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Original Research

Differentiating Cultural Ecosystem Services (CESs) in Young Glacial Landscapes Using Weighted and Unweighted Matrix Approaches: A Case Study from Poland

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Abstract

Cultural ecosystem services (CESs), defined as the nonmaterial benefits people derive from ecosystems such as recreation, aesthetic enjoyment, cultural identity, and heritage, are commonly perceived as difficult to assess due to their intangible and subjective nature. These challenges often limit the incorporation of CESs into environmental management and landscape planning. This study aims to evaluate the potential supply of CESs at the local scale in postglacial landscapes using the young glacial region of the Zbąszyń municipality in western Poland as a case study. A set of 42 biophysical indicators was developed using spatial datasets to represent ecological, cultural, and physiognomic landscape characteristics. In this study, CES potential was assessed within 27 spatial landscape units using the landscape audit database and the corresponding landscape typology and applying both weighted and unweighted matrix approaches. The results indicate that natural ecosystems, such as forests, wetlands, and watercourses, generally present the highest CES supply potential, especially in the categories of recreation, natural heritage, and aesthetics. In contrast, cultural and rural landscapes demonstrated greater potential for cultural heritage and cultural diversity. Notably, the use of a weighted matrix approach enhanced the degree of CES supply differentiation across landscape types and provided a more detailed understanding of ecosystem contributions. The findings underscore the importance of natural landscapes, especially young glacial landscapes, in delivering CESs and support the application of indicator-based assessments in local-scale spatial planning. This approach offers a transferable framework for evaluating CESs in other postglacial regions and contributes to sustainable land use management and conservation strategies.

Keywords: ecosystem service assessment, ecological indicators, landscape typology, postglacial areas, landscape management

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Introduction

Assessing and mapping ecosystem services (ESs) has become integral to landscape protection and management [1-6]. According to Version 5.1 of the Common International Classification of Ecosystem Services (CICES) [7], ecosystem services are defined as "the contributions that ecosystems make to human well-being and are distinct from the goods and benefits that people subsequently derive from them." Similarly, the European Landscape Convention (ELC) acknowledges the essential role of landscapes in individual and societal well-being across urban and rural areas, whether they represent iconic or everyday landscapes [8, 9].

Over the past two decades, ESs have contributed to the full recognition of ecosystems, emphasizing their role in promoting human prosperity. Consequently, they have become essential tools for supporting spatial decision-making at various levels of environmental management [3, 10-14]. Accordingly, the European Union has promoted the protection and restoration of ecosystem benefits through the EU Biodiversity Strategy for 2030, which explicitly acknowledges biodiversity and ecosystem services as critical foundations of employment, economies, wealth, and well-being [8]. Given this potential, ESs have become instrumental in forming ecological policies and guiding global, national, regional, and local decision-making. Accordingly, most EU countries, which predominantly feature cultural landscapes, have already undertaken ES assessments [15].

ESs have been associated mainly with rural areas, but urban areas are also becoming increasingly important in their assessment [16, 17]. Furthermore, many studies underscore the value of the immaterial benefits of ecosystems, especially considering cultural landscapes, which are shaped by intimate human interactions with nature [15, 18]. On the other hand, owing to methodological challenges, the evaluation of cultural ecosystem services remains largely overlooked and poorly comprehended because they are "intangible" and "invisible" in comparison with other tangible ecosystem services [11, 19-20].

The term cultural ecosystem services (CESs) refers to "the aesthetic, artistic, educational, spiritual, and scientific values of ecosystems" [21]. The Millennium Ecosystem Assessment expanded this definition to include "the intangible benefits people gain from ecosystems through spiritual enrichment, cognitive development, recreation, and aesthetic experience".

Stange and Rusch [22] reported various possible approaches for conducting ecosystem service assessments and mapping [11, 23-25]. Furthermore, the choice of method should depend on the availability of data and its accuracy, as well as on access to an expert base. The spatial resolution, geographic extent, accuracy, and reliability of the used ES data are combined to establish the approach [26].

The interdisciplinary nature of the ES concept permits the creation of different measures [27]. Indicators of ES potential and supplies are generally part of a broader group of indicators related to environmental conditions. According to Burkhard et al. [28, 29], the potential to provide ESs is the capacity to provide services determined by human–natural interactions. Therefore, to determine the potential supply of CESs, it was necessary to propose appropriate and informative measures that have also been normalized and standardized.

Cultural ecosystem services (CES) in Poland have gained increasing attention in recent years, particularly in the context of landscape planning, nature conservation, and sustainable regional development [27, 30, 31]. In Poland, the growing integration of CES into research and policy frameworks has been supported by developments in landscape audits and spatial planning reforms, which emphasize the need to account for nonmaterial benefits provided by ecosystems. Despite this progress, the assessment and operationalization of CES remain methodologically challenging, particularly in their quantification and spatial representation. Therefore, advancing approaches that integrate biophysical indicators, spatial analysis, and participatory methods is essential to effectively incorporate CES into decision-making processes and ensure its role in sustainable land management.

Poland provides a particularly relevant context for CES research because of its high landscape diversity, strong contrasts between natural and cultural landscapes, and the presence of extensive young glacial areas in its northern and western parts. These features make Poland a useful setting for testing spatially explicit approaches to CES assessment in relation to landscape planning and regional development.

The innovation of this study lies in combining a landscape-typology-based CES assessment with a comparison of weighted and unweighted matrix approaches, supported by hierarchical clustering and spatial mapping at the local scale. Accordingly, this study was guided by the following research questions: (1) how does CES potential vary among landscape units in a typical young glacial landscape; (2) how do weighted and unweighted matrix approaches affect the assessment and spatial differentiation of CES potential; and (3) to what extent can these results support the classification and planning relevance of landscape units at the local scale?

Using biophysical landscape assessment methods, this study examined local differences in the potential for cultural ecosystem services (CESs) in typical young glacial landscapes. The analysis focused on the municipality of Zbąszyń, which, owing to its natural genesis and associated landscape diversity, is representative of the study context (see Section 2.1). The study objectives were to (a) identify and characterize landscape units (ecosystems) in the study area, following the methodology of the current landscape divisions of Poland and the ELC; (b) develop a set of indicators for diagnosing, assessing, and mapping CES potential using available spatial databases; (c) characterize the quantitative and spatial variation in CES potential, both in an assessment that treats the supply of each CES category equivalently across all landscape units and in one that accounts for variation in weights by ecosystem type, which in Poland is often considered synonymous with landscape type as the spatial unit, and CES categories, applying the ecosystem service potential matrix [24]; and (d) statistically analyze CES potential indicators and classify landscape units based on the supply of CES categories. The results provide a basis for integrating different aspects of research on ecosystem service potential and for determining their relevance to landscape conservation and management.

Study Area

On the basis of the developed methodology, an assessment of the potential for postglacial landscapes to provide CESs in the test area was carried out (Fig. 1). The purposeful selection of this case study was based on two basic criteria: 1) good representation of the typical/representative postglacial landscape and 2) high functional and structural diversity of landscape typology. The municipality of Zbąszyń is located in the western part of Wielkopolskie Province near the border with Lubuskie Province. The analyzed area covers 17,900 hectares and has a population of 13,800. The municipality is characterized by a favorable transportation location related to the proximity of the A2 motorway, which connects Berlin with Poznań and Warsaw, and the S3 expressway, which runs from Świnoujście toward Prague.

Zbąszyń is located within the South Baltic Lake District, which covers the northern and central parts of Wielkopolskie Province [32, 33]. The eastern and central parts of the municipality belong to the physical-geographical mesoregion of the Nowy Tomyśl Plain, which is a vast sandy area intersected by subglacial troughs in the valleys of small rivers. The average terrain elevation is 70 m above sea level, and most slopes do not exceed 2% [34]. The western part of the municipality is located in the Zbąszynek Basin mesoregion, which is a meridional depression of land filled with the waters of the Obra River and Zbąszyńskie Lake (Błędno). The average terrain elevation is 60 m above sea level, and the slopes in the vicinity of the lake trough are 5–10%. Much of this mesoregion is covered by various forms of natural and protected landscapes. The only town is Zbąszyń (population 7,300), where the clothing and furniture industries are developing. The city has

