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Geosystem Services of Erratic Boulders in Selected Regions of Central Poland

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Abstract: Scandinavian erratic boulders in central Poland represent a significant element of the region's geodiversity, fulfilling important natural, scientific, and cultural functions. As objects of high perceptual value, they integrate into the landscape and provide a wide range of geosystem services. The main objectives of research conducted in two areas of the Małopolska Upland are to determine the concentration of these boulders and identify the geosystem benefits they offer, with particular emphasis on lichen species inhabiting their surfaces. Research has confirmed the currently limited use of geosystem services provided by the 25 erratic boulders studied. However, this may change with growing ecological awareness among local communities, enabling a deeper appreciation of inanimate nature. Erratic boulders have the potential to attract geotourists and thus support economic development (by improving the residents' quality of life), but this potential requires broader promotion. Although the Central Register of Geosites of Poland is an appropriate platform for their registration, none of the analysed boulders have yet been included. The research findings are also partly directed at local government units to help them recognise the value of erratic boulders for sustainable development, in line with existing legal frameworks and development strategies. The detailed characterisation of 25 boulders may inspire broader initiatives and foster knowledge transfer to support regional development through geotourism. The ability to identify the ecosystem benefits provided by erratic boulders is essential for maintaining ecological balance and sustaining natural processes. However, there is growing evidence of the systematic disappearance of erratic boulders from the landscape, which disrupts geosystem balance and leads to further environmental degradation, negatively affecting human well-being. In light of the lack of effective nature protection measures in the study area, it is proposed that some of these boulders be designated as geological protected features. Such a conservation approach could help maintain ecological balance in the designated area.

Keywords: ecological awareness; geosystem services; Scandinavian erratic boulders; lichens; Radom Plain; Połaniec Basin; Central Poland

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1. Introduction

Scandinavian erratic boulders represent a significant component of Europe's abiotically formed natural environment. They contribute to geodiversity (e.g., [1–4]), offering valuable reception objects for audiences with diverse and increasingly sophisticated needs (e.g., [5–11]). These stone blocks function within their unique geosystem and, in accordance

with the concept of geosystem services (e.g., [1,12,13]), provide regulatory, supporting, provisioning, cultural, and knowledge-based services to society.

Examples indicate (e.g., [14,15]) that in certain regions of Poland, the natural environment is experiencing a gradual loss of geodiversity, leading to the depletion of the Earth's surface heterogeneity. This encompasses aspects of geology (e.g., rocks, minerals, fossils), geomorphology (landforms, topography, physical and anthropogenic processes), hydrology, soil science, and climatology, including their interrelationships, structures, exogenous processes, systems, and contributions to the landscape. A salient example of this phenomenon is the irreversible disappearance of erratic boulders, which are extensively utilised as fundamental construction and decorative materials. The current processing of these boulders is predominantly undertaken in stone-cutting plants situated in proximity to cemeteries, as well as in architectural firms specialising in interior design and in landscape architecture studios (hereafter called "Stones in your garden"). The demand for stone-based interior décor or garden rockeries is driven by specific human preferences, often influenced by limited environmental awareness. Ensuring equilibrium within geosystems inhabited by humans is imperative for the preservation of abiotic resources. Disruptions to this balance result in environmental degradation, which, in turn, has a detrimental effect on human psychophysical stability.

Geodiversity, defined as the variety of geologic features within a specified region, is an inherent property of any given territory. It serves as the foundation for sustaining life on Earth and the proper functioning of geosystems and their services in the future. Furthermore, geodiversity plays a crucial role in regulating geochemical cycles and supplying materials, energy, water, food, and various other resources, including cultural and knowledge-based assets, thereby enhancing societal well-being. The collective of these benefits, encompassing regulatory, supporting, and provisioning services, as well as cultural, scientific, and educational contributions, is designated as geosystem services.

The contemporary necessity of assessing the current state of geodiversity is crucial for forecasting environmental changes and, most importantly, for evaluating the suitability of natural conditions for specific functions [16], such as geotourism, in accordance with the principles of sustainable development.

In order to prevent a decline in human well-being, it is essential that individuals are equipped with the knowledge required to mitigate adverse changes. The effective dissemination of knowledge, presented in an engaging manner through geostorytelling [17,18] and supplemented with elements of geowatching [19], delivered by a professional geointerpreter (e.g., [20–23]), for example, can address the presence of erratic boulders in Pleistocene glaciation areas and the geosystem services they provide to society. The capacity of individuals to assimilate and apply this knowledge exerts a significant influence on their quality of life while concurrently stimulating regional economic development. It also ensures environmental protection and management in accordance with the principles of sustainable development.

2. A Review of the Existing Literature on the Topic

In the context of the concept of (geo)ecosystem services (e.g., [1,12,13]), erratic boulders provide regulatory, provisioning, supporting, cultural, and knowledge services, thereby benefiting human societies.

The regulatory service under discussion pertains to the role of geodiversity and its elements in maintaining the equilibrium of natural processes and conditions across the Earth. Erratic boulders, as part of the wider geomorphological process, are subject to a variety of physical and chemical changes, including the rock cycle, erosion, and the regulation of floods as a result of their function as mineral filters. The provisioning service

refers to the utilisation of erratic boulders as sources of construction materials and objects of ornamental significance. The supporting service encompasses anthropogenic activities where erratic boulders serve as foundations for human development, participating in soil formation processes (through rock weathering and subsequent soil profile development) and providing habitats for living organisms.

The cultural services of erratic boulders are evident in their incorporation into the landscape, manifesting in local legends and identity, and serving as points of reference in the local imagery of the surrounding communities. They are also associated with recreational activities, particularly in geodiverse environments. These services encompass five abiotic goods and processes [1]: (1) environmental quality (e.g., local landscape characteristics, therapeutic landscapes enhancing well-being), (2) geotourism (e.g., collecting interesting rock specimens and gravel fractions during excursions; visiting lapidaria), (3) cultural, spiritual, and historical associations (e.g., legends about erratic boulders, stone monuments marking historically significant events), (4) artistic inspiration (e.g., erratic boulders in art, poetry, music; decorative craftsmanship workshops focused on erratic stones), and (5) the development of social competencies (e.g., participation in rock-collecting societies).

The knowledge service underscores the scientific significance of erratic boulders, particularly as subjects of geological research, while also emphasising their value as unique components of the abiotic environment. Erratic boulders bear vestiges of geological and geomorphological processes that have shaped them over billions of years across diverse geosystems. Their formation is understood to span a range of geological processes, including the initial stages of landmass development, diastrophic cycles, glacial erosion, transport, and deposition, as well as periglacial environments and contemporary anthropogenic pressures.

In glacial deposition areas, erratic boulders represent all petrographic rock types, though igneous and metamorphic rocks predominate. This quantitative dominance is attributable to the geological structure of the source region in Scandinavia (e.g., [24–36]) and their greater resistance to weathering. It has been determined that merely approximately 2% of large erratic boulders are sedimentary rocks [37,38].

