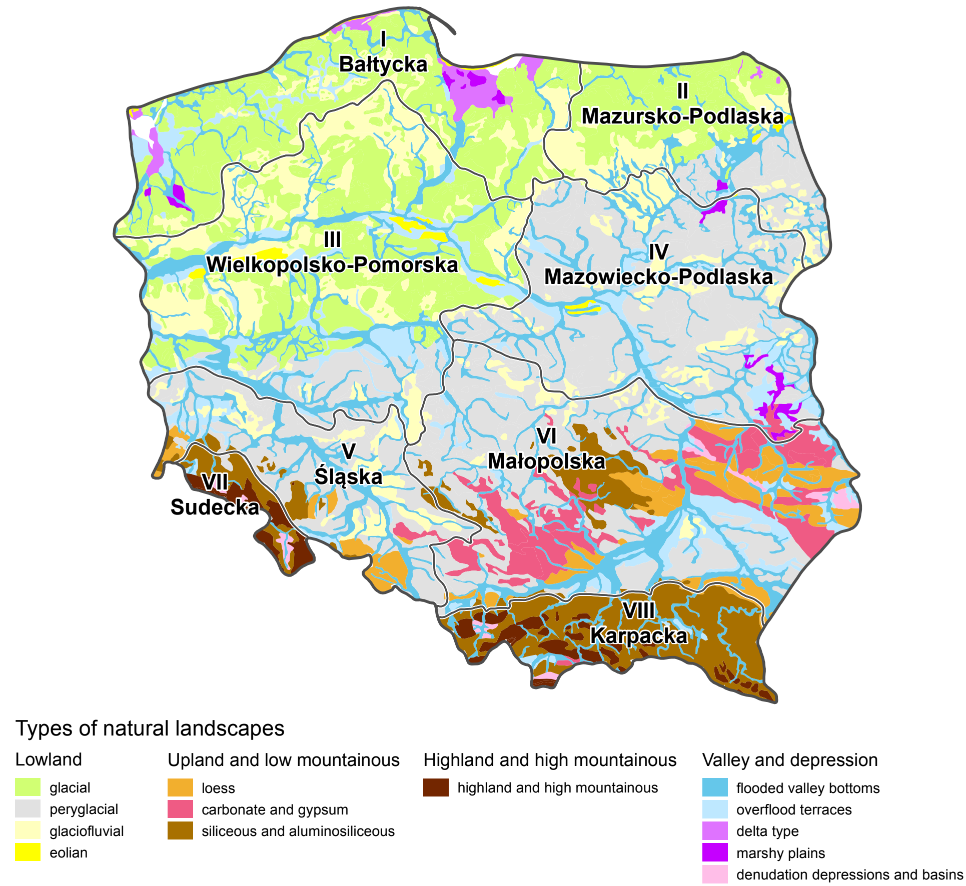

Figure 2. Forest regions (Pol. *krainy przyrodniczo-leśne*) in Poland against the background of types of natural landscapes

Source: own elaboration, the division into forest regions (I-VIII) after Zielony & Kliczkowska (2012), typology, and delimitation of natural landscapes after Richling & Dąbrowski (1995).

proposed by Burkhard et al. (2014) and were already used earlier in Poland (Solon et al., 2017; Affek et al., 2020). The extent of the scale refers to the values recorded in Poland. Aggregated partial potentials (provisioning, regulating, cultural) are the arithmetic mean of individual indicators of ES potential belonging to a given CICES section, with the mean first taken from the indicators characterizing the same service and then used for the calculation of the final mean. The overall multi-service potential, covering all analyzed services, is the arithmetic mean of three partial potentials. To compare the multi-service potential of forests in individual regions, we combined the rank values calculated for forest habitat types with their area share in a given region.

For this work, we assigned the status of a multi-service hotspot to those forest types that show high or very high (rank 4 or 5) potential to provide at least 2/3 of the ES considered (see Anderson et al., 2009; Holt et al., 2015).

Results

Multi-service potential

In the assessment matrix presenting the results for the entire Poland, we included the ranked values of the potential of 35 forest habitat types to provide 17 key forest ES (Tab. 2).

Provisioning potential

The potential of forests to provide provisioning services was analyzed based on five ES: wood, forest fruits, mushrooms, game, and honey. The range of values obtained on a nationwide scale extends from 1.6 for swamp mixed broadleaved forest *LMb* and swamp mixed coniferous forest *BMb* to 4.0 for several types of montane forests: moist coniferous *BGw*, moist mixed coniferous *BMGw*, mesic coniferous *BGśw* and mesic mixed coniferous *BMGśw* (Fig. 3). A comparison of 6 main groups of forest types (see Tab. 2) shows that 5 of them have similar provisioning potential (2.7-3.1), and only alder forests have a substantially lower potential (1.7). In terms of provisioning potential in individual forest regions (per hectare of forest), the Sudecka mountain region ranks highest, clearly ahead of the other mountain region – Karpacka (4.0 vs 3.0) (Fig. 4). In turn, the northern postglacial regions show slightly higher potential (by 0.2-0.3) than the regions of central and eastern Poland.

Regulating potential

The potential of forests to provide regulating services was analyzed based on seven ES: pollination, global climate regulation, local climate regulation, air purification, soil erosion control, flood control, and habitat maintenance. The range of values obtained on a nationwide scale extends from very low for the dry coniferous forest *Bs* (1.3) to very high for the montane broadleaved forests: mesic *LGśw* and moist *LGw* (4.6-4.7) (Fig. 3). Other montane types also have high potential: riparian forest *LłG* and mesic mixed coniferous forest *BMGśw* (both 3.9). In general, broadleaved forests have the highest potential to provide regulating services (4.0), while coniferous – the lowest (2.5). A comparison of regulating potential in individual forest regions shows that by far the highest potential among all regions have forests in the Karpacka region (4.6), clearly lower – forests of the Sudetes and northern and eastern Poland (3.2-3.6), and the lowest – forests in the midwest of the country (2.6) (Fig. 4).