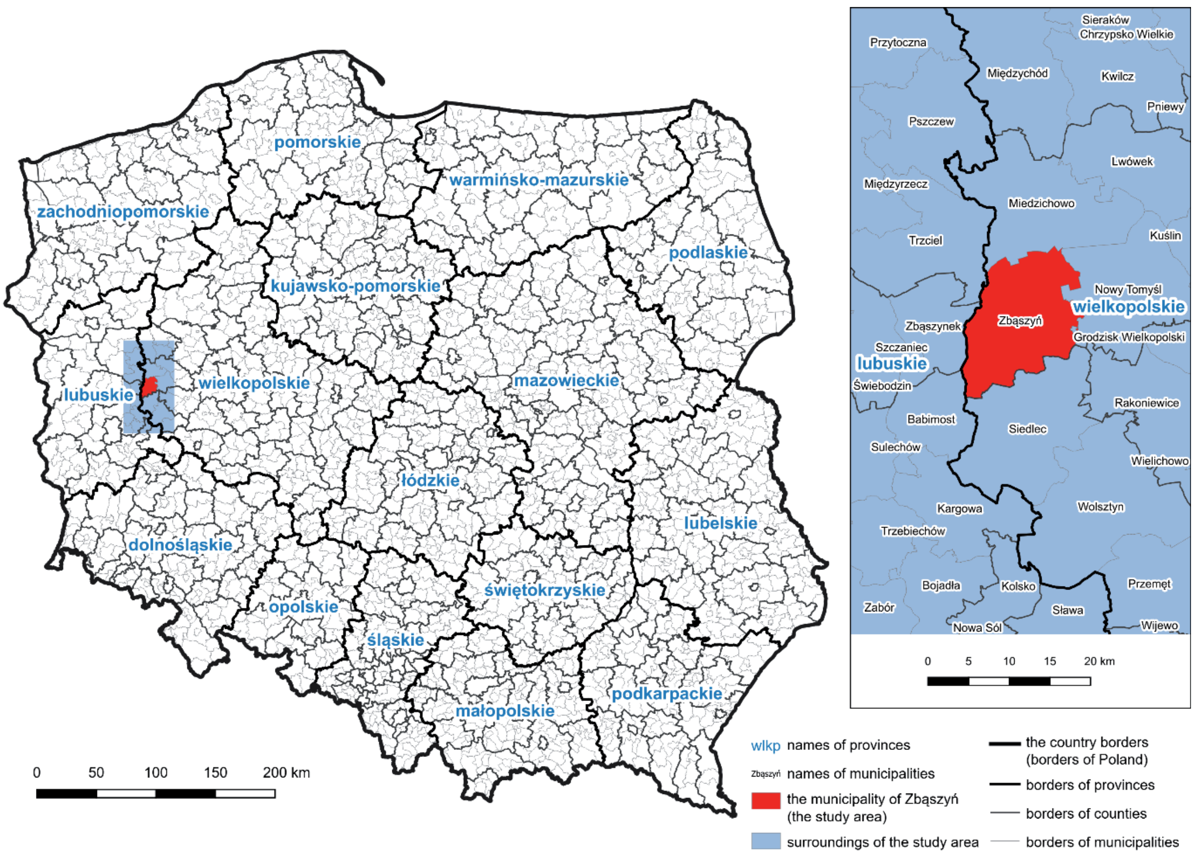

Fig. 1. Location of Zbąszyń municipality within the context of surrounding administrative units, including Wielkopolskie and Lubuskie Voivodeships, and the national context of Poland.

unique cultural assets, including the remains of a castle in the form of earth bastions, a tower with an entrance gate from the 16th and 17th centuries, and a two-tower baroque church from the second half of the 18th century. The area around Zbąszyń is included in the Kozioł (Bagpipe) Region, where folk traditions of playing that musical instrument are maintained. The city's proximity to lakes and forests, as well as its accessibility to transportation, are conducive to recreational activities and contribute to tourism development.

Zbąszyń municipality is a small urban–rural unit characterized by a mixed economic structure combining services, agriculture, and small-scale entrepreneurship. It retains important local service functions, while its development profile reflects challenges typical of smaller peripheral municipalities. The local economy benefits from relatively good transport accessibility and proximity to larger urban centers, supporting commuting and regional integration. Key development needs include diversifying the labor market and strengthening the potential of tourism and infrastructure.

Methodology

Spatial Data

All spatial datasets used were primarily accessed online within the National Geoportal (https://geoportal.gov.pl), mainly as a part of the State Geodetic and Cartographic Resource, which includes high-precision vector datasets corresponding to Polish topographic maps on a scale of 1:10,000 or higher [35]. Through the National Geoportal web services, the Head Office of Geodesy and Cartography shares considerable thematic spatial data, e.g., detailed land cover maps as part of the Database of Topographic Objects, the 1 m resolution Digital Terrain Model, the Land and Building Register, and sozological and hydrographic maps. However, many thematic spatial data resources are distributed and developed by various scientific and governmental institutions (Table 1). They are available online in thematic geoportals, Web Map Services (WMS), or Web Feature Services (WFS). All data and services are available under the guidance of the EU INSPIRE Directive of 2007 (Directive 2007/2/EC).

For the objectives of the study, the landscape audit database provided by the Wielkopolska Bureau of Spatial Planning in Poznań, which contains the current landscape divisions of Wielkopolskie Province and thematic data on the natural and cultural values of the landscape, was beneficial. The landscape division was adapted for analyses at the local scale. The correction included all designated landscape unit types, numbers, and boundaries. General and regional directorates of the State Forest typically share their spatial data on a corresponding scale of 1:5,000. The data precision of the General Directorate for Environmental Protection WMS/WFS is no less than 1:25,000. The numerical edition of the Geomorphological Map of the Wielkopolska-Kujawy Lowland was compiled based on previous works by B. Krygowski and researchers from the AMU Institute of Geoecology and Geoinformation [36]. To date, there is no alternative or complementary geomorphological map of such an extensive area in Poland (approx. 68,000 km^2), the scale and content of which would be appropriate for the selected study area. Genetic landscape forms can also be identified from geomorphological drafts to the Detailed Geological Map of Poland by the Polish Geological Institute, which develops and shares spatial data resources on a scale of at least 1:50,000. The State Water Holding Polish Waters and the Chief Inspectorate of Environmental Protection provide exact data on surface water bodies. Other spatial data resources crucial to the study include cultural heritage data, also available within the National Geoportal and WMS/WFS, provided by the National Heritage Institute. Studies of land use and the integration of local development plans are available online in the public information bulletins of specific local governmental institutions (Table 1).

Landscape Typology

This study used the assumptions and methodology of the current landscape divisions of Poland developed for landscape inventory and conservation according to ELC recommendations and standards [23]. The classification includes three hierarchical levels that can be applied at regional and local scales [37], making it a practical tool for landscape analysis. Level 1 organizes landscapes according to a gradient of replacement of natural forms and landscape-forming factors with anthropogenic forms and factors. This division considers 3 groups of landscapes: natural, natural and cultural, and cultural. Level 2 distinguishes landscapes based on dominant land cover types. The main types of landscape units include forest, surface water, wetland, forestless (xerothermic grasslands, heathlands, and inland dunes), rural, mosaic, urban, suburban, metropolitan, water-economic, industrial, mining, communication, and folk-cultural areas. At level 3, landscapes are identified based on differences in spatial structure and type of objects. This lowest level of division contains 51 landscape subtypes. The classification criteria adopted allow the combination of different goals and research directions related to the diagnosis of ecosystem conditions, assessment of ecosystem services, conservation, and landscape planning at lower levels of management. This is also evident in the naming and description of landscape subtypes (see Appendix 1).

The study area comprises 27 spatial units belonging to 3 landscape groups, 6 types, and 10 subtypes (Fig. 2). Within the group of natural landscapes, 12 units were distinguished. The largest area is occupied by forest landscapes (54.7%), which have developed in low- and medium-moisture habitats (A1–A7). These are coniferous or mixed tree stands with an age range of 60–100 years. More than 11% of the forests serve

Table 1. Characteristics of the spatial data used in assessing the potential of cultural ecosystem services (CESs).

Resource name	Abbreviation	Map scale or corresponding data precision	Publisher; Online sources
Forest Data Bank	BDL	1:5,000	General Directorate of the State Forests; https://www.bdl.lasy.gov.pl/
Digital Forest Map	LMN	1:5,000	Regional Directorate of the State Forests; https://www.lasy.gov.pl/
Natural protected areas	NPA	>1:25,000	General Directorate for Environmental Protection; https://sdi.gdos.gov.pl/ (web services), https://crfop.gdos.gov.pl/CRFOP/
Central Register of Nature Conservation Forms	CRNC	>1:25,000	
Geomorphological map of the Wielkopolska-Kujawy Lowland	GMW	1:300,000	Institute of Geoecology and Geoinformation, Adam Mickiewicz University, Poznań; https://igig.amu.edu.pl/
Detailed Geological Map of Poland	SMGP	1:50,000	Polish Geological Institute; https://geoportal.pgi.gov.pl/, https://dane.gov.pl/
Central Register of Geosites	CRGP	≥1:50,000	
Geohazards	GH	≥1:50,000	
Surface water bodies (PGW vector thematic data layers)	SW	≤1:10,000	State Water Holding Polish Waters, Chief Inspectorate of Environmental Protection; https://wody.isok.gov.pl/, https://dane.gov.pl/
Landscape Audit	LA	≥1:50,000	Regional Office for Spatial Planning in Poznań; https://wbpp.poznan.pl/
Sozological Map of Poland	MSP	1:50,000	Head Office of Geodesy and Cartography; https://www.gov.pl/web/gugik/, https://www.geoportal.gov.pl/
Hydrographic Map of Poland	MHP	1:50,000	
Database of Topographic Objects (BDOT10k)	BDOT10k	1:10,000	
Land and building register	EGiB	geodetic, up to 0.0001 ha (1 m^2)	
Digital Terrain Model	DTM	up to 1 m	
Study of Land Use, Integration of Local Development Plans	LDP	from 10,000 up to 1,000	Head Office of Geodesy and Cartography; https://www.gov.pl/web/gugik/, https://geoportal.gov.pl/
			Public Information Bulletin; (available from various local government websites)
Immovable Monuments	IM	≥1:50,000	National Heritage Institute; https://nid.pl/, https://www.geoportal.gov.pl/
Archeological Monuments	AM	≥1:50,000	
Records of historical monuments	RHM	≥1:50,000	

protection purposes. The standing water landscape type includes Zbąszyńskie Lake, with an area of 679.9 ha and an average depth of 3.5 m (B3). It is a trough lake with an elongated shape and a poorly developed shoreline. The trough of Zbąszyńskie Lake has a meridional course in which several smaller bodies of water exist. On the western side, the lake shore is cliff-like and reaches relative heights of up to 20 m. Flowing water landscapes include the Obra River, which, together with adjacent areas, covers an area of 368.5 hectares (B2). The Obra River is a left tributary of the Warta River, characterized by a complex river system. Within the Zbąszyń municipality, the Obra River retains a natural, unregulated course, characterized by gentle, partially wooded banks. Several smaller watercourses of local importance are discharged into the river. Wetland habitats, covering approximately 905 ha, occur in proximity to surface waters. These include extensively managed meadows dominated by sedges and rushes (B1, B4, B5).