Erratic boulders represent a component of the geological heritage [8,39,40], thereby contributing to geodiversity (e.g., [1,2,41–47]), and are currently regarded as geosites [48–50]. These sites facilitate knowledge transfer from experts and geointerpreters to the public (e.g., [18]). They serve as documentation of past geological processes occurring within the source area (e.g., weathering or subglacial erosional processes such as exaration, detersion, and detraction) and those related to their transport within the ice sheet to glacial deposition areas (e.g., rounding of edges or detersion of the substratum over which the ice sheet moved). The surface of erratic boulders also bears traces of various processes, such as periglacial ones, that occurred in extraglacial zones. When an erratic boulder remains in situ since its deposition (i.e., has not been displaced by anthropogenic factors), it is of primary scientific value. They are utilised in statistical analyses to determine the primary direction of ice sheet transport and in cosmogenic isotope dating (e.g., ^{10}Be) to establish the onset of deglaciation in glaciated areas (e.g., [51–55]). Should an erratic boulder be subject to legal protection, it will fulfil a conservation function. Large, well-exposed boulders can serve a decorative role [9,56,57], providing aesthetic satisfaction [58]. When positioned along a designated tourist trail and accompanied by an informative sign, an erratic boulder can also fulfil an educational role (e.g., [47]), in addition to its significant recreational value.

Despite the existence of extant literature that provides examples of the functions that geosources perform, it is challenging to locate references to the concept of geosystem benefits in these works. Noteworthy exceptions include [59–61], where the authors underscore the relevance of the concept of ecosystem services in tourism, emphasising its

capacity to offer tangible benefits derived from natural environments. Furthermore, it has been recognised quite recently in [10,11,62] that Scandinavian erratic boulders also secure geosystem benefits.

Erratic boulders that have been relocated for preservation purposes and assembled in lapidaria (or stony gardens) (e.g., [8,9,63,64]) also serve geoethical and environmental functions by raising awareness about the importance of preserving and protecting all elements of nature [65–68].

Erratic boulders have been identified as a significant potential asset for the development of geotourism (see, i.e., [5,7,8,40,69–74]). This field of nature-based tourism is underdeveloped in Poland. The aim is to protect the country's geological and geomorphological heritage through effective geosite conservation, the broad promotion of geological sciences, and the dissemination of their educational and tourism-related functions. Geotourism is defined as a harmonious integration of natural features into local policies for sustainable social and economic development (see [45]).

In the course of the field studies conducted by Dr. R. Zabielski from the Polish Geological Institute—National Research Institute in 2022, as part of the update of the Wierzbica sheet (743) of the Detailed Geological Map of Poland at a 1:50,000 scale (abbr. in Polish: SmgP), and also during the detailed inventory work carried out by the authors in 2024 (author M.G.–Z. was guided by local nature lover Zbigniew Walenciak), a significant presence of erratic boulders was observed in the area under study. These boulders had previously been inventoried by [75,76], but without detailed characterisation. On the map (study area I in Figure 1), Czernicka delineated clusters of erratic boulders with a circumference not exceeding 8 m. In the subsequently published Explanations to the SmgP (Wierzbica sheet), Ref. [77] briefly noted their presence in surface sediments deposited during the Middle Polish Glaciation and indicated their locations on the geomorphological sketch of the geological map sheet.

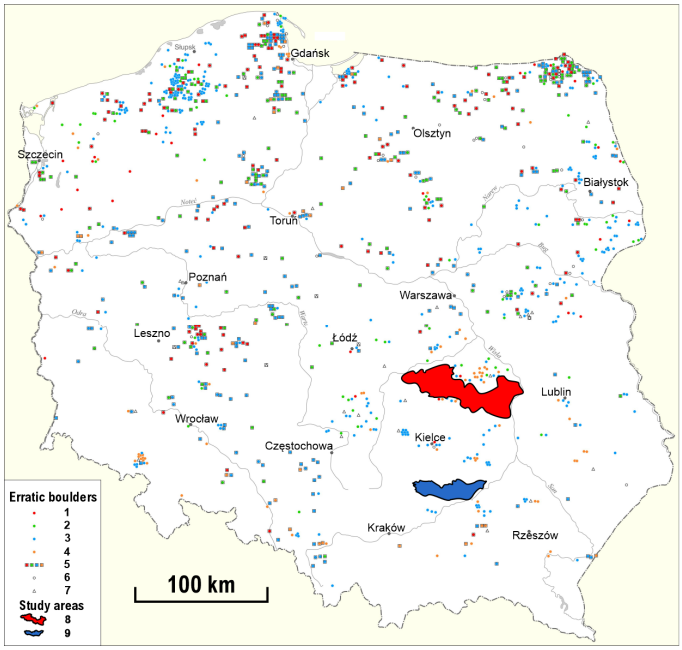


Figure 1. Location of two study areas against the map of distribution of erratic boulders in Poland (based upon [75,76,78]). Explanation of legend: boulders' circuit: 1—bigger than 10 m, 2—10-8 m, 3—4–8 m, 4—smaller than 4 m, 5—boulder cluster legally protected, 6—natural, 7—artificial; study areas: 8— I (Radom Plain area), 9—II (Połaniec Basin area). More information in the text.

The studies of [74–77,79–85] indicate regions of increased presence of erratic boulders at the boundary between the Przedbórz and Kielce Uplands. These zones of increased boulder populations are most commonly associated with glaciomarginal zones that were in dynamic equilibrium. This phase of enhanced glacial deposition of rock material transported by the ice sheet is still evident in the vicinity of Wierzbica today.

Walczowski [86] was conducting geological research on the Staszów sheet (886) of the Detailed Geological Map of Poland at a scale of 1:50,000 when he determined that during the Eemian interglacial period, and due to the erosion of glacial clay which was correlated with the Middle Polish Glaciation, erratic boulders were exposed. However, on Walczowski's map, these boulders are likely concealed under the designation of Pleistocene sands and gravels with boulders, as they do not appear as independent specimens with a dedicated cartographic symbol. The region near Staszów is depicted on the map (study area II in Figure 1) as devoid of erratic boulders, based on the inventory by [75,76,78]. However, the authors' recent research has confirmed the contemporary surface presence of these boulders, and it can be linked to the relatively recent construction of the area's water and sewage infrastructure system.

Notably, none of the aforementioned studies in either region documented the colonisation of erratic boulders by epilithic lichen biota. However, erratic boulders also provide regulatory, support, and provisioning services for living organisms that utilise such habitats [87]. Erratic boulders, as habitats for epilithic lichens, are irreplaceable in this respect. These large stones, provide unique substrates that support the growth of specific lichen species—these serve as irreplaceable habitats for acidophilic epilithic lichens (e.g., [88–90]). Such stones play a crucial role as habitat islands for regionally rare lichens. This highly specialised substrate represents a distinct category of rock surfaces, alongside calciphilous rocks. The characteristics of microhabitats formed on these boulders are influenced by various factors, including the mineral composition of the rocks, their porosity, weathering capacity, and size, all further modified by the surrounding environmental conditions, such as exposure to sun, shade, and proximity to forests and roads [91,92]. By introducing an additional type of natural substrate and providing shelter, erratic boulders play a crucial role in supporting and maintaining the biodiversity of living organisms—not only lichens but also fungi, plants, and animals. Studies on the lichens of erratic boulders in Europe are not the most common (e.g., [89,90,93]); so, data from this type of habitat are extremely important for recognising the species diversity of these organisms and their ecological requirements.

Fałtynowicz [94], in his research on epiliths of large erratic boulders in the Polish Lowlands, called for the protection of erratic boulders hosting lichens, even those of smaller dimensions. The area affected by the San II glaciation of the South Polish complex and the Odra stadial of the Middle Polish glaciations has been identified as an ideal research site. The studies conducted in [8,9,40,55,74,84,85,95,96] have revealed that the erratic boulders in this region are significantly smaller in size compared to those in northern Poland (see, e.g., [4,39,40,72,97–101]).

From the perspective of documenting the geological history of a given area and/or illustrating specific geological and geomorphological processes, erratic boulders have been registered as geosites in the Central Register of Geosites in Poland [102], which is administered by the Polish Geological Institute—National Research Institute.