Cultural potential

The potential of forests to provide cultural services was analyzed based on five ES: mushroom picking, hunting, science and education, recreation, and health regeneration. The range of values obtained on a nationwide scale extends from 1.2 for the upland alder-ash forest *Oljwyż* and 1.3 for the riparian forest *Lł* to 4.3 for the montane mesic coniferous forest *BGśw* (Fig. 3). High values (3.9-4.1) were also recorded for other montane forest types (e.g., upper montane *BWG*, and montane moist mixed broadleaved *LMGw*) and some types of forests on mesic soils (e.g., mixed coniferous *BMśw* and mesic mixed broadleaved *LMśw*). The comparison of the 6 main groups of forest types shows that broadleaved, coniferous, and mixed have a comparable, relatively high cultural potential

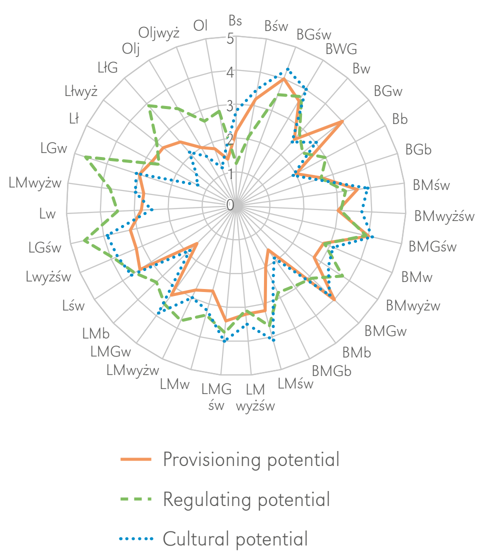

Figure 3. Provisioning, regulating, and cultural ES potential of forest habitat types (per hectare) in Poland. The values shown are the means from individual services assessed on a 1-5 scale, where: 1 – very low potential, 5 – very high potential. Explanation of abbreviations of forest habitat types in Figures 5 and 7

Table 2. Assessment matrix showing the potential of forest habitat types to provide key ecosystem services. Potential on a 1-5 scale, where: 1 – very low potential, 2 – low, 3 – medium, 4 – high, 5 – very high potential, and "-" – no data. Some services are described by more than one indicator (see Tab. 1)

		Provisioning ES					Regulating ES										Cultural ES					
		Wood	Forest fruits	Mushrooms	Game	Honey	Pollination	Global climate regulation (1)	Global climate regulation (2)	Local climate regulation	Air purification	Soil erosion control (1)	Soil erosion control (2)	Flood control	Habitat maintenance (1)	Habitat maintenance (2)	Mushroom picking	Hunting	Science and education (1)	Science and education (2)	Recreation	Health regeneration
Coniferous	Dry (Bs)	1	4	3	1	2	2	1	1	1	1	2	1	1	1	1	3	1	1	1	4	5
	Mesic (Bśw)	2	5	5	1	3	3	3	2	2	2	1	1	2	2	3	5	1	2	3	4	5
	Montane mesic (BGśw)	-	4	5	5	2	2	1	-	4	4	2	5	5	2	3	5	5	2	3	4	5
	Upper montane (BWG)	2	5	4	4	3	3	1	1	4	4	4	5	4	3	3	4	4	3	3	4	5
	Moist (Bw)	2	3	4	1	3	3	3	2	3	3	4	1	4	2	1	4	1	2	1	1	5
	Montane moist (BGw)	-	3	-	5	-	-	-	-	-	-	3	5	-	1	1	-	5	1	1	-	-
	Swamp (Bb)	1	3	1	1	4	4	1	1	3	3	4	1	4	1	2	1	1	1	2	1	5
	Montane swamp (BGb)	-	3	-	4	1	1	1	-	-	-	4	5	4	1	1	-	4	1	1	-	-
Mixed coniferous	Mesic (BMśw)	3	4	5	2	4	4	3	3	3	3	2	2	4	4	3	5	2	4	3	4	5
	Upland mesic (BMwyżśw)	3	4	5	1	2	2	3	3	3	3	3	3	4	4	3	5	1	4	3	4	5
	Montane mesic (BMGśw)	4	4	5	4	3	3	3	4	4	4	5	5	5	3	2	5	4	3	2	4	5
	Moist (BMw)	3	3	4	2	2	2	3	3	3	3	3	2	4	3	2	4	2	3	2	2	5
	Upland moist (BMwyżw)	3	-	5	1	2	2	3	3	4	4	-	-	5	-	-	5	1	-	-	2	5
	Montane moist (BMGw)	-	4	5	5	2	2	3	-	3	3	5	4	4	3	1	5	5	3	1	2	5
	Swamp (BMb)	1	3	1	2	1	1	2	1	4	4	4	2	4	2	1	1	2	2	1	1	4
	Montane swamp (BMGb)	-	2	1	4	1	1	1	-	3	3	5	4	4	2	1	1	4	2	1	1	5
Mixed broadleaved	Mesic (LMśw)	4	2	5	2	3	3	4	4	4	4	2	3	4	5	4	5	2	5	4	5	4
	Upland mesic (LMwyżśw)	5	2	5	1	3	3	3	4	3	3	2	4	4	2	3	5	1	2	3	5	4
	Montane mesic (LMGśw)	4	3	5	3	2	2	4	5	5	5	2	5	4	3	3	5	3	3	3	5	4
	Moist (LMw)	3	2	4	2	2	2	3	3	4	4	2	2	4	5	3	4	2	5	3	2	4
	Upland moist (LMwyżw)	4	-	3	1	2	2	3	3	4	4	-	-	5	-	-	4	1	-	-	2	5
	Montane moist (LMGw)	-	2	5	4	2	2	4	-	4	4	4	4	4	4	3	5	4	4	3	2	5
	Swamp (LMb)	1	2	1	2	2	2	2	1	4	4	4	2	4	4	1	1	2	4	1	1	3
Broadleaved	Mesic (Lśw)	5	1	5	2	4	4	5	4	4	4	1	3	3	4	5	5	2	4	5	5	2
	Upland mesic (Lwyżśw)	5	2	4	1	4	4	5	5	4	4	3	4	3	5	5	4	1	5	5	5	4
	Montane mesic (LGśw)	4	2	4	2	4	4	5	5	5	5	5	5	4	4	5	4	2	4	5	5	4
	Moist (Lw)	3	1	3	2	5	5	4	3	4	4	2	3	2	4	3	3	2	4	3	2	2
	Upland moist (Lwyżw)	4	-	3	2	4	4	4	3	4	3	-	-	3	-	-	3	2	-	-	2	3
	Montane moist (LGw)	3	2	3	2	5	5	4	3	5	5	5	4	5	4	3	3	2	4	3	3	4
Riparian	Riparian (Lł)	5	1	1	2	5	5	5	3	3	3	1	3	1	2	1	1	2	2	1	1	1
	Upland riparian (Lłwyż)	3	-	1	2	5	5	4	2	3	3	-	-	1	-	-	1	2	-	-	2	1
	Montane riparian (LłG)	-	2	1	2	5	5	4	-	4	4	4	4	3	5	2	1	2	5	2	2	2
Alder	Alder-ash (OlJ)	2	1	1	2	4	4	4	2	4	4	2	3	2	5	2	1	2	5	2	1	1
	Upland alder-ash (OlJwyż)	2	1	1	1	4	4	3	2	3	3	3	3	1	-	2	1	1	-	2	1	1
	Alder (Ol)	1	1	1	2	2	2	3	2	4	4	2	3	2	3	2	1	2	3	2	1	2

(3.1-3.4), while the other two groups (riparian and alder) have a substantially lower potential (1.5-1.6). In terms of cultural potential in individual forest regions, again the Sudecka region ranks highest (4.2), forests of the Carpathians and northern Poland show medium potential, and the lowest – forests in central Poland (3.4-3.5) (Fig. 4).