A separate group comprises natural and cultural landscapes (12 units), among which rural areas with arable fields dominate (C1–C6, C8, and C10–C12). These are small- to medium-sized fields with a mosaic layout and a total area of 5,400 ha. The characteristic layout and size of the fields are conducive to maintaining a network of linear and small-scale woodlots. The other two units (C7 and C9) are landscapes with predominantly rural buildings surrounded by cultivated arable land (97.6 ha). Their well-preserved habitat layout distinguishes these small clusters of compact building development. The last group is composed of cultural landscapes,

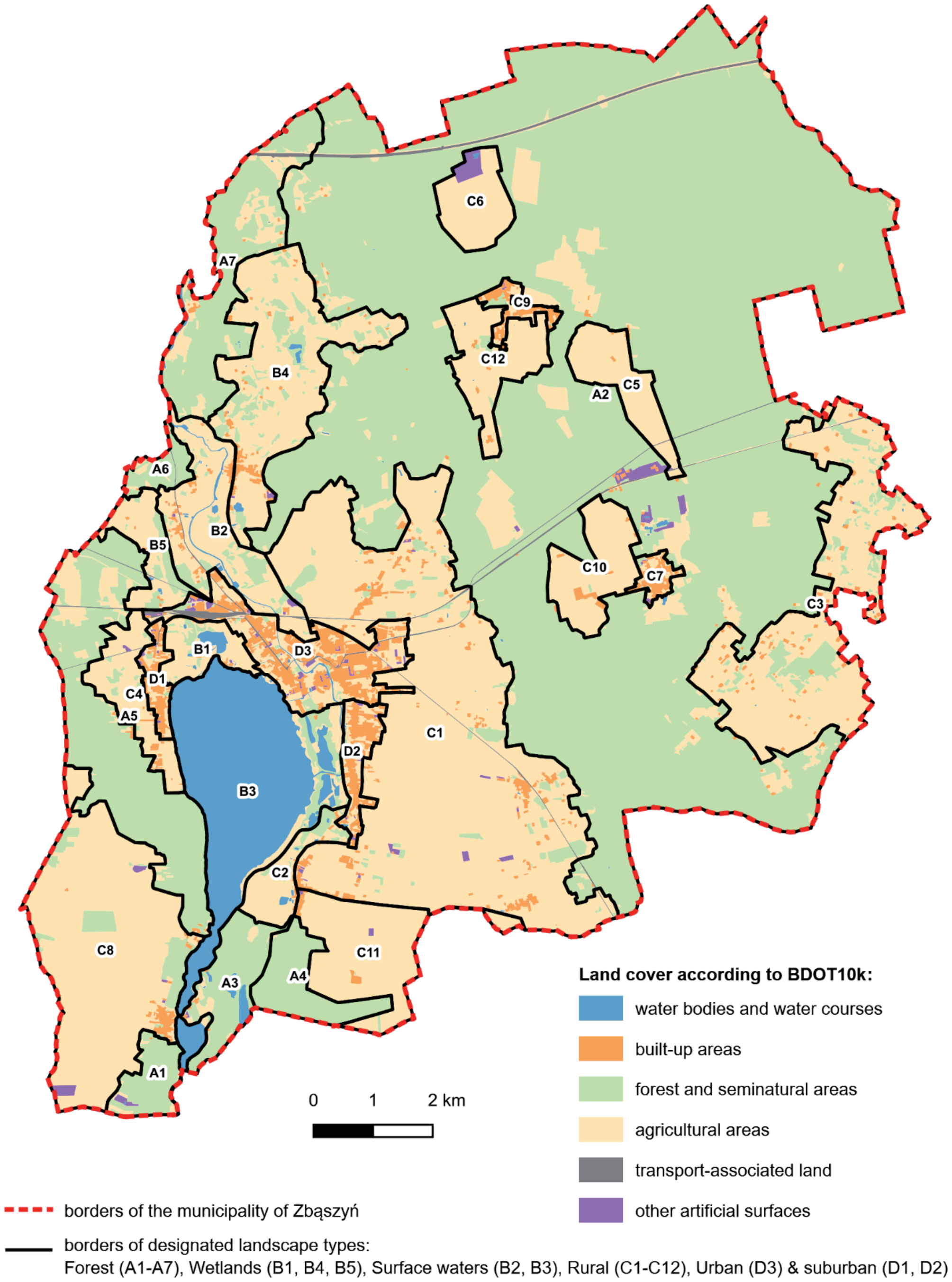

Fig. 2. Classification of landscape units within Zbąszyń municipality via land cover data from the BDOT10k database, illustrating the distributions of natural, natural-cultural, and cultural landscapes.

which include the urban landscape of Zbąszyń with a historical urban layout and an area of 376 ha (D3) and two suburban landscapes (D1 and D2) with a share of compact nonagricultural buildings (168.9 ha).

Assessment And Mapping Of Cultural Ecosystem Services (CESs)

The CES potential was assessed via 42 indicators characterizing biophysical landscape features that were identifiable from the available spatial databases (see Appendix 2). Detailed methodological materials are provided in Appendices 1–3, including the characteristics of landscape types, the indicator list, and the CES matrix used. The main rationale for selecting these indicators was to identify differences in local CES potential (supply) between different types of ecosystems but at the level of spatial units belonging to the same class. The assessment considers ecosystems' ecological, cultural, and physiognomic features, which are stimulants and a source of social benefits related to recreation, cognitive development, and aesthetic and spiritual experiences (Group A and B indicators). A separate group comprises indicators of ecosystem conditions, which affect the reduction in the CES potential and act as destimulants (Group C indicators). When developing the list of indicators, the experience of other authors was also used [20, 30, 31, 38-41].

Owing to the different numbers of specific indicators assigned to each CES category, they were initially preweighted so that the sum of the weights within each category was always equal to 10 (w_j), making them all comparable (see the methodological equation below, corresponding to Appendix 2 and Table 3). As a result, not having an equal number of indicators within each category does not affect the scores of the CES potential for each category, as their number has always been recalculated by dividing 10 (w_j) by the total number of indicators within the given CES category (n). All the standardized values of the analytical indicators were aggregated via the following formula:

$$M_i = c_i \sum_{j=1}^{n} w_j \, x \, m_{ij}$$

where M_i denotes the value of the potential indicator for the evaluated CES category in a given ecosystem type, c_i is the weight assigned to the CES category in a given ecosystem type (Table 3), w_j is the weight of the diagnostic indicator used to evaluate a given CES category, and m_{ij} is the value of the diagnostic indicator expressed on a scale of point values (as follows in the paragraph below).

Because the proposed features and indicators are expressed in different measurement units, they are unified by scoring on a five-point scale (where 1 indicates very low potential and 5 indicates very high potential; m_{ij} refers to the above methodological equation). In the case of indicators expressing a share of a feature in the area of a landscape unit, the scale of assessment is as follows: above 80% – 5; 60.1–80.0% – 4; 40.1–60.0% – 3; 20.1–40.0% – 2; and below 20% – 1. Similarly, for indicators related to the number or density of objects per unit area, higher scores (4–5) were awarded to indicators (stimulants) achieving a higher-than-average value for landscape units, and lower scores (1–2) were awarded to indicators with a lower-than-average value, in contrast to the Group C indicators (destimulants), where the scoring rules were reversed.

To better illustrate the relationships between landscape unit types and the ability to provide different types of CESs, an ecosystem service potential matrix was developed (Table 2; see Appendix 3). Many authors have emphasized the considerable usefulness of this approach for assessing the supply of ecosystem services [24-26, 28, 29, 42, 43]. The prepared aggregate assessment matrix shows the relationships between the CES categories, which are placed in rows, and the ecosystem types, which are described in the columns. The highlighted CES categories are those in line with the recommendations of the Mapping and Assessment of Ecosystems and Their Services [44]: recreation and tourism (I), knowledge system (II), natural heritage and natural diversity (III), cultural heritage and cultural diversity (IV), landscape aesthetics and inspiration (V), and religious and spiritual experience (VI). In addition, a separate category related to environmental conditions and threats (VII) was distinguished, as it has a corrective influence on the potential for ecosystem service provision and warrants independent analysis [45-47]. The matrix approach enabled differentiation in the weights assigned to the aggregated indicators.

In this study, the weights applied to the matrix reflect literature-informed expert judgment developed by the authors, rather than direct elicitation of stakeholder preferences. Thus, the weighted approach should be interpreted as an analytical scenario designed to reflect differences in the expected CES potential of particular ecosystem types, and the unweighted approach serves

Table 2. Evaluation matrix for assessing the potential of cultural ecosystem services (CESs), including weights assigned to each CES category for different ecosystem types.

Categories of CES potential	Landscape types				
	Forests	Surface waters	Wetlands	Rural	Urban and suburban
I. Recreation and tourism	0.8	0.7	0.4	0.4	0.5
II. Knowledge system	0.7	0.6	0.6	0.4	0.4
III. Natural heritage and natural diversity	0.8	0.6	0.7	0.3	0.3
IV. Cultural heritage and cultural diversity	0.7	0.6	0.5	0.5	0.4
V. Landscape aesthetics and inspiration	0.8	0.7	0.6	0.5	0.5
VI. Religious and spiritual experience	0.5	0.5	0.4	0.3	0.4
VII. Environmental conditions and threats	0.7	0.6	0.7	0.4	0.3

Source: Authors' own work, based on 10, 21, 39-40, 43-45.