3. Objectives and Research Methods

The present study was preceded by a bibliographic query and an in-depth field reconnaissance analysis in two selected regions at the boundary between the lowland and upland zones of central Poland.

This research was accompanied by two main goals and accompanying objectives. The primary intent was to identify the (geo)ecosystem services of glacial erratic boulders. In order to do this, side objectives were realised, i.e., an examination of (1) the fundamental physical properties of erratic boulders, (2) their petrographic classification, and (3) their affiliation with the group of indicator erratics (e.g., [103–105]), and (4) a record of morphogenetic environments in which these deposits existed at various stages of their geological history. The second main research objective was to identify and inventory the epilithic organisms colonising erratic boulders. Our study represents the inaugural application of these analyses in the Malopolska Uplands.

In light of these research objectives, a total of 25 erratic boulders from both study areas were subjected to analytical procedures (selected from 50 previously inventoried in the Wierzbica SmgP sheet and 15 from the Staszów SmgP sheet), meeting the established methodological assumptions. In this context, the rocky substrate provides provisioning, regulatory, and supporting ecosystem services for lichens that have found their habitat on these boulders.

The present study directly follows the appeal made by [94] to investigate and protect erratic boulders colonised by epilithic lichens outside the Polish Lowlands. It is noteworthy that research at the intersection of glacial geomorphology and lichen ecology in Poland remains limited, with the most recent studies dating back to the 1990s (e.g., [106–109]).

All field photographs were taken by the corresponding author (MGZ), unless stated otherwise.

3.1. Methods of Erratic Boulder Research

The present study was conducted during fieldwork on erratic boulders in the summer seasons of 2022 and 2024. The methodology comprised a detailed characterisation of seven selected specimens in the Staszów region and eighteen specimens in the Wierzbica area (see Table 1). The selection of boulders was partly subjective, with a particular focus on those colonised by lichens. The secondary criterion was the presence of indicator erratics. These erratics are of particular significance due to their uniqueness, with each originating from a single known outcrop on the Scandinavian Peninsula (see Figure 2), enabling precise identification of their source area. The study of indicator erratics, frequently used to determine the primary directions of glacial transport, is methodically conducted within the coarse gravel fraction (20–60 mm; [110]). Research indicates that within the entire population of erratics in the European Lowlands, indicator erratics constitute only about 10%, making them relatively rare.

Table 1. Species identified in the surveyed areas with the total number of erratic boulder recorded.

No.	Species	Total Number of Boulders (In Brackets—The Boulders Numbers Themselves)
1. →	*Acarospora fuscata* (Schrad.) Arnold	4 (31, 85a, 90c, 92d)
2. →	*Acarospora privigna* (Ach.) A. Schneid.	1 (92d)
3. →	*Acarospora versicolor* Bagl. & Carestia	3 (31, 33, 66c)
4. →	*Amandinea punctata* (Hoffm.) Coppins & Scheid.	5 (31, 66c, 66e, 90c, 92d)
5. →	*Athallia holocarpa* (Hoffm.) Arup, Frödén & Søchting	3 (29, 66c, 92d)
6. →	*Bacidina modesta* (Zwackh ex Vain.) S. Ekman	3 (4, 5, 7)
7. →	*Calogaya decipiens* (Arnold) Arup, Frödén & Søchting	3 (31, 66c, 89a)
8. →	*Calogaya saxicola* (Hoffm.) Vondrák	2 (66c, 89a)

Table 1. *Cont.*

No.	Species	Total Number of Boulders (In Brackets—The Boulders Numbers Themselves)
9. →	*Candelariella aurella* (Hoffm.) Zahlbr.	15 (13, 14, 31, 33, 66a, 66c, 66e, 84a, 85b, 89a, 90a, 90c, 92d, 96b, 96c)
10. →	*Candelariella vitellina* (Hoffm.) Müll.Arg.	11 (31, 33, 66c, 66e, 84a, 85a, 89a, 90a, 90c, 92d, 96c)
11. →	*Circinaria caesiocinerea* (Nyl. ex Malbr.) A. Nordin, S. Savić & Tibell	4 (11, 31, 66e, 90c)
12. →	*Cladonia coniocraea* (Flörke) Spreng.	2 (7, 13)
13. →	*Flavoplaca flavocitrina* (Nyl.) Arup, Frödén & Søchting	1 (90a)
14. →	*Hypogymnia physodes* (L.) Nyl.	1 (66a)
15. →	*Hypogymnia tubulosa* (Schaer.) Hav.	1 (66a)
16. →	*Lecidella stigmatea* (Ach.) Hertel & Leuckert	2 (33, 66e)
17. →	*Lepraria elobata* Tønsberg	1 (11)
18. →	*Lepraria incana* (L.) Ach.	1 (11)
19. →	*Micarea viridileprosa* Coppins & van den Boom	2 (4, 7)
20. →	*Myriolecis albescens* (Hoffm.) Śliwa, Zhao Xin & Lumbsch	8 (10, 11, 14, 31, 66e, 84a, 85a, 96c)
21. →	*Myriolecis crenulata* (Hook.) Śliwa, Zhao Xin & Lumbsch	4 (31, 66c, 90c, 92d)
22. →	*Myriolecis dispersa* (Pers.) Śliwa, Zhao Xin & Lumbsch	8 (31, 84a, 85a, 85b, 86a, 90a, 90c, 92d)
23. →	*Myriolecis hagenii* (Ach.) Śliwa, Zhao Xin & Lumbsch	1 (14)
24. →	*Myriolecis semipallida* (H. Magn.) Śliwa, Zhao Xin & Lumbsch	11 (13, 14, 29, 31, 33, 66c, 66e, 85a, 85b, 90a, 90c)
25. →	*Parmelia sulcata* Taylor	4 (13, 66a, 66c, 96c)
26. →	*Phaeophyscia nigricans* (Flörke) Moberg	8 (29, 31, 66c, 84a, 85b, 89a, 92d, 96c)
27. →	*Phaeophyscia orbicularis* (Neck.) Moberg	13 (10, 14, 29, 31, 66a, 66c, 84a, 85b, 86a, 89a, 90a, 92d, 96c)
28. →	*Physcia adscendens* (Fr.) H. Olivier	10 (13, 14, 29, 31, 66a, 66c, 84a, 85a, 85b, 86a)
29. →	*Physcia dubia* (Hoffm.) Lettau	1 (66a)
30. →	*Physcia caesia* (Hoffm.) Fürnrohr	4 (13, 14, 31, 66a)
31. →	*Physcia tenella* (Scop.) DC.	9 (10, 13, 14, 29, 31, 66a, 66c, 85b, 96c)
32. →	*Placynthiella icmalea* (Ach.) Coppins & P. James	1 (7)
33. →	*Porina chlorotica* (Ach.) Müll.Arg.	3 (4, 5, 7)
34. →	*Porpidia crustulata* (Ach.) Hertel & Knoph	1 (13)
35. →	*Porpidia soredizodes* (Lamy) J.R. Laundon	3 (11, 13, 66e)
36. →	*Protoparmeliopsis muralis* (Schreb.) M. Choisy	13 (13, 14, 31, 33, 66c, 66e, 84a, 85a, 89a, 90c, 92d, 96b, 96c)
37. →	*Rhizocarpon distinctum* Th.Fr.	1 (66e)
38. →	*Rinodina* sp.	2 (31, 33)
39. →	*Scoliciosporum umbrinum* (Ach.) Arnold	5 (66a, 66e, 70, 75b, 96c)
40. →	*Xanthoparmelia conspersa* (Ach.) Hale	2 (13, 33)
41. →	*Xanthoria parietina* (L.) Th.Fr.	10 (14, 29, 31, 66a, 66c, 84a, 86a, 90a, 92d, 96c)
42. →	*Verrucaria* sp. 1	13 (4, 7, 14, 70, 75b, 84a, 85a, 85b, 86a, 90a, 92d, 96b, 96c)
43. →	*Verrucaria* sp. 2	1 (85b)