Links between aggregated potentials

The multi-service ES potentials calculated for individual CICES sections (provisioning, regulating, and cultural) are not independent of each other, also because some of the indicators were used to assess the potential of services belonging to different sections. The analysis of the strength of the relationship showed that the provisioning and cultural potentials are most strongly related (Pearson's r correlation coefficient = 0.80; $p < 0.001$), and the regulating and cultural potentials are slightly less related, although still statistically significant ($r = 0.40$; $p = 0.019$), and the weakest correlation, below the significance threshold, was reported for the provisioning and regulating potentials ($r = 0.30$; $p = 0.077$).

Overall potential

The overall multi-service potential of forest habitat types, which is the arithmetic mean of the provisioning, regulating, and cultural potentials, ranges from 1.9 for the upland alder-ash forest *OIjwyż* to 4.0 for the montane mesic mixed coniferous forest *BMGśw* (Fig 5). Generally, dry coniferous forests, riparian forests, and all types of swamp forests have a low overall potential, not exceeding 2.4, and in the case of montane variants: ≤ 2.8. At the other extreme (≥ 3.7) there are most types of mesic and moist forests, including all montane forests (mesic coniferous *BGśw*, upper montane *BWG*, mesic mixed broadleaved *LMGśw* and mesic broadleaved *LGśw*).

The comparison of the overall forest potential in individual forest regions shows that the highest potential is recorded in the forests of both mountain regions (Sudecka – 3.9, Karpacka – 3.8), followed by the forests of the northern postglacial regions (Fig. 4). The lowest overall ES potential is shown by forests in central Poland, especially in the Wielkopolsko-Pomorska region (3.0).

Wood vs other services

Due to the practical importance for forest management, the overall potential and partial potentials (provisioning, regulating, cultural) were compared (after excluding wood supply services) with the potential of forest types to supply wood. The comparison showed that the upper montane forest *BWG*, the dry coniferous forest *Bs*, and swamp forests: coniferous *Bb*, mixed coniferous *BMb* and mixed broadleaved *LMb* belong to the types for which the difference between the overall potential and the potential for wood supply is the largest (Tab. 3). This means that the management of these types of forests should be focused on ES other than the provision of wood.

Multi-service hotspots

From the point of view of forest management, it is also important to identify forest types with a high potential to provide many services, i.e., the so-called ES hotspots. Forest types with this status should be managed in such a way that their high multi-service potential can be realized to the benefit of society.

The analysis carried out showed that the provisioning ES hotspots are montane forests: upper montane *BWG*, mesic coniferous *BGśw*, mesic mixed coniferous *BMGśw* moist mixed coniferous *BMGw* (Tab. 4). In their case, 75-80% of provisioning ES can be provided at a high or very high level. Montane mesic broadleaved forest *LGśw* stands out among the regulating hotspots, characterized by high or very high potential to provide all seven analyzed regulating ES. The status of a regulating ES hotspot (6 out of 7 regulating ES, 71%) can also be attributed to other mesic and moist, broadleaved, and mixed broadleaved forests.

In turn, as many as 9 out of 35 forest habitat types considered, including both coniferous and mixed coniferous forests, as well as broadleaved and mixed broadleaved forests,

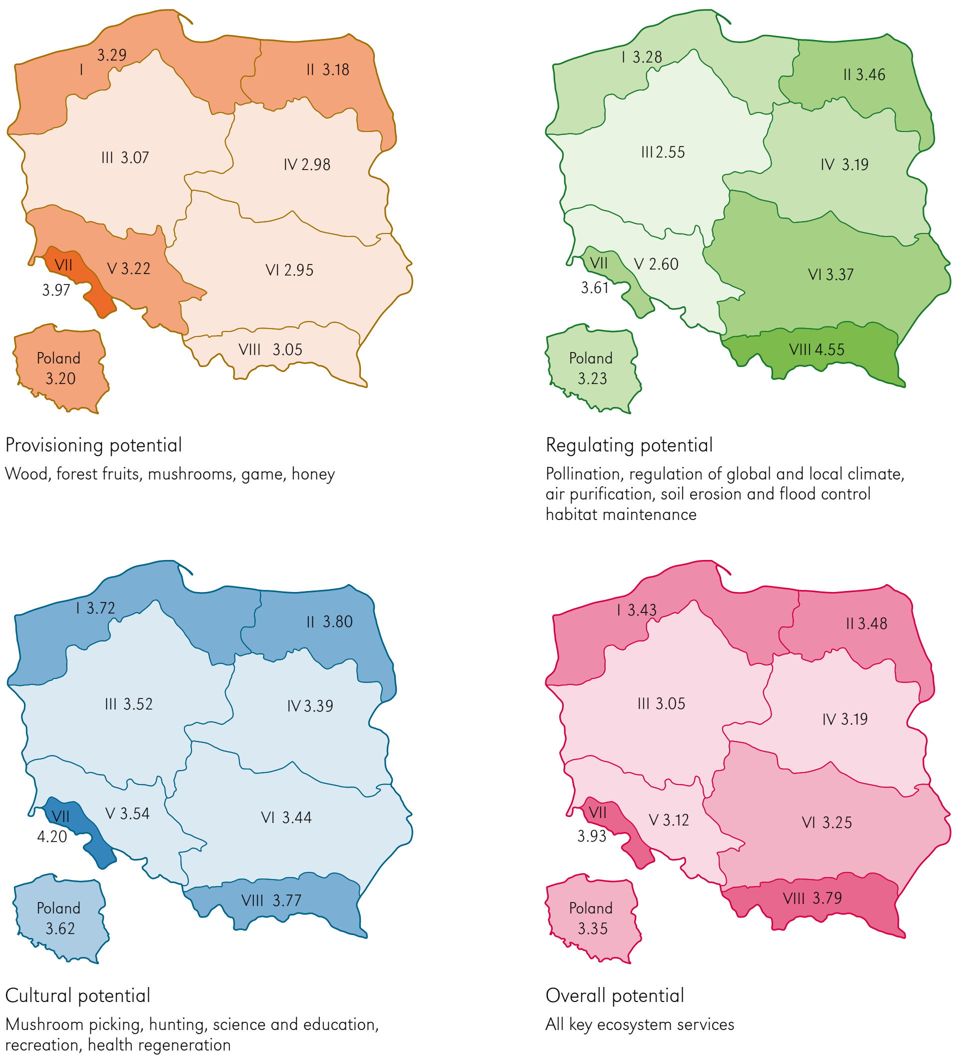

Figure 4. Provisioning, regulating, cultural, and overall ES potential of forests (per hectare) in the entire Poland and in individual forest regions. The values shown are the means from individual services assessed on a 1-5 scale, where: 1 – very low potential, and 5 – very high potential, weighted by the area of individual forest habitat types. Forest regions: I – Bałtycka, II – Mazursko-Podlaska, III – Wielkopolsko-Pomorska, IV – Mazowiecko-Podlaska, V – Śląska, VI – Małopolska, VII – Sudecka, VIII – Karpacka