Table 3. List of indicators recommended for assessing the potential of cultural ecosystem services (CESs) at the local scale, categorized into Groups A, B, and C (see Appendix 2).

Categories of CES potential	Indicator code		
		Core indicators	Additional indicators
I. Recreation and tourism	A	1/2/3/4/6/7/10/11/12/15/17/19/20/23/24	5/8/9/13/14/16/18/21/22/25/26
	B	27/28	29/30/31/36/37/38
	C	40/42	39/41
II. Knowledge system	A	5	22/26
	B	28/31/33/34	20/29/32/35
	C	-	39/40/41/42
III. Natural heritage and natural diversity	A	5/22/26	1/2/3/4/6/7/8/9/10/11/12/13/14/15/16/17/18/19/21/23/24/25
	B	28/29/30/31/34	27/37
	C	-	39/40/41/42
IV. Cultural heritage and cultural diversity	A	20/22/26	5/15/19/21/23
	B	28/32/33/34/35/36	29/37
	C	-	39/40
V. Landscape aesthetics and inspiration	A	2/3/6/7/9/10/12/14/16/18/19/21/23/24	1/4/5/8/13/15/17/20/22/25/26
	B	27/28/37/38	29/30/31/33
	C	39/40	42
VI. Religious and spiritual experience	A	-	1/3/5/6/7/10/16/20/22/26
	B	32/33/35/36	28/29/31/37/38
	C	-	-
VII. Environmental conditions and threats	A	5	22/26
	B	28/30	29/31/32/33
	C	39/40/41/42	-

as a neutral comparative baseline. The selection of CES indicators followed the same procedure, aiming to ensure completeness by including well-known indicators representing the main dimensions of CES that are relevant to the study area and consistently mappable across the municipality. Redundancy was reduced by excluding variables describing very similar landscape attributes or overlapping CES functions. At the same time, indicators were omitted when spatial data were unavailable or insufficiently credible, when their local relevance was limited, or when they duplicated information captured by other variables.

Notably, although a dozen studies across Europe have already applied the discussed methodological approach to assess CESs at local or regional scales, they have not focused on comparing weighted and unweighted approaches or the landscape typology used [11, 24, 28, 29, 42-50]. The results of these studies show that certain types of ecosystems have a greater influence on the provision of cultural services than others. For example, forests, water bodies, and wetlands typically exhibit high CES potential [24, 43]. Ecosystems that are more heavily transformed by human activity tend to have a much lower CES supply, except for selected ecosystem services that may be provided in urban areas [28, 29, 42, 50].

No formal sensitivity analysis was conducted, as the aim of the study was to compare weighted and unweighted matrix variants rather than to test alternative weighting scenarios. Therefore, the weighted variant should be interpreted as an analytical scenario that complements the unweighted baseline rather than as a definitive representation of CES potential. A formal sensitivity analysis of alternative weighting schemes would be a valuable direction for future research. The overall assessment results can also be visualized using CES potential maps. According to Burkhard and Maes [11], ecosystem service (ES) maps play a crucial role in the practical application of ES concepts, as they effectively convey complex spatial data in an accessible and engaging way. Users often prefer maps to explore spatial relationships, assess the relevance of ecosystem services, and understand how benefits are distributed across regions. Consequently, ES maps are powerful tools for increasing public awareness of the supply and demand for ecosystem goods and services, educating communities about the importance of specific ecosystems in supporting human well-being, and illustrating the flow of these services across regions. The maps developed in this study are based on two assessment approaches: the first assumes equal supply for each CES category across all landscape units, whereas the second adjusts supply weights according to ecosystem type and CES category.

Statistical Analysis

First, we chose multidimensional clustering techniques to distinguish between weighted and unweighted indicators of the potential of CESs. This approach enables their comprehensive evaluation, incorporating quantitative methods and increasing confidence in our assessments, making their perception less subjective. It also allows us to understand how different indicators and their weights affect the assessment of the CES potential of a specific landscape type. Moreover, these methods enhance our understanding of the nuanced implications of indicator weighting in ES valuation by identifying and analyzing data patterns for weighted and unweighted data.

Second, on this basis, we assessed a range of clustering methods. This exploration was integral to our workflow, as it allowed us to investigate and validate the effectiveness of these clustering techniques. The assessed methods include complete, single, mean linkage clustering, and Ward's minimum variance methods, which result in the most robust clustering structure [51]. The minimum variance method minimizes the total within-cluster variance at each step of the clustering, such that cluster pairs with minimum between-cluster distances are linked. Leveraging the versatile and efficient platform provided by the R programming language and RStudio software environment (version 2023.06.2+561), our analysis utilized the average silhouette method to assess clustering quality and define the optimal number of clusters for both unweighted and weighted indicators of CES potential. Supported by R packages such as "tidyverse" for data manipulation, "cluster" for clustering algorithms, "factoextra" for clustering visualization, and "dendextend" for dendrogram comparison, this methodological approach was pivotal in our analysis. Our datasets were first standardized via the "scale" function for data uniformity. Guided by the "fviz_nbclust" function from "factoextra," we identified the most robust clustering structures. Hierarchical clustering was performed via the "hclust" function with the "Ward.D2" method, with further insights gained through "plot" and "fviz_cluster" visualizations, alongside dendrogram comparisons using "tanglegram" and "entanglement" from "dendextend." This comprehensive analysis validated our datasets' optimal number of clusters and elucidated the inherent data structure, enhancing our understanding of the underlying patterns.

Results

Identifying Core Indicators

The analysis of the available spatial data confirmed that it is possible to distinguish an individual set of features of a specific type of ecosystem (Group A indicators) as well as some universal features, the occurrence of which is not closely connected with the type of landscape unit (Group B indicators) (see Appendix 2). In addition, features that affect the reduction in CES potential were separated, considering the occurrence of sources and forms of pressure as well as the vulnerability of ecosystems to threats (Group C indicators).

A set of 42 indicators allows the assessment of each category of CES potential (Table 3; see Appendix 2). The analysis revealed that the most widely used indicators are those in Group A, which can be used to assess the following CES categories related explicitly to recreation and tourism (I), natural heritage and natural diversity (III), and landscape aesthetics and inspiration (V). The Group B indicators allow us to identify categories related to the knowledge system (II), natural heritage and natural diversity (III), cultural heritage and cultural diversity (IV), and religious and spiritual experience (VI). The Group C indicators are used to assess the CES categories of recreation and tourism (I), natural heritage and natural diversity (III), landscape aesthetics and inspiration (V), and environmental conditions and threats (VII).

Assessing Cultural Ecosystem Services (CESs) Within Specific Landscape Types

The highest CES potential in almost all categories was found in the forest landscapes (units A2, A3, A5, A6, and A7). Forests outperform the other spatial units in terms of recreation and tourism (Table 4; maximum value, 32.4 ([A5] and mean value, 26.7 for weighted indicators), natural heritage and natural diversity (maximum value, 32.2 [A3] and mean value, 19.6), and landscape aesthetics and inspiration (maximum value, 24.2 [A3] and mean value, 18.5). The measured values for the studied CES categories indicate the significant role of individual characteristics such as habitat conditions, species, and age structure of the tree stand, and the protective functions of forests. With respect to features shared with other spatial units, an important role is played by the diversity of relief, nature conservation forms, and landscape interiors and viewpoints. Slightly lower values are achieved by the aggregate indicators for environmental conditions and threats (Table 4; maximum value, 28.0 [A5, A7] and mean value, 23.4), which is related to the greater vulnerability of some spatial units to human pressure and the presence of ecological barriers crossing forest areas. This result shows that environmental quality has little effect on the value of the CES potential for forests (Figs. 3 and 4). Our results are consistent with those from 2020 [52], which indicated that CESs are currently highly relevant in European forests. Furthermore, forest landowners and managers favor promoting CES through forest management.

Similar relationships are found for surface waters (units B2 and B3) and wetlands (units B1, B4, and B5). The potential of these units is determined by indicators describing recreation and tourism (maximum value, 20.4 [B3] and mean value, 19.2 for weighted indicators). Natural heritage and diversity are also highly rated (maximum value, 27.2 [B1 and B4] and mean value, 20.8), e.g., due to the natural condition of the water and the morphometric features of the lake and river. Wetlands, with their unique features and extensive use, are distinguished by extensive use and, similar to surface waters, are covered by various forms of legal protection. These wetlands are internally diverse because of rushes and sedge meadows, and the density of local watercourses and reservoirs. Areas of moist forests and thickets of varying sizes, most common near the lake, are typical of surface waters and wetlands. The features mentioned above affect the assessment of indicators related to landscape aesthetics and inspiration (maximum value, 18.6 [B2 and B3] and mean value, 13.1) and religious and spiritual experience (maximum value, 16.0 [B4] and mean value, 11.3). Compared with forests, spatial units related to surface waters and wetlands score worse for the environmental conditions and threats category (maximum value, 19.3 [B4 and B5] and mean value, 17.5), which is influenced by the lower ecological potential of waters and the greater vulnerability of these ecosystems to threats (Figs. 3 and 4). Church et al. [53] noted a tendency in studies of water-related CESs, concentrated on recreation and tourism (I) and landscape aesthetics and inspiration (V), and paid less attention to other categories, such as knowledge systems (II) and religious and spiritual experiences (VI).