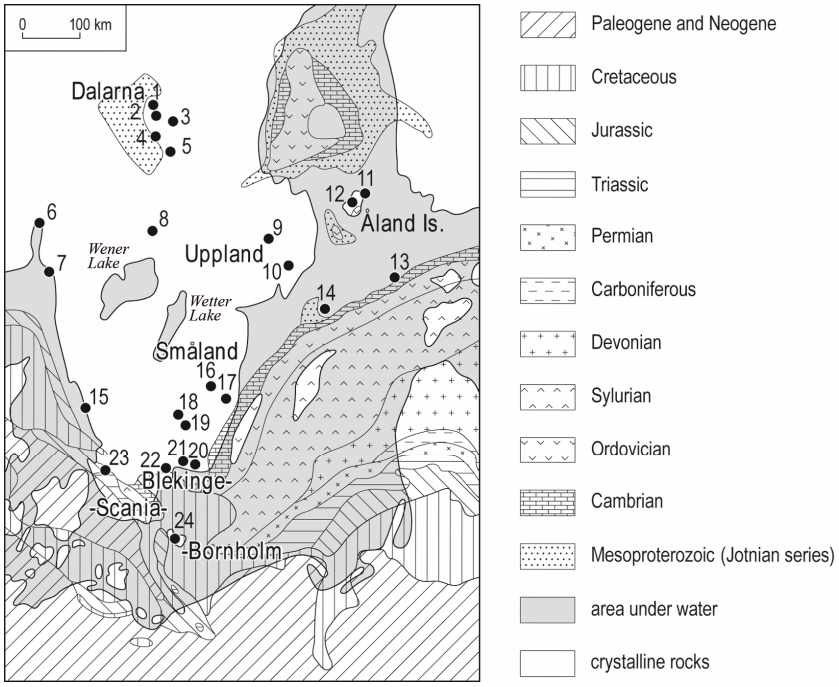


Figure 2. Schematic map of the source area of selected indicator erratic boulders found in the area of glacial deposition in Poland. Explanation of numbers: 1—Bredvad porphyry, 2—Garberg granite, 3—Grönklitt porphyry, 4—Dalarna porphyry, 5—Siljan granite, 6—Oslo porphyry, 7—Bohus granite, 8—Filipstad granite, 9—Uppsala granite, 10—Stockholm granite, 11—Åland granite and Åland rapakivi granite, 12—Åland quartz porphyry, 13—red Baltic porphyry, 14—brown Baltic porphyry, 15—charnockite, 16—Småland granite, 17—Påskallavik porphyry, 18—grey Växjö granite, 19—red Växjö granite, 20—Karlshamn granite, 21—Halen granite, 22—Vånga granite, 23—Scania basalt, 24—granites and gneisses of Bornholm.

Conversely, large-sized erratic boulders hold significance for tourism valorisation and their potential for future educational and geotourism applications.

During the inventory process, data were collected on the dimensions (length, width, height), petrographic classification (igneous, sedimentary and metamorphic rocks), and type of erratic boulder (indicator and indicative), thus providing insights into the rock's genesis and age, as well as its distinctive features. The estimated volume of the boulders was calculated using Schulz's [38] formula: V = 0.523 × length × width × height. The weight was determined based on an assumed density of 2.75 t/m^3.

Special attention was given to various microforms present on the surface of the erratic boulders, such as crescentic gouges and glacial striations, which are characteristic of the subglacial environment where boulders were transported within the basal ice layer, abrading against a harder substrate. The condition of the boulders' edges was also examined, particularly in terms of rounding, which serves as evidence of transport within high-energy subglacial and englacial tunnels. Furthermore, distinctive micromorphological features formed in the periglacial environment, such as wind-faceted stones (ventifacts), aeolian polishing (eolian gliptolites), and faceted boulders (dreikanters), were documented.

Furthermore, contemporary morphogenetic processes affecting the boulders' surfaces (e.g., exfoliation, aeolian abrasion; cf. [39,84]) were analysed in the field. Furthermore, the cultural heritage associated with these boulders was considered, as their presence in local customs and traditions reflects their historical significance to past generations.

3.2. Methods of Lichenological Research

A detailed inventory of all lichen species growing on each erratic boulder was conducted in the field. For the purpose of species identification, a ×230 magnification hand

lens equipped with a built-in light source was utilised. In instances where identification at the locality proved challenging, specimens were collected in minimal quantities for subsequent analysis in controlled laboratory settings.

Microscopic preparations were made from transverse sections of fruiting bodies, and spore sizes were measured. The chemical properties of the thalli were then analysed using standard reagents, including 10% potassium hydroxide (K), sodium hypochlorite (C), p-phenylenediamine in ethanol (Pd), and iodine solution (I). The species' nomenclature follows the most recent classification in [111].

4. Research Area

Field analyses were conducted in two research areas in central Poland (Figure 3): I—smaller in area, situated to the north of Wierzbica (SmgP sheet No. 743); and II—bigger in area in the vicinity of Staszów (SmgP sheet No. 886). Research area I is located in the southeastern part of the macroregion of the Southern Mazovian Uplands (318.8, [112]), and belongs to the mesoregion of the Radom Plain (318.86). A comprehensive investigation was undertaken on 18 erratic boulders (see Figure 4). Research area II is situated mainly in the macroregion of the Nida Basin (342.2), specifically in its eastern part, the mesoregion of the Połaniec Basin (342.28). This study area also covers a small area in the neighbouring mesoregion—Szydłowskie Foothills. The inventory in this area encompassed seven erratic boulders (Figure 5).

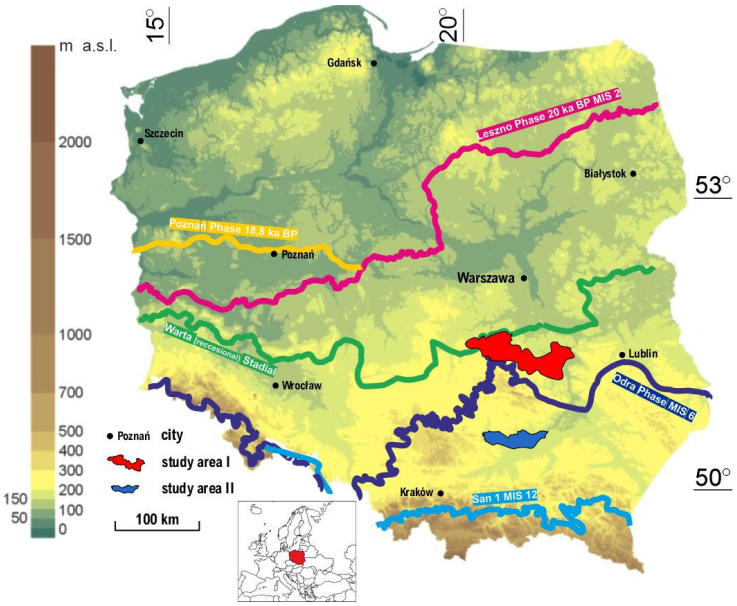


Figure 3. Location of the two study areas I and II in central Poland against the background of Scandinavian glaciation limits. On the bottom—location of Poland in Europe. Source: hypsometric map of Poland (only) released under the GNU Free Documentation Licence, changed by the authors.