Source: own elaboration, the division into forest regions (I-VIII) after Zielony & Kliczkowska (2012).

meet the criteria of a multi-service cultural ES hotspot. Moreover, a substantial number of them have also been given the status of regulating or provisioning ES hotspot. Only the mesic mixed coniferous forest in the lowland (*BMśw*) and upland (*BMwyżśw*) variants is a hotspot solely in terms of cultural ES. Five forest habitat types have the status of an overall multi-service ES hotspot. The highest-ranked montane mesic broadleaved forest *LGśw* has a high or very high potential to provide 14 of the 17 ES considered (82%) (Tab. 4). It is worth noting that this is the most common montane forest type in Poland,

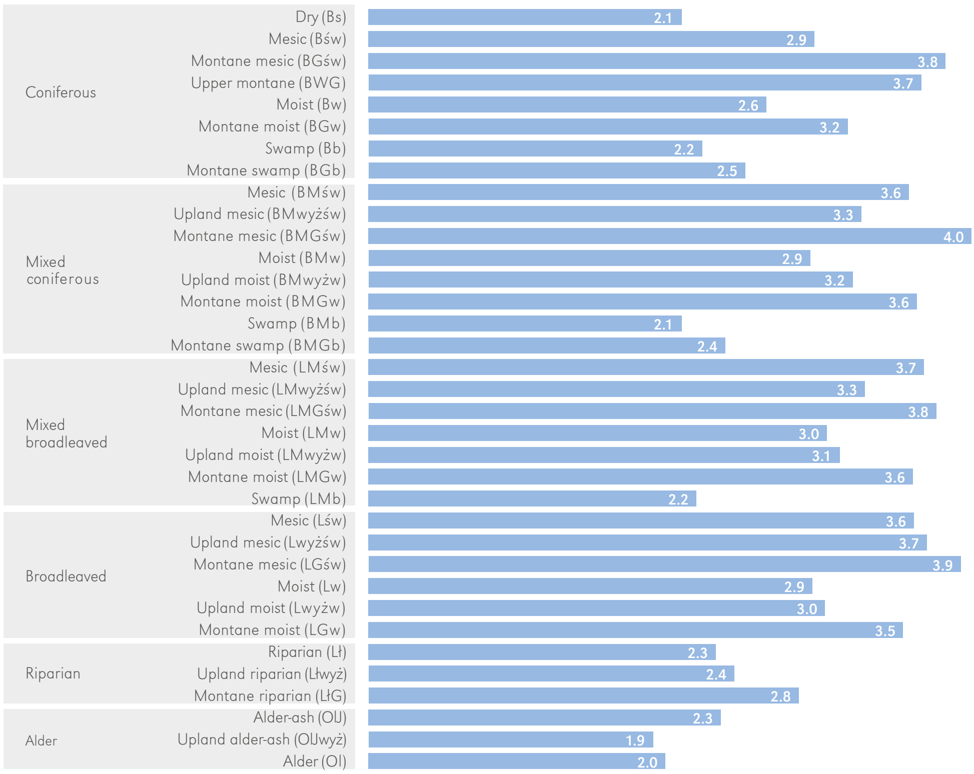

Figure 5. The overall potential of forest habitat types to provide all key ecosystem services in Poland. Values averaged from partial potentials (provisioning, regulating, cultural) per hectare of forest, where: 1 – very low potential, 5 – very high potential

Table 3. Forest habitat types for which the difference between the aggregate potential (partial and overall) and the potential to supply wood is the largest (>1.0)

Aggregate POTENTIAL minus POTENTIAL to supply wood							
Provisioning	dif.	Regulating	dif.	Cultural	dif.	Overall	dif.
Upper montane *BWG*	2.0	Swamp mixed broadleaved *LMb*	2.0	Upper montane *BWG*	2.0	Upper montane *BWG*	1.8
Dry coniferous *Bs*	1.5	Alder *Ol*	1.8	Dry coniferous *Bs*	1.8	Swamp coniferous *Bb*	1.3
Mesic coniferous *Bśw*	1.5	Swamp coniferous *Bb*	1.7	Mesic coniferous *Bśw*	1.5	Swamp mixed broadleaved *LMb*	1.2
Swamp coniferous *Bb*	1.3	Swamp mixed coniferous *BMb*	1.7			Dry coniferous *Bs*	1.2
		Montane moist broadleaved *LGw*	1.5			Swamp mixed coniferous *BMb*	1.1
		Upper montane *BWG*	1.4				
		Alder-ash *Olj*	1.3				

Table 4. Forest habitat types with outstanding potential to provide many ecosystem services (ES hotspots). The percentages show the proportion of services for which a given forest type has high or very high potential to provide

HOTSPOTS							
Provisioning		Regulating		Cultural		Overall	
	%		%		%		%
Montane mesic mixed coniferous *BMGśw*	80	Montane mesic broadleaved *LGśw*	100	Montane mesic coniferous *BGśw*	80	Montane mesic broadleaved *LGśw*	82
Montane mesic coniferous *BGśw*	75	Mesic mixed broadleaved *LMśw*	71	Upper montane *BWG*	80	Montane mesic mixed coniferous *BMGśw*	71
Upper montane *BWG*	75	Montane moist mixed broadleaved *LMGw*	71	Mesic mixed coniferous *BMśw*	80	Upland mesic broadleaved *Lwyżśw*	71
Montane moist mixed coniferous *BMGw*	75	Mesic broadleaved *Lśw*	71	Upland mesic mixed coniferous *Bwyżśw*	80	Upper montane *BWG*	69
		Upland mesic broadleaved *Lwyżśw*	71	Mesic mixed broadleaved *LMśw*	80	Montane moist mixed broadleaved *LMGw*	69
		Montane moist broadleaved *LGw*	71	Montane moist mixed broadleaved *LMGw*	80		
		Montane riparian *LłG*	71	Upland mesic broadleaved *Lwyżśw*	80		
				Montane mesic broadleaved *LGśw*	80		

covering 3 thousand km^2 of land managed by the National Forest Holding.

Links between ecosystem services

Grouping of ecosystem services

The obtained similarity dendrogram allowed the identification of six ES bundles (similarity >0.50): three multi-service and three dual-service (Fig. 6). The first multi-service bundle includes four regulating ES: soil erosion control and flood control, and two described with the same indicator – local climate regulation and air purification. There are significant positive correlations between potentials to provide all services forming this bundle ($p < 0.01$), with 0.56 as the average Spearman's rs correlation coefficient (Tab. 5). The common feature of the ES that makes up this bundle is their dependence on the plant species composition and structure of vegetation. Multi-species and multi-layered forests achieve the highest potential.