In the case of rural landscapes (C1–C12), the values of aggregate indicators of CES potential are substantially lower than those of the group of natural landscapes. The exception is the potential related to cultural heritage and cultural diversity. In both variants of our assessment, that potential was significantly greater, highlighting the rich cultural heritage and cultural diversity of rural landscapes. For the weighted variant of the aggregate indicators, the maximum value was 20.0 (C9), and the mean value was 9.1. Bryce et al. [54] suggested that cultural heritage and cultural diversity (IV) can promote a sense of place and place identity, which are part of a broader dimension of cultural well-being.

Furthermore, cultural heritage and cultural diversity have substantial social and symbolic value for local communities that are not necessarily connected to use value, tourism, or economic imperatives [55]. Relatively favorable results were found for recreation and tourism (Table 4; maximum value, 14.4 [C9] and mean value, 9.3), natural heritage and natural diversity (maximum value, 13.6 and mean value, 5.6), and landscape aesthetics and inspiration (maximum value, 18.2 and mean value, 10). These high values result from the internal differentiation of these units, consisting of small and

Table 4. Values of weighted indicators for assessing the potential of cultural ecosystem services (CESs) across different landscape types.

CES categories		Landscape types				
		Forests	Surface waters	Wetlands	Rural	Urban and suburban
I. Recreation and tourism	max.	32.4	20.4	16.0	14.4	7.2
	mean	25.7	19.2	14.7	8.9	5.1
II. Knowledge system	max.	8.0	5.6	5.6	4.8	6.0
	mean	7.2	5.3	5.2	4.2	5.3
III. Natural heritage and natural diversity	max.	32.2	26.4	27.2	13.6	8.4
	mean	19.2	23.4	20.8	6.4	7.0
IV. Cultural heritage and cultural diversity	max.	10.0	11.7	9.8	20.0	20.6
	mean	6.0	9.6	4.2	9.1	10.0
V. Landscape aesthetics and inspiration	max.	24.2	18.6	14.2	18.2	15.2
	mean	18.5	15.0	12.0	10.0	10.9
VI. Religious and spiritual experience	max.	22.0	16.0	16.0	10.0	12.0
	mean	18.8	12.5	9.3	8.3	10.7
VII. Environmental conditions and threats	max.	28.0	18.0	19.3	14.0	12.0
	mean	23.2	16.0	17.5	12.7	9.5

medium mosaically distributed fields and accompanying agricultural objects, which are related to many of their historical landscape features, a relatively high density of balks and mid-field woodlots, and various forms of nature conservation. Smith and Csurgó [55] proved that a CES framework has the potential to help improve understanding and management, with a clearer picture of local and tourist priorities and the interrelationships between them.

Figs 3 and 4 show the values of potential indicators for each CES category in different types of ecosystems. Fig. 3 shows the spatial variation in the study results for

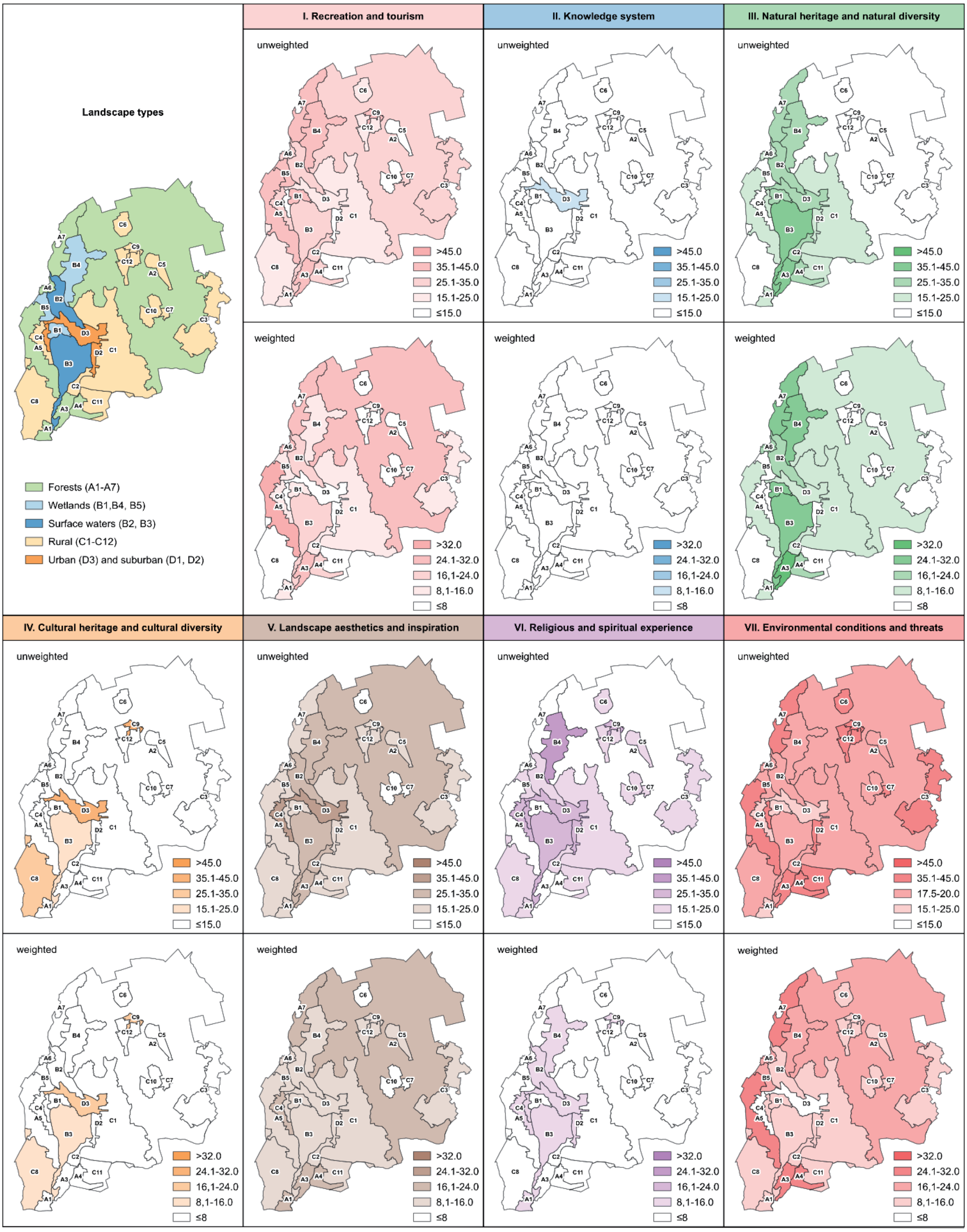

Fig. 3. Comparison of unweighted and weighted values of potential indicators of cultural ecosystem services (CESs) across different landscape types in Zbąszyń municipality.

five classes of aggregate indicator values. In contrast, Fig. 4 shows the average aggregate indicator values obtained for units of a specific landscape type. The calculations are presented in two assessment variants: weighted and unweighted. Many scientists have created and applied complex measures to evaluate sophisticated phenomena in several fields. In addition, they often suggest aggregating and weighing their indicators according to various patterns [56, 57].

Typically, the potential of CESs in cultural landscapes is perceived as diverse [58]. Our research shows that urban and suburban (D1–D3) areas have high potential for cultural heritage and cultural diversity. The aggregate indicators' maximum and mean values for this CES category are similar to those of rural areas (20.6 [D3] and 10.1 for weighted indicators). An analogous situation exists for landscape aesthetics and inspiration, as well as for natural heritage and natural diversity, but the aggregate indicators are generally lower than those for rural areas. These assessment results are influenced by the density of cultural objects related to the historical features of the landscape, the presence of intangible landscape values, the diversity of relief and the presence of viewpoints and panoramas, the location within the range of legal forms of nature conservation, and the density of local forms of nature conservation. A marked difference from other landscape types is related to recreation and tourism. In urban and suburban areas, the indicator for this CES category had the lowest value (a maximum value of 7.2 [D3] and a mean value of 5.1 for weighted indicators). This situation is related primarily to the small areas of urban parks and undeveloped green spaces, particularly in the suburban type (Figs. 3 and 4).

Individual landscape units do not reach the maximum theoretical value of aggregate indicators, i.e., a score of 50 for particular categories of CES potential (unweighted variant). The indicators closest to the maximum theoretical value are those for recreation and tourism and natural heritage and natural diversity in forests (42.5 and 38.0 for A3 and A5, respectively), surface waters (36 and 40.0 for B3), and wetlands (36 and 34 for B4). High indicator values are also found for cultural heritage and cultural diversity, as well as for landscape aesthetics and inspiration in rural, urban, and suburban areas (40 and 36 for C4, C8, C9, and D3, respectively).