The topography of the Radom Plain is dominated by old glacial relief, like plains and water–glacial accumulation forms [113], sculpted during the Odranian Glaciation (MIS6). In the western part of the mesoregion, there are out-wash-plains and forms of glacial and water–glacial accumulation, denuded in the old glacial area. The eastern part is characterised by the presence of numerous dune forms. In the southern part of the Radom Plain, plateaus and tablelands are found, underlain by Neogene deposits with a Pleistocene cover. Consequently, the landscapes within the research area are predominantly characterised by old glacial, flat, and undulating topography, with the western part exhibiting old glacial

hilly, fluvio-glacial plains and undulating forms, and the southern part featuring carbonate landscapes of undulating plateaus.

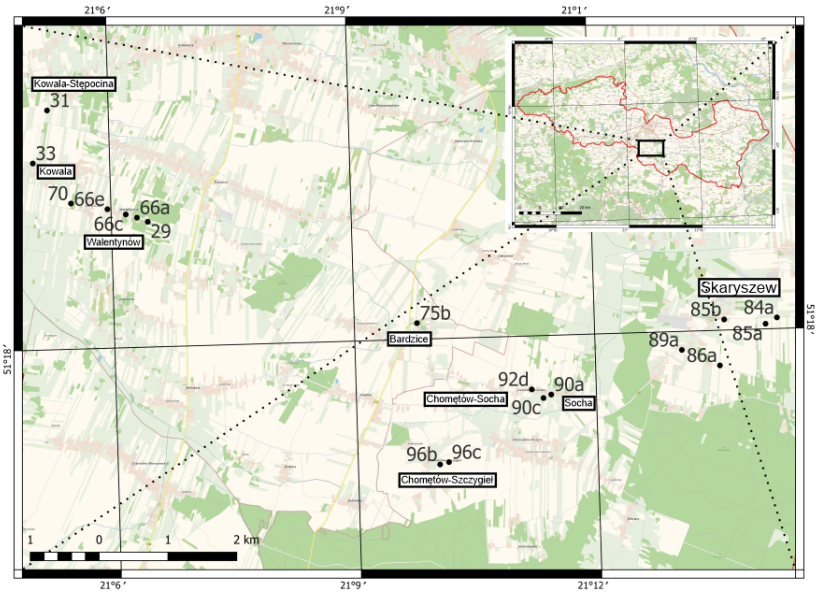


Figure 4. Detailed location of the numbered erratic boulders studied within the central part of the Radom Plain mesoregion. The study area within the Radom Plain mesoregion is visible in the upper right corner. Source: Database of General Geographical Objects and Database of Topographic Objects in scale 1:10,000, available in QGIS, changed.

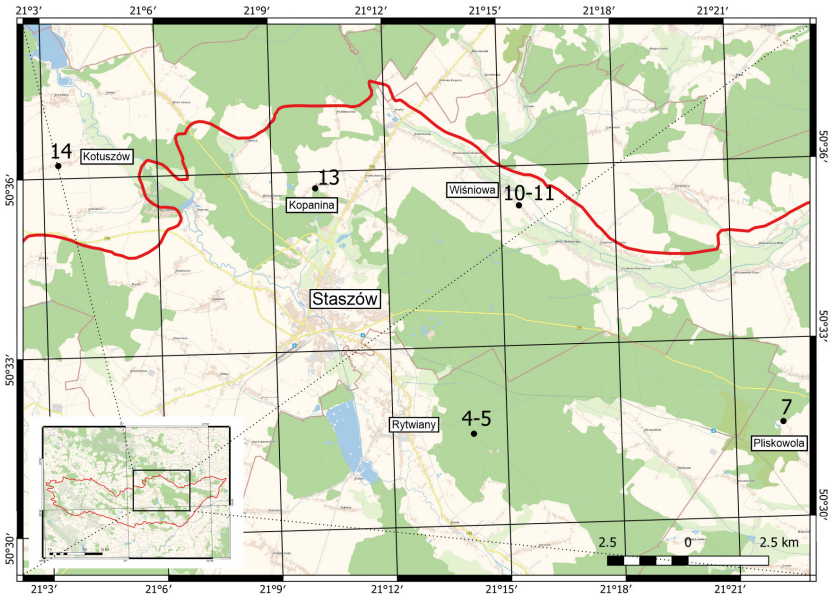


Figure 5. Detailed location of the numbered erratic boulders along the northern border of the Połaniec Basin mesoregion. The study area within the Połaniec Basin mesoregion is visible in the lower left corner. Explanation: Red line marks the border between two mesoregions: the Połaniec Basin (in the centre) and the Szydłowskie Foothills (in the north). Source: Database of General Geographical Objects and Database of Topographic Objects in scale 1:10,000, available in QGIS, changed.

The substrate deposits of the Radom Plain are composed of basal moraines, with moraine clays and glacial erratics being the dominant features. The glaciomarginal zone is characterised by the presence of sands, gravels, and erratic boulders. Sands and gravels also form the substrate of the water–glacial accumulation area.

The Radom Plain's environmental protection is inadequate, as demonstrated by the paucity of legal safeguards for biotic resources and landscape values. According to [112], there is only one nature reserve (a peatland reserve—"Borowiec"; Inspire Code: PL.ZIPOP.1393.RP.1249, Central Register of Nature Protection Forms (Polish abbr. CRFOP), accessed on 10 March 2025), one landscape park (Spalski Landscape Park), and a small fragment of another (Kazimierski Landscape Park). Within the Natura 2000 network, two Special Protection Areas for Birds and one Special Area of Conservation for Habitats can be identified. Furthermore, a single nature protection form, designated as the nature–landscape complex "Sycyna" (Inspire Code: PL.ZIPOP.1393.ZPK.312, CRFOP, accessed on 10 March 2025), is recorded. According to the CRFOP, there is not a single erratic boulder within the research area that is protected as a natural monument. Furthermore, the Central Register of Geosites of Poland (Polish abbr. CRGP [102]) does not record any geosites in the area.

The topography of the Połaniec Basin, as delineated by [112], is characterised by the presence of a subsiding depression sloping towards the southeast, accompanied by an axially aligned valley of the Wschodnia River and Sanica, as well as the north–south valley of the Czarna Staszowska River. The topography is further diversified by numerous moraine hills (associated with the San 1 glaciation, MIS 12) and local gypsum karst formations.

In the superficial layer of the western part of the mesoregion, chalk marls are present. The remaining part, extending towards the east, is composed of Miocene rocks, including Sarmatian sandstone plateaus with a descending 20–30 m step of the Szaniecki Plateau, limestones, marls, Kraków clays with evaporites from the Miocene Sea, such as gypsum, anhydrite, and sulphur. These rocks are overlaid by Pleistocene deposits, comprising till clays, gravels, sands, and locally loesses, and by Holocene deposits, including river sediments and peat. Richling et al. [112] have indicated that the research area predominantly features upland, carbonate, and gypsum landscapes.