The second multi-service ES bundle consists of wood, global climate regulation, habitat maintenance, and science and education. This bundle is characterized by strong positive correlations between ES potentials – the average rs = 0.72, which results, on the one hand, from the interdependence on the characteristics of the forest stand (mainly species composition and biomass), and on the other hand, from the overall species richness related to habitat fertility. Species-rich, mesic broadleaved forests have the greatest potential for providing these services. ES potentials from this bundle are significantly positively correlated with the ES potentials of the next bundle grouping: mushrooms, mushroom picking, and recreation. Characteristic features of this bundle include dependence on the composition and spatial structure of forest stands and on some soil qualities (primarily soil moisture).

The next bundle consists of two very highly correlated (rs = 0.89) services: one provisioning (forest fruits) and one cultural (health regeneration). Both services are linked to the presence of specific groups of plant species

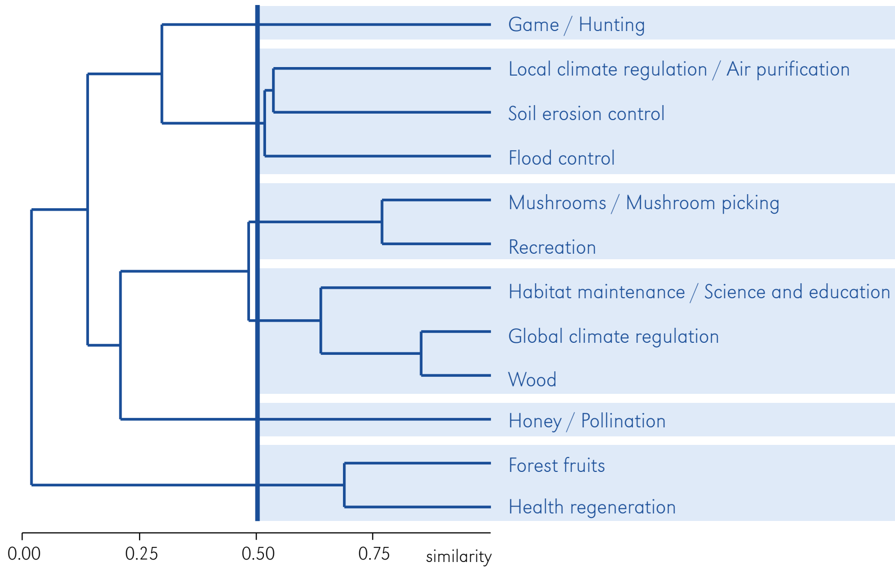

Figure 6. Grouping of ecosystem services in relation to the potential to provide them by forest habitat types (UPGMA hierarchical clustering method, distance measure: correlation similarity index)

Table 5. Correlations between ecosystem services (the values of Spearman's rank coefficient shown with $p \leq 0.05$, with $p \leq 0.01$ in bold; positive correlations – in green, negative – in red)

	Wood	Forest fruits	Mushrooms / Mushroom picking	Game / Hunting	Honey / Pollination	Global climate regulation	Local climate regulation / Air purification	Soil erosion control	Flood control	Habitat maintenance / Science and education	Recreation	Health regeneration
Wood												
Forest fruits												
Mushrooms / Mushroom picking	**0.59**	**0.51**										
Game / Hunting												
Honey / Pollination	0.38	-0.42										
Global climate regulation	**0.91**	-0.42			**0.58**							
Local climate regulation / Air purification		-0.40				0.37						
Soil erosion control							**0.55**					
Flood control		0.40	**0.53**				**0.46**	**0.67**				
Habitat maintenance / Science and education	**0.57**		0.39		**0.48**	**0.68**	**0.54**					
Recreation	**0.68**		**0.80**			**0.55**				**0.63**		
Health regeneration		**0.89**	**0.46**		**-0.57**	**-0.52**			**0.51**			

necessary for the service to be provided. The highest potential for providing these services have coniferous and mixed coniferous forests. Both services are negatively correlated with the other two services forming the next bundle: honey and pollination, which depend on the presence of melliferous plants.

The last bundle consists of two services, game, and hunting, which, like in the previous bundle, are described by one indicator. The lack of significant correlations with other services may result from their specific nature and measurement method (indicated directly by the number of animals, and data collected for hunting units).

Grouping of forest types

Forest habitat types group at several levels in relation to their ES potential (Fig. 7). As a result of hierarchical cluster analysis,

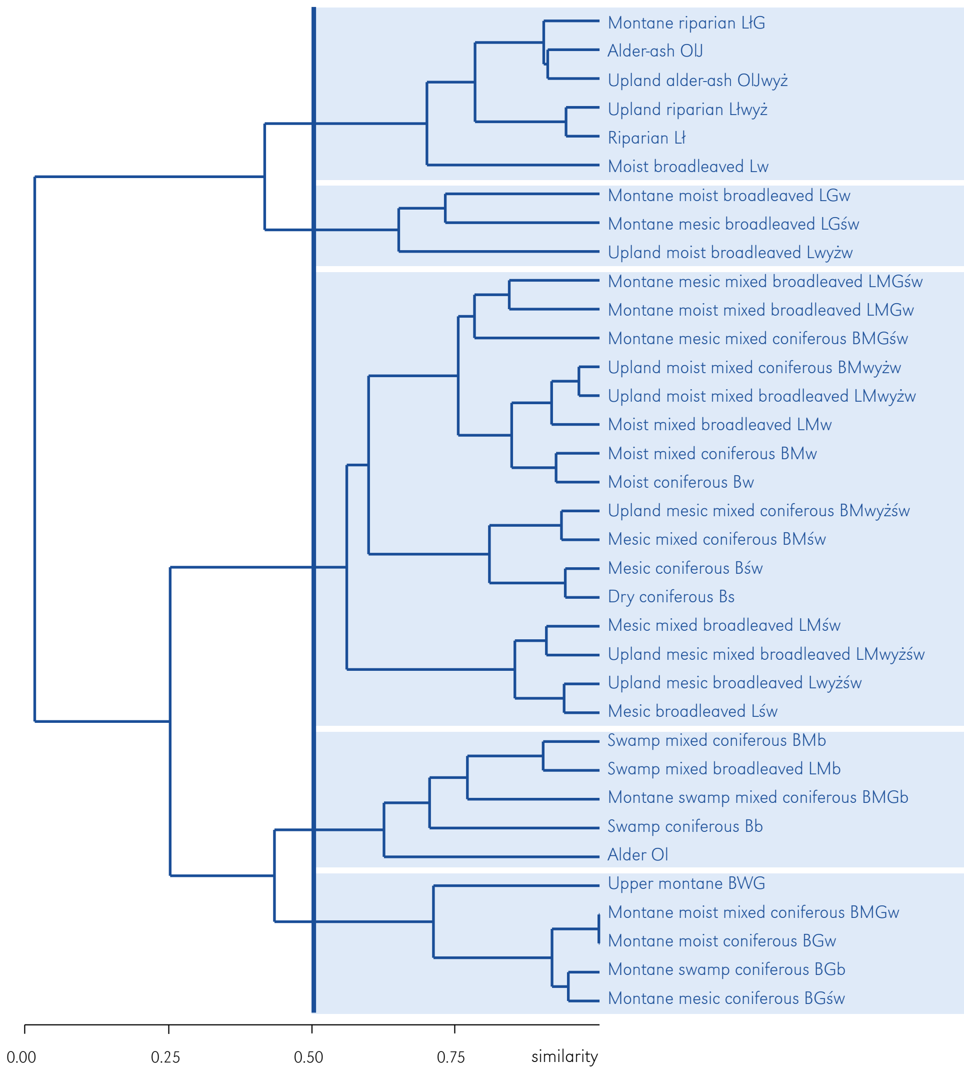

Figure 7. Grouping of forest habitat types in relation to their potential to deliver ecosystem services (UPGMA hierarchical clustering method, distance measure: correlation similarity index)