Considering the spatial distribution of the CES potential, owing to the dominance of forests in the municipal area (54%), the study area has potential for use in CES categories related to recreation and tourism, natural heritage, natural diversity, and landscape aesthetics and inspiration. A similar spatial structure of CES potential is found for surface waters and wetlands, although their area within the municipality is significantly lower (11.8%). This situation is further underscored by assessing the environmental

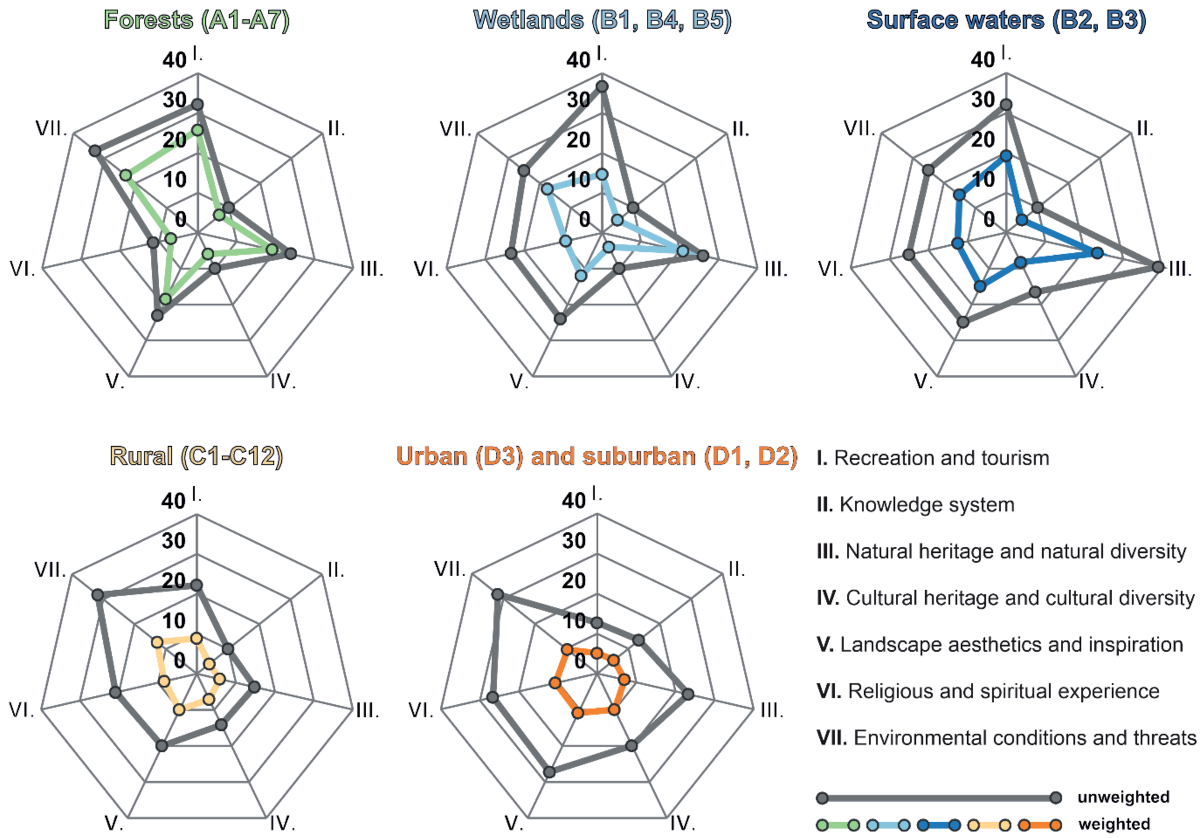

Fig. 4. Radar charts showing the mean values of weighted and unweighted indicators of the potential of cultural ecosystem services (CESs) for different landscape types.

conditions and the category of threats, especially for forests. These areas are mainly within the range of the southern physical-geographical region known as Bruzda Zbąszyńska (Zbąszyń Groove). This area includes landscape units associated with the vast dip of land occupied by the Obra River, Zbąszyńskie Lake (B1–B5), and forested areas (A3–A7). The proximity of urban and suburban landscapes (D1–D3) to natural areas creates opportunities for effective leisure programming for different target groups (residents and tourists).

Discussion

The proposed indicators allowed us to study the diversity and conditions of ecosystems at the local scale. Furthermore, they fill a gap in the context of cultural ecosystem services because they can be used to diagnose the natural, cultural, and physiognomic features of a landscape and assess the potential of CESs [10, 18, 28, 29, 59-63]. CES are mainly immaterial, meaning that their value depends more on individual and collective subjective perceptions than that of other ES categories [64]. Furthermore, CESs inherently depend on human interaction with nature [65-68].

In fact, our results prove that CESs can be an important driving force for any kind of stakeholder or local authority in landscape conservation, planning, and management [16, 69, 70]. Specifically, they expose the multiple use and nonuse values that various stakeholders perceive in the landscape and that have been overlooked in previous ES assessments [69-72]. Thus, CES evaluation is now attracting the attention of various disciplines and industries. However, as Blicharska et al. [68] noted, the variety of definitions, approaches, and applications of CESs has led to the concept of so-called "shades of grey" CESs, which can hinder stakeholder communication and utility in decision-making and planning processes.

Using hierarchical cluster analysis [73-75], it was possible to group all the CES-providing units, i.e., 28 spatial units, based on distinct CES categories and their potential supply. Therefore, it was possible to verify whether every landscape within a group followed its type. In other words, clustering allows the assessment of indicators of cultural ES potentials that match landscapes of defined types, i.e., forests (A), surface waters and wetlands (B), rural (C), and urban and suburban (D), as well as an evaluation of how well they reflect landscape types. Each landscape has specific characteristics of ES potential supply, which are described by a set of values for all identified CES categories (I–VII). Moreover, clustering can help to determine whether unweighted or weighted indicators are better suited for assessing CES potentials by comparing the results of both clusterings. First, all the input data were normalized to avoid dependency on an arbitrary variable unit. Second, the input data consisted of separate datasets for unweighted and weighted variants. There were some visible patterns in the composition of the average scores, which can be shown and compared in radar charts (Fig. 4). In general, the introduction of weighting is more crucial for landscapes that have been more transformed by human action, e.g., urban and suburban landscapes are visibly more prone to defined weights than are forest landscapes.

In our study, hierarchical clustering was applied to analyze the potential of cultural ecosystem services (CESs) across different landscapes following the statistical approaches outlined by Kaufman [73], James et al. [74], and Kassambara [75]. These methodologies facilitate the grouping of landscapes based on their CES potentials, illustrated through dendrograms and other related plots, including scatterplots and tanglegrams.

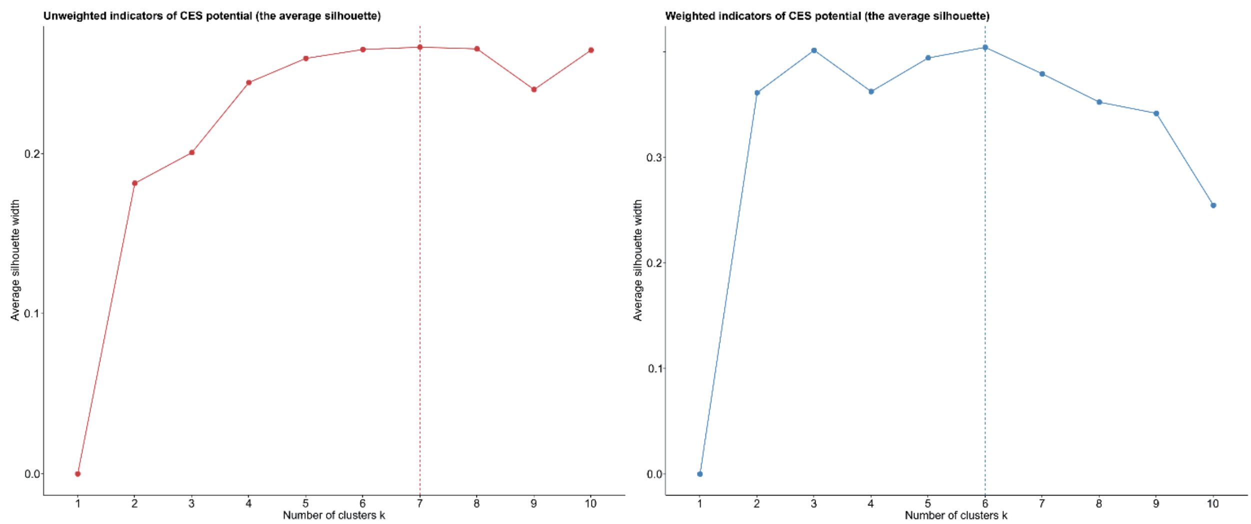

Fig. 5. Determination of optimal clusters for the potential of cultural ecosystem services (CESs) via the average silhouette width of unweighted and weighted indicators.

They depict landscapes grouped according to their ES cultural potential on the basis of the developed CES categories. Generally, each dendrogram leaf corresponds to a single landscape of a specific type and a unique set of ES potential values for each cultural category. The greater the distance on the tree (moving along a vertical axis), the more similar landscapes (units) are combined into branches linked at a specific part of the dendrogram. They indicate the dissimilarity between every two grouped units. However, obtaining optimal clustering results, i.e., the most interpretable solution, requires much testing. Several issues impacting clustering must be considered and resolved before its final interpretation. Therefore, it was essential to our analysis to choose dissimilarity measures and linkage types and to determine the optimal cluster count. We compared weighted and unweighted assessment methods, recognizing that each has distinct advantages and limitations. Weighted assessments adjust for the varying significance of specific CES categories but introduce potential bias, necessitating judicious weight allocation.

Alternatively, unweighted assessments are more superficial and may capture only part of the spectrum of ecosystem service values. Therefore, exploring both methodologies aims to enhance our understanding of changes in the CES distribution at the local scale. On the other hand, this may indicate the importance of the expert approach within CES analysis. Generally, the methods used allowed us to group landscape units by different CES categories and determine which assessment options, i.e., weighted or unweighted, are better for studying CES potential at the local scale. Therefore, the study results emphasize the importance of implementing statistical methods in environmental studies. Broader spatial studies also show that combining multiple spatial-statistical tools can help reveal regional differentiation, directional change, and key drivers of spatial patterns [76-78].