The legal protection of biotic resources and landscape values in the Połaniec Basin is highly diversified and, in comparison to the Radom Plain, is much more developed. The area is home to three nature reserves, encompassing peatland, water, and forest reserves, in addition to two landscape parks and as many as five protected landscape areas. Additionally, Special Protection Areas for Birds and Special Areas of Conservation have been designated within the Natura 2000 network. It is imperative to acknowledge the numerous individual forms of nature protection, including 111 geological monuments (but including only two erratic boulders: Diabelski Kamień and Gwarek; [109]), 200 monument trees, 5 ecological sites, 4 nature–landscape complexes, and 1 documentation site: the gypsum exploitation pit of Gartatowice-Sądziejowice (Inspire Code: PL.ZIPOP.1393.SD.8; [114]).

5. Research Findings

5.1. General Results of Lichenological Studies

In study areas I and II, a total of 43 lichen species were found on erratic boulders (Table 1). The lichen community was very poor, with most species observed on only 1–3 boulders, such as *Acarospora privigna*, *Micarea viridileprosa*, *Porpidia crustulata*, and *Rhizocarpon distinctum*. In the lichen biota, species representing the main thallus types have been identified: crustose lichens (thalli adhering to the substrate, innate entire lower thallus surface), foliose lichens (dorsiventrally flattened thalli, forming rosettes attached to the substrate at multiple points), and fruticose lichens (highly branched, attached to the substrate at a single point). Crustose lichens are considered the most resistant to various external factors, such as pollution, dust, and water scarcity, while foliose lichens are sensitive, and fruticose lichens are among the most sensitive [87]. Crustose

lichens dominated the assemblage, with fewer foliose species and only one fruticose lichen—*Cladonia coniocraea* (Figure 6).

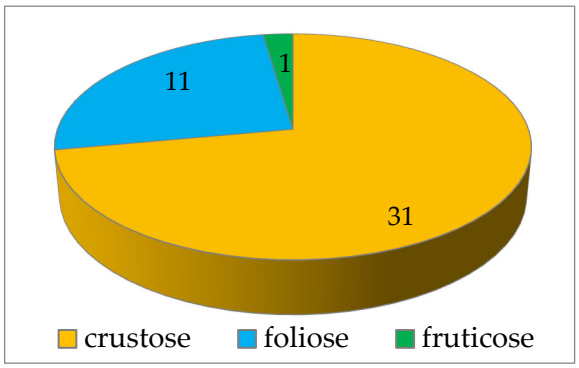


Figure 6. The number of lichen species characterised by a specific thallus type.

According to geosystem services concept, all epilithic lichens benefit from the provisioning services provided by erratic boulders. The most frequently occurring lichen was *Candelariella aurella*, a species with a broad ecological range that typically grows on calcareous rocks and, in acidic environments, on substrates enriched with dust and soil particles. Alongside typically epilithic species like *Circinaria caesiocinerea*, *Myriolecis albescens*, *Porpidia crustulata*, and *Protoparmeliopsis muralis*, the lichen community also included epiphytic species, primarily foliose lichens that usually inhabit tree bark and, less frequently, dead wood. Notable examples among these were *Hypogymnia physodes*, *Hypogymnia tubulosa*, *Parmelia sulcata*, and *Physcia tenella*. These epiphytes colonised rock surfaces where thin layers of soil had accumulated from decomposing leaves, needles, and mosses. Boulders hosting epiphytic lichens were typically situated in sun exposed areas near trees.

In the identified biota, several epilithic lichen species are particularly noteworthy: *Acarospora privigna*: this lichen, relatively rare in Poland, often goes unnoticed due to its inconspicuous thallus, and black colouring, resembling a non-lichenised fungus [111]. It was observed on boulder No. 92d. *Acarospora versicolor*: a very rare species in Poland, previously recorded on acidic rocks in the Sudetes and Central Polish Lowlands [111]. In the studied area, it was found on boulders No. 31, 33, and 66c. *Rhizocarpon distinctum*: scattered across Poland [111], this species is associated with acidic rocks in open, sunlit areas. It was identified on boulder No. 66e in the study area. *Xanthoparmelia conspersa*: a foliose lichen with a widespread distribution in Poland [111], typically found on acidic rocks, often large boulders located in open and sun exposed places. It was recorded on boulders No. 13 and 33 in the study region.

5.2. Review of Erratic Boulders Colonised by Epilithic Biota Providing Geosystem Services to the Public

Erratic boulders have been shown to provide geosystem services to both society and nature. The following section will identify these services following a detailed characterisation of the studied georesources.

5.2.1. Erratic Boulders of the Radom Plain Area

This study focuses on erratic boulders present within the geographical area of the Radom Plain, of which 18 were analysed (Figure 4). The analysis revealed that only seven of these boulders exhibited a volume that was equal to or greater than the average value of 0.19 m^3 (Table 2). Of these, only five exceed the calculated average of 0.8 tons. One boulder (75b) is of particular note due to its exceptional dimensions, with a volume of 2.76 m^3 and a weight of 7.34 tons.

Table 2. Characteristics of erratic boulders studied in the Radom Plain area.

No of the Boulder	Site	Coordinates	Vol. [m^3], Weight [t], age [Ga]	Petrographical Type, Kind of an Erratic	Specific Features of the Boulder Morphology	Currently Secured Geosystem Services
29	Walentynów	51.316364 21.107587	0.19 0.52 1.75–1.5	Igneous, indicator erratic, Småland granite	Granite with an eolised surface, visible from the cross road; protects the place name sign from being hit by vehicles	Regulation, support, provisioning, cultural and knowledge services
31	Kowala-Stępocina	51.331264 21.087253	0.23 0.64 1.75–1.5	Igneous, indicator erratic, Småland granite	Granite, poorly weathered in places, located on a bend, together with other smaller boulders, prevents vehicles from stopping on the grassy verge	Regulation, support, provisioning, cultural and knowledge services
33	Kowala	51.324395 21.08398	0.39 1.07 1.7–1.54	Igneous, indicator erratic, Åland rapakivi granite	Granite with a glacial polish on the south-western side, with a clear eolian corrasion micro-relief; it serves as protection for the signpost; locally, the boulder is known as the 'Wooden Stone'	Regulation, support, provisioning, cultural and knowledge services
66a	Walentynów	51.31694 21.10536	0.34 0.94 difficult to assess	Igneous on a contact with metamorphic zone	The granitoid gneiss lies in the vicinity of other erratic boulders (including pebbles) on the edge of the forest next to the buildings of Walentynów; colonisation by lichens prevents accurate petrographic identification	Regulation, support, provisioning and knowledge services
66c	Walentynów	51.3174 21.10305	0.06 0.16 1.75–1.5	Igneous, indicator erratic, Småland granite	Granite with glacial polish of a small area; located where the Radom City Tourist Walking Trail runs, Polish Tourist and Sightseeing Society Łucznik Branch (lucznik.org.pl); the boulder (sentimental value?) has been marked with the number (12) of the property at Walentynowska St	Regulation, support, provisioning, cultural and knowledge services
66e	Walentynów	51.31815 21.09926	0.15 0.40 1.75–1.5	Igneous, indicator erratic, Småland granite	Partially weathered granite, with glacial polish still visible on the western wall; located along the road in front of a new residential building; dates back to the time when the foundations were laid	Regulation, support, provisioning, cultural and knowledge services
70	Walentynów	51.319031 21.091703	0.03 0.09 difficult to assess	Igneous, fine-grained granite	Granite with a glacially smoothed surface on the south-western side and rounded corners and edges, with slight eolisation of the surface in places; located in a small forest, next to the blue tourist and sightseeing trail	Regulation, support, provisioning and knowledge services