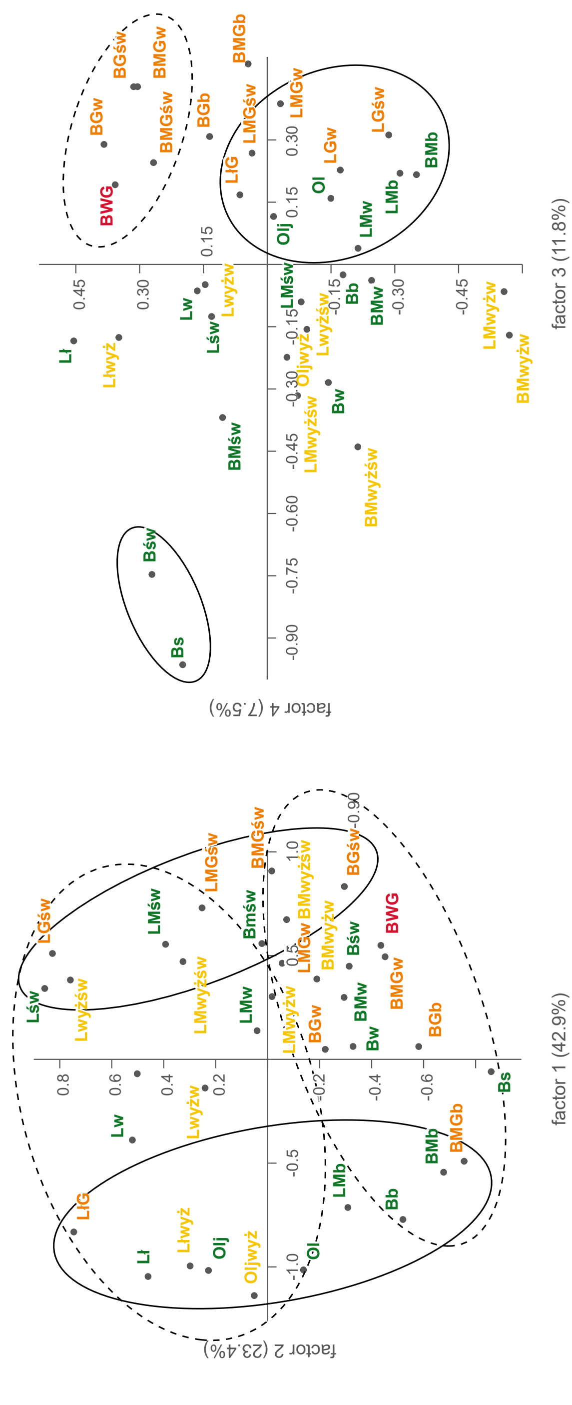

Figure 8. Factor coordinates for forest habitat types obtained as a result of principal component analysis. Upper montane forest type in red, montane types in orange, upland types in yellow, and lowland types in green. Explanation of abbreviations of forest habitat types in Figure 5

five main groups were obtained at a similarity level of 0.5, reflecting the diversity of species composition, vegetation structure, and soil conditions (soil moisture and fertility) of the considered forest types.

The most clear division is into coniferous and broadleaved forests, with transitional types: mixed coniferous and mixed broadleaved co-occurring in both groups. The coniferous and broadleaved forest types are further divided into several smaller groups, primarily due to soil moisture. Furthermore, lowland and highland types tend to group together, just as mountain types tend to group together.

In turn, in principal component analysis (PCA), the first component, explaining 43% of the variance, arranges forest habitat types primarily according to the moisture gradient (Fig. 8). At one extreme there are swamp and riparian types, and at the other extreme, there are mesic habitat types with medium soil moisture. The moisture content, in addition to tree species composition, primarily determines the potential of forests for providing mushrooms and mushroom picking. Mesic forest habitat types are also more willingly chosen for recreation.

The second component explains 23% of the variance and differentiates forest habitat types in terms of soil fertility. On the one extreme, there are coniferous forests developing on poor sandy soils, while on the other extreme, broadleaved forests growing on fertile soils. This feature affects services such as global climate regulation, honey, and pollination. The species composition of the tree layer and other forest layers also influences the potential to provide these services. The negative correlations of both services with the cultural ES: health regeneration support this interpretation (Tab. 5), because coniferous forests have greater therapeutic potential, while deciduous forests have greater potential for regulating the global climate and providing honey and pollinating plants.

The third component explains 12% of the variance and is related to the spatial and species structure of vegetation. At one extreme, there are multi-layered and multi-species mixed broadleaved and coniferous forests, which have a high potential for regulating the local climate, purifying the air, and preventing floods, and at the other extreme, there are coniferous forests, poorer in species and having a less dense stand and understory. The fourth component explains 7.5% of the variance and clearly separates the group of montane coniferous forests with a high potential for providing game and hunting services.

Discussion

We showed that forest ecosystems differ in ES potential, both at the level of a single service and at the level of aggregate potential, both partial (combining services from one CICES section) and overall (combining services from all sections). Furthermore, we demonstrated that forest types are also different in terms of multifunctionality, and only certain types of forest ecosystems can be considered multi-service hotspots. In our research, we used a typology of forest habitats, developed in Poland and widely used by foresters, to group and compare different types of forests. Studies on ES potential conducted in other parts of the world have used different forest typologies, but their results also show that individual forest types differ in their ES potential. This was for instance demonstrated when using very broad forest classification, at the level of CORINE land cover class (e.g., in Lithuania – Depellegrin et al., 2016), but also when applying a vegetation formation approach (e.g., in Australia – Alamgir et al., 2016), and a narrower typological approach (e.g., in Canada – Sutherland et al., 2016, or in Spain – Roces-Díaz et al., 2021).