First, guided by the "fviz_nbclust" function from "factoextra," we identified the most robust clustering structures, which were optimal at 7 clusters for unweighted indicators and 6 for weighted indicators. The distinct peaks in average silhouette width, indicating the highest degree of separation and cohesion within the clusters, confirmed the optimal cluster count, as illustrated in Fig. 5.

Second, the most appropriate linkage method for hierarchical clustering was chosen based on the agglomerative coefficient, which measures the clustering structure. Values closer to 1 suggest a stronger clustering structure, which was observed for weighted CES categories and Ward's method. The measured values varied from 0.60 (unweighted) and 0.63 (weighted) for single linkages to 0.90 (unweighted) and 0.93 (weighted) for Ward's linkages. Finally, after measuring dissimilarity values for each of the assessed clustering methods, dendrograms were visualized for the best solutions obtained and cut following the previously determined optimal number of clusters (k), i.e., k = 7 for the unweighted dataset and k = 6 for the weighted dataset (Fig. 6).

Another way to visualize the results is a scatter plot, which shows all clustered data as a cloud of points in a two-dimensional space. When data points are more similar, i.e., have more characteristics in common, they fall closer to each other and create distinct groups that are consistent with previously determined clusters. Clusters can also be observed within the shapes of distinct geometric figures. Simultaneously, all the clusters had relatively concise forms and were well separated; i.e., the within-cluster similarity was relatively high, whereas the between-cluster similarity was relatively low (Fig. 7).

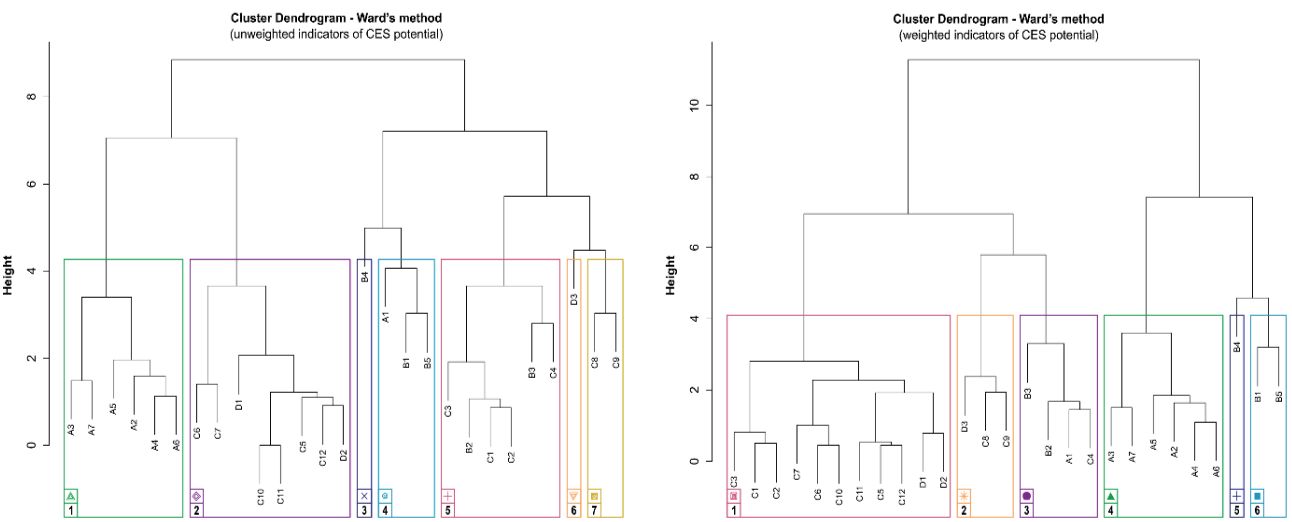

Fig. 6. Dendrograms of unweighted and weighted indicators of the potential of cultural ecosystem services (CESs) using Ward's method, illustrating the optimal clustering solution.

As shown in Figs. 6–7, forest landscape units mostly occurred within a single cluster (A2–A7), excluding one relatively small peripheral unit (A1), which made them the most consistent for both unweighted (cluster 1) and weighted data (cluster 4). This indicates that the characteristics of their landscape potential are similar to each other and highly depend on the specific mix of partial potential values following the distinguishing assessment criteria. Moreover, all the landscape units related to water, i.e., water bodies and watercourses or wetlands, are typically grouped together but also mixed with rural landscape units or some outliers, which primarily include small, peripheral units, i.e., A1 (forest) and some units adjacent to urban or suburban landscape units. However, the largest individual wetland (B4) is also the most unique landscape unit and does not cluster with any other unit for either the unweighted or weighted indicators. In general, all rural landscape units grouped together with only minor outliers, whereas the weighted data were more frequently grouped within a single cluster. This indicates that weighting had a relatively strong influence on distinguishing rural landscapes from other landscape types. However, among rural landscape units, there were also some outliers that had relatively large settlements within their borders, i.e., C7 and C9, which created a separate cluster with the main urban unit, i.e., D3. In some cases, it was difficult to assign specific landscape units unambiguously to the rural, urban, and suburban types (C and D). Generally, landscape composition may vary, and the characteristics of both types may tend to mix within the borders of each unit. However, each unit can have only one defined landscape type, which results in unavoidable generalization. C- and D-type units can ultimately have quite similar structures and landscape potentials. Recent CES studies likewise show that multisource spatial methods can reveal heterogeneity in CES provision and its relationship to landscape characteristics [79, 80].

To visualize differences in Ward's hierarchical clustering of unweighted and weighted indicators of CES potential within a specific landscape type, a tanglegram (Fig. 8) can be plotted. This graph shows the linkages between two dendrogram variants as lines connected to labels that indicate specific landscape units.

The entanglement measure was used to determine if data weighting introduced significant changes to the clustering. The entanglement values vary from 0 to 1, and increasing values indicate greater entanglement and lower alignment, i.e., more changes between the two dendrogram branches. The acquired entanglement was 0.68, which indicates medium alignment and visibly significant changes between unweighted and weighted data clustering. All the common branches, i.e., unchanged branches, are the same color; all the connections that have changed are black. The majority of unchanged branches belonged to the forest cluster (A2–A7). However, the issue of differentiating among urban, suburban, and rural landscapes is again visible (D3 and C8–9). There were also some unchanged branches for wetlands, i.e., B1 with B5 and B4 individually. Generally, most changed branches belonged to urban and suburban (D) or rural (C) landscape units.

Statistical analysis revealed that better grouping of landscape units was associated with the variant that used weighted assessment results based on the CES category and ecosystem type. This revelation confirms the validity of methods based on the ecosystem service potential matrix [24, 43, 81]. These results show that introducing data weighting has the greatest impact on clustering C and B units, with branches changing the most. However, the relatively small differences

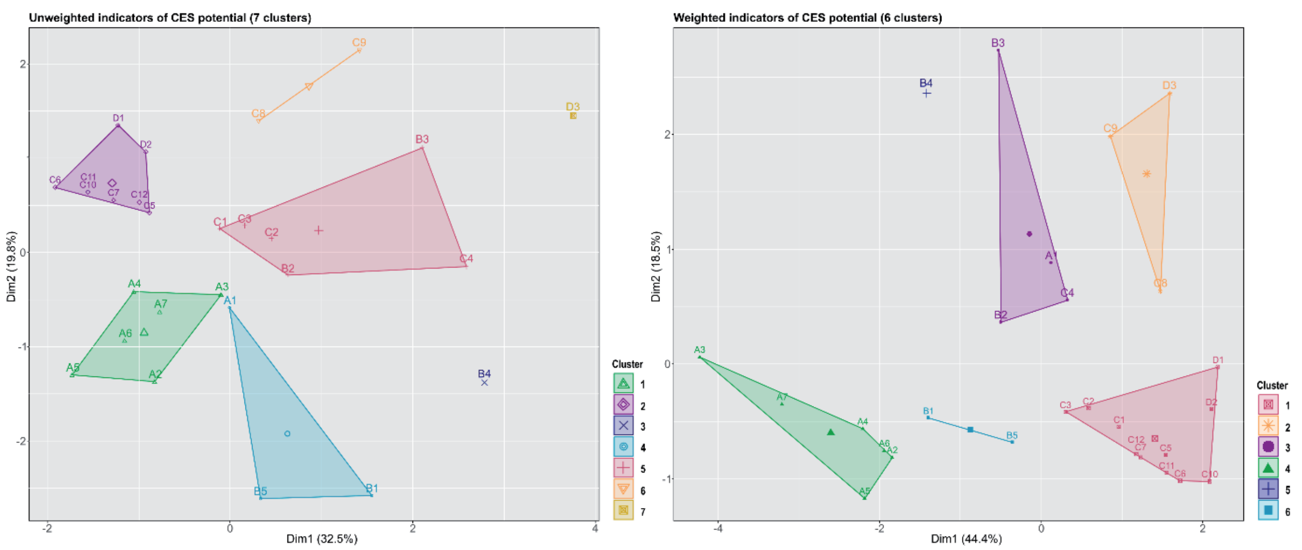

Fig. 7. Scatter plots of unweighted and weighted indicators of the potential of cultural ecosystem services (CESs) for a specific landscape type, illustrating how designated spatial units group according to their landscape types.