Table 2. *Cont.*

No of the Boulder	Site	Coordinates	Vol. [m^3], Weight [t], age [Ga]	Petrographical Type, Kind of an Erratic	Specific Features of the Boulder Morphology	Currently Secured Geosystem Services
75b	Bardzice	51.30211 21.16305	2.67 7.34 1.75–1.5	Igneous, indicator erratic, Åland pyterlite granite	The granite is heavily weathered, partly due to exfoliation; glacial polish is visible on one of the walls; despite the anthropogenic cutting of a fragment of the boulder, it stands in front of the Church of St. Andrew Bobola in Bardzice and commemorates a historical event—the establishment of the parish in 1943	Regulation, support, provisioning, cultural and knowledge services
84a	Skaryszew	51.30145 21.23805	0.18 0.49 1.7–1.54	Igneous, indicator erratic, Åland rapakivi granite	The granite lying on the boundary next to the tree marks a crossroads of dirt roads; it is a boulder with rounded corners and edges	Support, provisioning, cultural and knowledge services
85a	Skaryszew	51.30067 21.23564	0.07 0.20 1.46–1.35	Igneous, indicator erratic, Blekinge granite	Heavily weathered granite lies in a clump of trees in the middle of a agricultural land	Support, provisioning and knowledge services
85b	Skaryszew	51.3014 21.22705	0.13 0.37 1.7–1.54	Igneous, indicator erratic, Åland granite	Granite, on the private property of an engraving craftsman at 47 Partyzantów St, lies anchored in the ground	Support, provisioning, cultural and knowledge services
86a	Skaryszew	51.29541 21.22588	0.09 0.26 1.75–1.5	Igneous, indicator erratic, Småland granite	Granite with a glacial polish surface visible in the upper part of the specimen; weathered, including chemically on feldspar crystals	Regulation, support, provisioning and knowledge services
89a	Skaryszew	51.29758 21.21805	0.10 0.26 1.75–1.5	Igneous, indicator erratic, Småland granite	Granite with distinct glacial wear on corners and edges; lying against the wall of farm buildings on the field side	Regulation, support, provisioning and knowledge services
90a	Socha	51.29227 21.19057	0.02 0.06 difficult to assess	Igneous, granite with a vein	Granite with veins, with rounded edges, slight surface weathering in places	Regulation, support, provisioning and knowledge services
90c	Chomętów-Socha	51.29185 21.18894	0.51 1.41 1.46–1.35	Igneous, indicator erratic, Blekinge granite	The large single granite boulder is characterised by delicate eolisation of the surface on the south side, emphasised by the presence of microforms of wind erosion; the surface of the rock is subject to exfoliation; the erratic boulder is located in a local recreation area, i.e. a place dedicated to bonfires (fire pit, shelter, swing, benches, small pond); the fire pit is marked with smaller Scandinavian pebbles	Regulation, support, provisioning, cultural and knowledge services
92d	Chomętów-Socha	51.29246 21.18745	0.58 1,59 difficult to assess	Granitoid gneiss	A boulder not exposed, located in farm waste, behind buildings	Regulation, support, provisioning and knowledge services

Table 2. *Cont.*

No of the Boulder	Site	Coordinates	Vol. [m^3], Weight [t], age [Ga]	Petrographical Type, Kind of an Erratic	Specific Features of the Boulder Morphology	Currently Secured Geosystem Services
96b	Chomętów-Szczygieł	51.28358 21.16701	0.03 0.10 difficult to assess	Igneous, fine-grained granite	Partially weathered granite lies on the boundary between fields; next to it is another, smaller coarse-grained granite	Regulation, support, provisioning and knowledge services
96c	Chomętów-Szczygieł	51.28385 21.16887	0.05 0.14 1.75–1.5	Igneous, indicator erratic, Småland granite	Granite removed from agricultural land now lies on the boundary between fields	Regulation, support, provisioning and knowledge services

The estimated volume of the boulder was calculated using the formula of Schulz (1964): 0.523 × length × width × height, and the weight of the boulder was determined, assuming that 1 m^3 = 2.75 tons. The age of the rock is given according to the work of Górska-Zabielska (2008).

All 18 erratic boulders in the first research area, located near Wierzbica, are igneous rocks (providing regulation and knowledge services). The majority of these boulders are indicator erratics, primarily Småland granites, originating from the alimentary area in the southeastern part of Sweden. These include boulders numbered 29, 31, 66c, 66e, 86a, 89a, and 96c (see Table 2, Figure 7). Two Blekinge granites (85a, 90c) from the primary region of Skåne-Blekinge-Bornholm were also inventoried, along with four specimens from the Åland Islands in the northern Baltic: these were identified as Åland rapakivi granite (33, 84a), Åland pyterlite granite (75b) and Åland granite (85b). Among the remaining erratic boulders, three granites (numbered 90a, 92d, 96b) do not represent indicator erratics. The petrographic classification of boulder 70 is challenging to ascertain due to the complete coverage of the rock block by green algae and epilithic biota (which provides knowledge services).

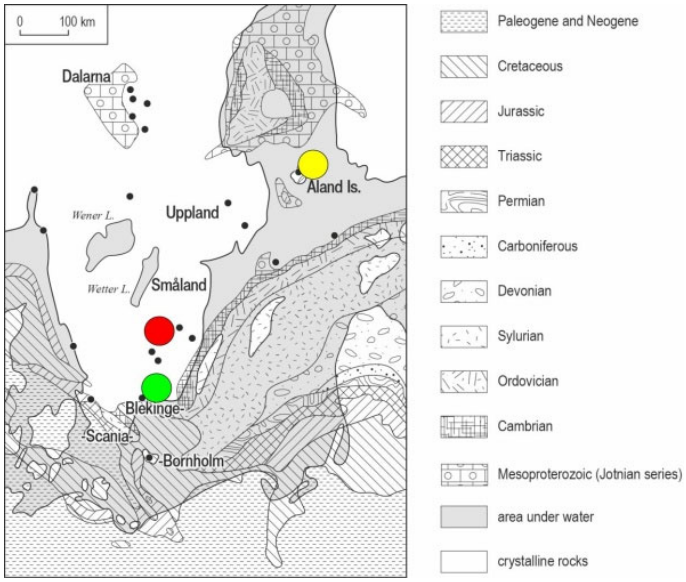


Figure 7. Scandinavian alimentation regions of indicator erratics within all glacial boulders of the Radom Plain discussed in this text: Småland granites (Nos.: 29, 31, 66c, 66e, 86a, 89a, 96c). Åland granites rapakivi (Nos.: 33, 75b, 84a, 85b). Blekinge granites (Nos.: 85a, 90c).

In consideration of the impact of diverse morphogenetic environments on the erratic boulders under scrutiny, it is imperative to acknowledge that one of the lateral surfaces of boulders numbered 33, 66c, 66e, 70, and 86a, under subglacial conditions and while still situated in Scandinavia, has undergone destructive processes—deterioration—which now manifests as a glacial polish on the surface. From this stage of the erratic boulder's functioning, it is also worth noting glacial striations on boulders not included in the current study, which reveal subglacial processes (Figure 8). It is noteworthy that only one boulder (No. 84a) is classified as a cobble, suggesting that its morphology is likely attributable to the high-energy conditions prevalent in sub-/englacial tunnels during the transgression of the ice sheet. This observation underscores the potential for such insights to provide valuable knowledge services.