Furthermore, many studies reported that the dominant tree species has a very strong influence on the potential of individual ES. For instance, a large-scale study in Central Europe showed that pest control, tree C storage, and edible fungi were mainly dependent on the share of pine in the tree stand, whereas the volume of timber production depended on the share of spruce, while the share of oak increased timber production and birdwatching potential and decreased local temperature regulation and pest control potential (Felipe-Lucia et al., 2018). In turn, in Swedish forests the share of spruce strongly positively correlates with dead wood occurrence, tree biomass production, and soil carbon storage, and negatively with game production while pine correlates positively with dead wood occurrence, bilberry production, and negatively with understory plant species richness[2] (Gamfeldt et al., 2013).

To obtain a reliable comparison of forest types, we selected only mature forests, i.e., those in which the process of rapid changes in the stand structure and its functioning has ended and a relatively stable period has begun. Operationally, this meant that only forests in which stands were over 80 years old were included in the analyses. However, additional analyses carried out showed that the average tree stand age of "mature" forests in various forest habitat types differed significantly (mean 101 years with standard deviation 10 years), for example, due to the different cutting age of dominant tree species or different dominant management/protection regimes. Therefore, the ES potential of individual forest types, especially for services related to stand maturity, may be affected to some extent by differences in the average age of trees growing in these forests. This is even more possible because the increase in ES potential with an increase in tree stand age has been demonstrated many times for different regions and different forest types (Sutherland et al., 2016; Solon et al., 2017; van der Plas et al., 2017; Vauhkonen & Ruotsalainen, 2017), also for services not directly related to the structure of the forest stand.

Estimating aggregate potential and identifying multi-service hotspots is a complex process. Even minor modifications to the procedure at any of its stages (assumptions, selection of services and their definition, construction of indicators, selection of source data) may affect the final results.

The selection of services and their indicators was preceded by an extensive literature search and consultations. We drew inspiration from methodological proposals developed, among others, as part of the MAES initiative established by the European Commission (see e.g., Maes et al., 2018), and the nationwide ECOSERV-POL project (Stępniewska & Mizgajski, 2023). However, due to the lack of standard solutions to quantify ES potential, knowledge gaps regarding the assessment of services, and the need to adapt the construction of indicators to existing data[3], a significant number of indicators are original proposals by the authors (e.g., Solon et al., 2017; Affek et al., 2020; Kowalska et al., 2021).

The joint analysis of many services also required several assumptions. One of the most important is that each service was treated the same, which means that all services were given a weight equal to 1. This is consistent with the concept of *ecosystem function multifunctionality*, which assumes the need for a standardized approach to quantify ecosystem functions and services and for long-term monitoring of ecosystem condition (Manning et al., 2018). Assigning different weights to ecosystem functions and services would reflect *ecosystem service multifunctionality*, and these weights would have to be adapted to a given forest management scenario and could be very different for the same service, depending on the scenario (van der Plas et al., 2017; Manning et al., 2018). Furthermore, it should be noted that the perception of the forest and its services is shaped not only by its "objective" ES potential but also by many other factors, including personal experience in using services (Affek & Kowalska, 2017). As in our nationwide study, we quantified the ES potential independently

[2] Dead wood occurrence and understory plant species richness can be seen as proxies for habitat maintenance service.

[3] A recommendation often found in the literature, see Maes et al., 2015.

of current local forest management and stakeholder views, the latter approach was beyond the scope of the study.

Since the indicator values were calculated for types of forest ecosystems, maps showing the ES potential of forests in forest regions do not take into account the landscape context (spatial relationships resulting from the specific shape and configuration of forest patches) (Bastian et al., 2014). The presented values of ES potential for a given forest type, obtained from a large sample of data and additionally differentiated by region, can be highly representative input data characterizing forest types in local scale studies, which can then be supplemented with detailed spatial analyses.

The use of narrowly defined forest habitat types limits the possibilities of direct comparison of the results obtained with the works of other authors. However, grouping forest types into units similar in terms of soil properties or tree composition allows for such comparisons. Our research shows, for instance, that within the broad group of coniferous forests, the overall ES potential is the highest for forests with moderately fertile and moderately moist soils, and clearly lower in less fertile, dry, moist, and swamp forests. Similar relationships were also described in other world regions, e.g., in the Urals (included ES: timber supply, air protection, water protection, climate forming, and soil forming), regardless of whether the dominant coniferous species was pine or spruce (Lebedev et al., 2019). The existence of a similar relationship can also be concluded based on data from Sweden, where it was shown that the provision of many services is higher with greater tree species richness (Gamfeldt et al., 2013). However, in many cases, the relationship is positively hump-shaped (e.g., for berry production and game production), which, taking into account the typological diversity of Swedish forests (Sjörs, 1965; Arnborg, 1990), also means that the ES potential is highest in forest communities corresponding to Polish mixed coniferous and mixed broadleaved forests (Gamfeldt et al., 2013).

In multi-service studies conducted in the Eastern Suwałki Lakeland in Poland, where 42 types of ecosystems, including 25 forest ones, were evaluated using 29 ES indicators (Solon et al., 2017; Affek et al., 2020), the hierarchy of forest types in terms of aggregate potentials was similar to our study, despite the use of different indicators and research methods, e.g., the opinions of local communities. In both studies, coniferous and mixed coniferous forests were characterized by the highest provisioning ES potential and one of the lowest regulating ES potential, while swamp forests had the lowest cultural potential.

Furthermore, our research shows that the highest multi-service potential is found in montane forests. In relation to provisioning and cultural ES, these are primarily coniferous forests, while in terms of regulating ES – both coniferous and broadleaved forests. This result is similar to the results obtained for the entire EU, where forests of mountain regions were shown to provide substantial amounts of multiple services, and show remarkably high values for wood production, water supply, erosion control, climate regulation, and recreation (Orsi et al., 2020).

One of the most important tasks when analyzing multiple services is to determine ES bundles. The similarity dendrogram obtained in our research allowed us to identify six ES bundles. One such bundle includes the following set of services: timber, global climate regulation, habitat maintenance/science & education, and additionally recreation and mushrooms/mushroom picking, and is very similar to the bundle named *balanced*, identified in pan-European studies by Orsi et al. (2020). It is characterized by an average or above-average supply of five services, i.e., wood, habitat, soil, climate, recreation. It primarily occurs in forests of Northeastern part of the continent (particularly Poland, Baltic Republics, Southern Sweden, and Southern Finland), and covers an area equivalent to around 31% of EU forest, including 65% of Poland's forest area (Orsi et al., 2020). Other bundles recognized by these authors (*wood & water*, *soil carbon*, and *rural-recreational*) did not have their equivalents in our research, although, according to the cited research, they cover 14.0%, 8.1% and 12.9% of the forest area in Poland, respectively.