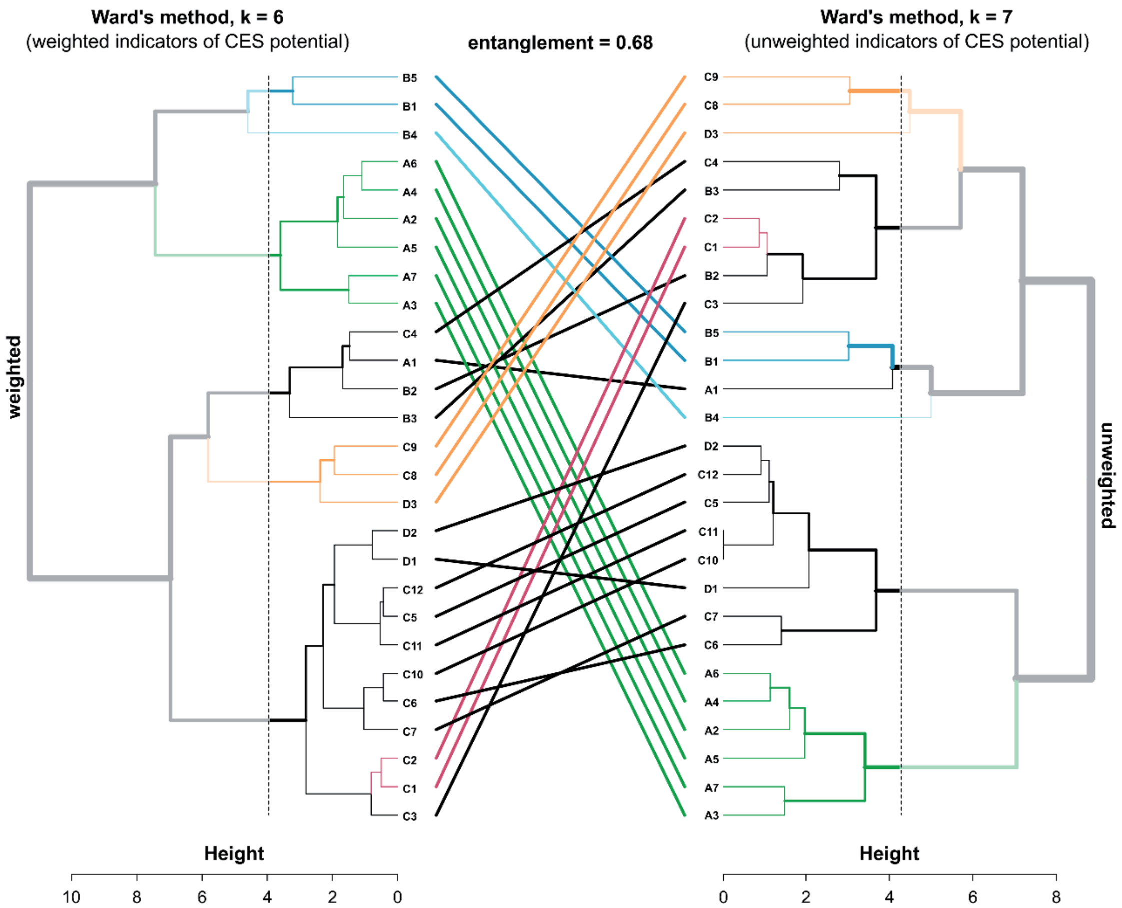

Fig. 8. Tanglegram showing linkages between dendrograms of weighted and unweighted indicators of the potential of cultural ecosystem services (CESs), illustrating their resemblance.

in the grouping of landscape units between the weighted and unweighted variants allow us to conclude that the developed indicators and their aggregation pattern adequately reflect the differences in CES potential across landscape unit types. Spatial scale was not explicitly analyzed in this study; however, the assessment was based on the best available spatial data for the study area, which were deemed appropriate in scope, detail, and resolution for the adopted methodological framework. At the same time, finer spatial resolution may reveal greater internal heterogeneity of landscape units and stronger CES contrasts, whereas coarser resolution may smooth local variation and reduce this differentiation, which is consistent with broader observations that input data quality, temporal coverage, and spatial resolution can influence ecosystem-assessment results [35, 82]. Notably, the differences between the weighted and unweighted variants are also relevant from a planning perspective. While the unweighted approach provides a transparent comparative baseline, the weighted approach may better support identifying landscape units where protection, recreation development, or green–blue infrastructure measures should be prioritized.

Conclusions

The analysis results demonstrate that it is feasible to establish a set of diagnostic features and indicators to evaluate CES potential at the local scale and to connect this potential with the demand for these services [10, 18, 28, 29, 59, 60]. Notably, the highest utility and complementarity of the available databases were found in the CES categories related to recreation and tourism, natural heritage and diversity, cultural heritage and diversity, and landscape aesthetics and inspiration. On the other hand, some gaps in data consistency and scope were also identified, particularly within the categories of knowledge systems, religious and spiritual experiences, and environmental conditions and threats. Addressing these gaps will require further research and the acquisition of expanded datasets to increase the efficiency and usability of the proposed indicators. Therefore, additional support from supplementary methods, including broader datasets and field studies, will be necessary for more comprehensive CES assessments.

Some of these indicators and spatial data have already demonstrated their value in the landscape audit of Wielkopolskie Province, as shown in previous studies [32-35, 83, 84]. Landscape audits encompass a broad range of landscape elements and provide valuable, indisputable insights for CES studies at the local scale. Integrating ecosystem conservation with landscape planning should be prioritized to support sustainable environmental management practices.

A broad set of diagnostic indicators can be applied to assess various CES categories locally. Indicators tailored to specific landscape types and their unique ecosystem characteristics provide the most accurate within-analysis representations. Statistical analyses indicate the importance of these indicators in assessing natural landscapes, where distinct groups emerge among forests, surface waters, and wetlands based on CES subcharacteristics. However, as ecosystems become more modified and cultural factors increase their influence, the grouping of spatial units becomes less distinct, particularly in urban and suburban areas and, to a lesser extent, in rural areas. This pattern results from the prominence of features and indicators that reflect more generalized landscape characteristics.

Since quantitative data based on various metrics and units of measurement create difficulties in comparing CES potentials, an approach based on scoring and weighting indicators is more integrative and much easier to implement. Refining the proposed methodological solutions may involve improving the CES matrix by incorporating expert evaluations and inputs from local stakeholders to more accurately capture differences in the CES supply across the defined categories and specific ecosystem types. Notably, those conclusions are particularly relevant for those diagnostic features that are more difficult to quantify, a view supported by many researchers [47, 85, 86].

The spatial analysis of the CES supply maps suggests that the potential for ecosystem services closely aligns with natural conditions. In this study, areas with the highest CES potential across nearly all categories were located within a single physical-geographical region (Zbąszyń Groove), an expansive land depression with trough lakes that exemplifies a young glacial landscape in Poland. The transferability of this approach is greatest in regions sharing key characteristics of young glacial landscapes, such as a mosaic of forests, wetlands, lakes, and agricultural land, relatively low-relief terrain, and the availability of comparable spatial data and landscape typologies. Its applicability may be more limited in strongly mountainous, highly urbanized, or otherwise structurally different regions, where the indicator set and weighting assumptions would require adaptation. Notably, our clustering of the CES indicators supports the inclusion of landscape classifications in ES studies, as landscape divisions reflect underlying natural conditions. Physical and geographical microregions show high congruence with landscape types [35, 83-87], substantiating their use for regional and local decision-making. In practical terms, the results may support landscape planners and decision-makers in identifying spatial units for prioritized protection, integrating CES mapping results into local spatial development plans, locating low-impact recreation infrastructure, and strengthening green–blue infrastructure in areas with high CES potential. Further research could build on these findings by developing more detailed recommendations for urban planning and landscape protection authorities.

Overall, the study objectives were achieved by identifying and characterizing landscape units, developing and applying a set of indicators for CES assessment, mapping CES potential, and statistically classifying spatial units according to CES supply. The results answer the research questions by showing that CES potential varies clearly among landscape units in a typical young glacial landscape, with the highest values concentrated in forest, wetland, and water-related units, while rural and cultural landscapes are more strongly associated with cultural heritage and diversity. They also show that the weighted matrix approach enhances CES differentiation and provides a more nuanced classification than the unweighted variant. An applied research approach that combines biophysical methods, quantitative assessments, and CES mapping can therefore serve as an accurate, quantified decision-making tool across various natural resource management areas. At the local scale, these tools are valuable for planning documents and strategic studies related to nature conservation, landscape management, tourism, and recreation. In Poland, recent progress in landscape audits and spatial planning reforms has further expanded the applicability of CES studies, particularly regarding CES supply. Therefore, assessing CES supply remains essential for integrating scientific knowledge with practical insights to identify, diagnose, and evaluate ecosystems across diverse ecological, economic, and social contexts [26, 88, 89].

Author Contributions

S.B. and W.P. conceptualized the initial idea of the study. W.P. designed all the statistical and GIS analyses, analyzed the data, and developed all the figures. S.B. developed all the tables and appendices. S.B., W.P., and M.K. collaboratively wrote the manuscript. S.B., W.P., and M.K. edited the drafts of the manuscript. All the authors contributed critically to the drafts, reviewed the manuscript, and approved the final version for publication.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability

The data supporting the findings of this study are available in Appendices 1–3 and from the corresponding author upon reasonable request.

Declarations

All authors have read, understood, and complied, as applicable, with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Appendices

Appendix 1 Characteristics of landscape types within the study area.

Appendix 2 Indicators used to characterize biophysical landscape features (abbreviations explained in Table 1).

Appendix 3 Matrix of specific indicator importance for assessing the potential supply of cultural ecosystem services (CES), developed by the authors.

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