Interestingly, Alamgir et al. (2016) identified two ES bundles for three types of forests in Australia. One of the ES bundles includes habitat provision, cyclone protection, air quality regulation, and erosion regulation. It corresponds to our bundle including soil erosion control, flood control, and two other services: local climate regulation and air purification, both described by the same indicator. The only major difference is the lack of habitat maintenance in our bundle, but this may be due to a different approach to this service. However, the question remains whether the co-occurrence of air quality regulation and erosion regulation in one bundle in both such distant areas reflects a more general pattern, or is just a coincidence. Drawing conclusions from comparing ES bundles from different areas may be additionally difficult due to the relationships between ES potentials changing over time (Roces-Díaz et al., 2017, 2021).

It is generally accepted that the composition of ES bundles depends on the spatial scale of analysis and is region-specific (Roces-Díaz et al., 2021). This may be because – at least on a pan-European scale – ES bundles are dependent on two main gradients: the type and intensity of land use and the climatic gradient, and in the case of some bundles – also on biodiversity (Mouchet et al., 2017). The regional specificity is evidenced by, among others, a set of bundles identified for south-east Spain: (1) erosion control – recreational hunting, (2) timber – beekeeping, and (3) mushroom harvesting – nature tourism (García-Nieto et al., 2013). Although similarly defined services are also analyzed in our study, they form different bundles.

In our research, we observed many positive correlations between potentials to provide services grouped not only into the same ES bundles but also across ES bundles, which indicates both the co-occurrence of many processes taking place in forest ecosystems and the dependence of services on the same ecological processes or common ecosystem service providers (e.g., specific groups of species). The identified bundles are formed by services representing different sections: provisioning services group with regulating and cultural services. This means that the same forests have the potential to provide very different ES. The predominance of positive relationships between services shows that excessive use of one service may directly reduce the benefits of another service. The few negative correlations result from the diversity of species composition (e.g., lack of specific species – providers of a given service, e.g., plants that produce edible fruits) and the biophysical vegetation structure characteristic of particular forest habitat types.

Biodiversity is considered one of the most important driving variables influencing ecosystem multifunctionality (Felipe-Lucia et al., 2018; Manning et al., 2018). This impact was demonstrated either on one selected ES (e.g., biomass production – Balvanera et al., 2014; Labrière et al., 2016), or many ES simultaneously (Quijas et al., 2010; Brandt et al., 2014). The latter authors found a positive effect of plant species richness on six out of eight ES analyzed (provisioning of plant products, erosion control, invasion resistance, pest regulation, pathogen regulation and soil fertility regulation). In our research, measures of plant species richness (as indicators of habitat maintenance potential) were significantly positively correlated with 5 other ES (wood, pollination, mushrooms/mushroom picking, global climate regulation, local climate regulation/air purification). This number is higher than in the case of other ES indicators used. Such a relationship confirms the view about the role of biodiversity in shaping ecosystem multifunctionality and, consequently, multi-service hotspots.

Summing up the discussion, our research on ES potential assessed for narrowly defined forest types on a nationwide scale, on the one hand, allowed for generalization of the results to more broadly defined categories of forest ecosystems, and on the other hand, enabled comparisons both with the local case studies and with pan-European large-scale assessments.

Conclusions and recommendations

We showed that forests in Poland have the capacity to provide many important ES and benefits for people and that their potential varies substantially depending on the type of forest habitat and forest region. Differences in provisioning, regulating and cultural ES potential should be taken into account when making decisions regarding the management, protection, and use of forests. From the point of view of forest management, it is also important to identify forest types with a high potential to provide many services, i.e., ES hotspots. Forest types with this status should be managed in such a way that their high multi-service potential can be realized to the benefit of society.

We found that montane mesic broadleaved forest *LGśw* has a high potential to provide the largest number of key forest ES (14 out of 17), which gives it the status of a multi-service hotspot. Furthermore, it is the only forest type that has a high potential to provide all the analyzed regulating ES. For this reason, we recommended conducting forest management in this type of forest aimed at maximizing the supply of regulating ES and at the same time refraining from activities that could hinder the realization of its potential.

Upper montane forest *BWG*, dry coniferous forest *Bs*, and mesic coniferous forest *Bśw* are the types of forests for which the difference between the cultural ES potential and the potential for wood supply is the largest. In the case of the first two habitat types, which occupy a small overall area and are particularly sensitive to damage caused by logging, we recommend refraining from such activities. In the case of mesic coniferous forest *Bśw*, much more common in Poland, we recommend conducting forest management focused on the supply of cultural ES in regions with a small overall forest area, as well as near large population centers, where logging may limit the possibility of cultural interactions with the forest ecosystem (e.g., recreation or health regeneration).

The key forest ecosystem services group into six bundles. These bundles are created by ES from different sections, and their coexistence results from the dependence on similar qualities of the forest ecosystem, such as soil moisture and fertility, species composition, and spatial structure of vegetation. When planning forest management, these links between ES should be taken into account. Knowing these links will help avoid situations where excessive use of one service substantially reduces the benefits of another service. Links between ES can also be used to assess ES potential in case of data shortages.

A large number of forest habitat types that occupy the smallest area in Poland (e.g., dry coniferous *Bs*, swamp coniferous *Bb*, swamp mixed coniferous *BMb* as well as riparian in the lowlands *Lł*, and several montane coniferous types) are also Natura 2000 habitats. Even though, compared to other types of forest, they usually have a low aggregate potential to provide ES, both provisioning, regulating and cultural, due to their intrinsic value resulting from their uniqueness, they should be protected for future generations.

The proposed methodological approach for assessing the ES potential of individual forest types is so universal that it can be used at various spatial scales. At the local scale, data characterizing forest types can be additionally supplemented with analyses that take into account the landscape context.

The motivation and commitment of forest owners and managers play a key role in shaping the potential of forests to provide the ES most desired by society. Many people depend on forests for their livelihood and currently, their main income comes from employment in various forestry works and selling wood. Providing other services that benefit the general public (including regulating and cultural ES, as well as non-timber forest products such as mushrooms and forest fruits) does not usually generate income for owners/managers. Therefore, if their interests do not meet the needs of society, consideration should be given to introducing a financial mechanism to compensate for the loss of income from wood production and to cover the costs of maintaining the multi-service potential of forests at an appropriate level.

Large and medium-sized enterprises can play an important role in maintaining and increasing the ES potential of Polish forests, which, like other entities operating in the European Union, have to achieve climate neutrality by 2050 and introduce activities to offset CO_2 emissions. One such activity can be covering the loss of income for forest owners or managers as a result of switching forest management from wood production to carbon capture and accumulation. This applies primarily to forests with a high potential for regulating the global climate, i.e., mesic broadleaved and mixed broadleaved, as well as riparian forests.

This is the first study of this type in Poland, taking into account the diversity of the potential of several dozen types of forest ecosystems to provide a whole range of key ES. It is a response to the need for mapping and assessment of forest ES on a nationwide scale. We believe that the developed solutions can be used as a reference point and a framework for standardized monitoring of the forest ES potential. The obtained results and the recommendations formulated on their basis may contribute to more sustainable management of forests and optimal use of their potential.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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Article first received • 31 October 2023
Article accepted • 7 February 2024