In the periglacial environment, at the forefront of the retreating ice sheet, wind–sand–snow streams must have impacted orographic obstacles, including some of the studied boulders. Their morphogenetic record can be observed on boulders numbered 29, 31, 33, 66b (Figure 9), 90a, 90c, 96b, in the form of aeolian processes affecting one of the boulder's surfaces (providing regulatory and knowledge services). The colonisation of lichen was facilitated on boulders numbered 75b, 85a, 86a, 90c, as the surface layer of rock was weathered (providing support and knowledge services). The attachment of epiliths was

also favoured by the exfoliation of the outer layer of the erratic boulder. This phenomenon is attributed to the circulation of water within the mineral crystal spaces, thereby facilitating physical and chemical interactions with the erratic boulder's surface.

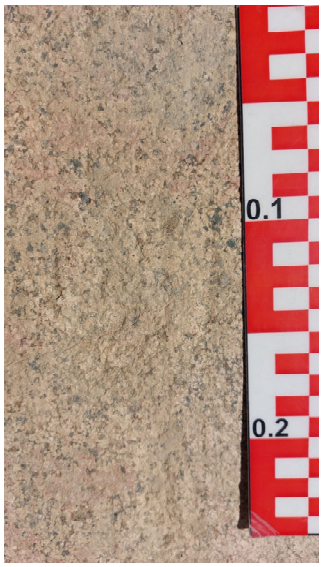


Figure 8. On one of the faces of boulder No. 72 in Maliszew (Radom Plain), glacial striations can be observed, indicating subglacial processes that likely affected the object still within the Scandinavian alimentary region; regulatory and knowledge services.



Figure 9. The upper part of the Åland rapakivi granite (No. 66b) in Walentynów (Radom Plain) is characterised by micro-corrugations formed as a result of prolonged abrasion by wind–sand–snow streams, which acted on the boulder as an obstacle on the outer margin of the retreating ice sheet in the periglacial climate zone; regulatory and knowledge services.

Despite the majority of the studied erratic boulders being located in areas distant from human settlements, some of them offer services to the local community. Three erratic boulders (29, 66c, 84a) have been identified as providing cultural services, either by inspiring the creation of a monument with a commemorative plaque or by serving as a part of the local landscape that indicates the direction of the road. The Åland rapakivi granite (No. 33; Figure 10) is locally recognised as the "Wooden Stone". Three boulders (29, 31, 33) have been deliberately utilised by humans to safeguard road signs and place-name plaques from destruction or displacement. Three additional boulders (66c, 66e, 85b) and a group of boulders situated in the village of Walentynów (Figure 11) hold sentimental value for the homeowners from the time their properties were developed. An interesting use is made of boulder number 90c (along with other smaller cobbles of Scandinavian erratics) in the village of Socha-Chomętów, where, in the village's recreation area, it serves an aesthetic function. Boulder number 92b has recently assumed a structural function, serving as the foundation for a small bridge that traverses a ditch adjacent to a recently developed property. The functions that boulders fulfil for the surrounding population are categorised as cultural services.



Figure 10. On the upper surface of the Åland rapakivi granite (No. 33) in the village of Kowala (Radom Plain), micro-corrugations and a ridge, microforms of the boulder's surface, can be observed, formed as a result of corrosion—the destruction of the boulder through abrasion by wind–sand–snow streams on the outer margin of the retreating ice sheet in the periglacial climate zone; regulatory, cultural ("Wooden Stone"), and knowledge services.



Figure 11. The high ecological awareness of the property owner in Walentynów allows them to derive aesthetic satisfaction combined with a sentimental function from the exposed erratic boulders (among them, No. 66e); regulatory, supportive, cultural, and knowledge services.

However, it is disheartening to note that several boulders have been adversely affected by anthropogenic pressures, including substantial destruction (75b) and abandonment in a forest area (66a). Four other georesources (85a, 89a, 96b, 96c) have not yet been utilised.

5.2.2. Epilithic Biota of Erratic Boulders of the Radom Plain Area

All the boulders discussed above performed, to a greater or lesser extent, support services for living organisms that are epilithic lichens. On average, there were about nine species per boulder. Småland granites No. 31 (Figures 12 and 13) and 66c (Figure 14), and Aland rapakivi granite No. 92d (Figures 15 and 16, Table S1) were distinguished by the highest species diversity, amounting, respectively, to 19, 16 and 13 species. These boulders, located in close proximity to roads or fields in sunny places, carried accumulated dust with a high content of nitrogen compounds on them. This resulted in the presence of nitrophilic lichens, i.e., lichens that prefer nitrogen-rich habitats and are often found on the bark and branches of roadside trees, e.g., *Phaeophyscia orbicularis*, *Myriolecis dispersa*, *Xanthoria parietina*, in addition to lichens that are typically acidophilic and characteristic of acidic pH substrates, e.g., *Acarospora fuscata*, *A. versicolor*. Slightly fewer species, from 10 to 11, were recorded on Småland granites No. 66a, 66e (Figure 11), and 96c, and Åland rapakivi granite No. 84a.



Figure 12. Erratic boulder No. 31 in Kowala-Stępocina is colonised by nineteen identified lichen species. It delivers regulatory, supportive and knowledge services.



Figure 13. Close up of the erratic boulder No. 31 (Figure 12) in Kowala-Stępocina shows *Myriolecis dispersa* and above the fragment of *Phaeophyscia orbicularis*.



Figure 14. Erratic boulder No. 66c in Walentynów is colonised by sixteen identified lichen species. It provides regulatory, supportive, cultural and knowledge services.



Figure 15. Erratic boulder No. 92d in Chomętów-Socha is colonised by thirteen identified lichen species. It delivers regulatory, supportive and knowledge services.

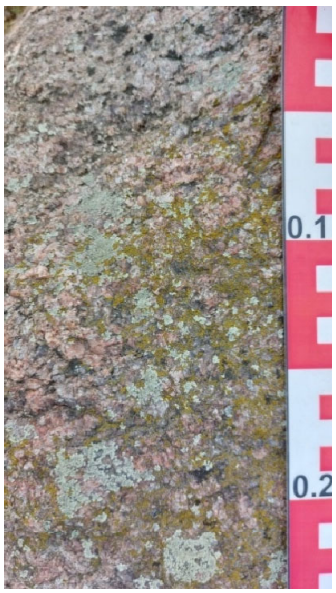


Figure 16. Close up of the erratic boulder No. 92d (Figure 15) in Chomętów-Socha shows at least five of the thirteen identified lichen species, i.e., *Candelariella aurella*, *Protoparmeliopsis muralis*, *Myriolecis dispersa*, *Phaeophyscia orbicularis* and *Phaeophyscia nigricans*.

Fine-grained granites Nos. 70 and 96b and Åland pyterlitic granite No. 75b (Table S1) were the poorest in lichen. These boulders, boulders No. 70 and 75b, were located in areas of high shade, under the canopy of trees, where the fall of leaves and tree needles formed a thick layer, covering these and preventing the development of lichen biota. Similarly, the negative impact of the external environment was observed in the case of boulder No. 96b, which lay on a spit between fields among tall and dense vegetation.

5.2.3. Erratic Boulders in the Połaniec Basin Area

In the second research area (Figure 5), four of the seven erratic boulders studied exceed the calculated average values in both volume and weight. These are specified here: 0.93 m^3 and 2.55 tons. Boulder number 13 is of particular interest as it possesses exceptional values: its volume is 2.25 m^3 and its weight is 6.2 tons (Table 3).

Six of the erratic boulders are classified as granites, which are defined as igneous magmatic rocks according to their petrological classification, while only one object (No. 7) is identified as a gneiss, a metamorphic rock. Furthermore, six of the erratic boulders represent the group of indicator erratics (Figure 17), originating from southeastern Sweden (four Småland granites) and the Åland Islands (two Åland rapakivi granites; providing knowledge services).

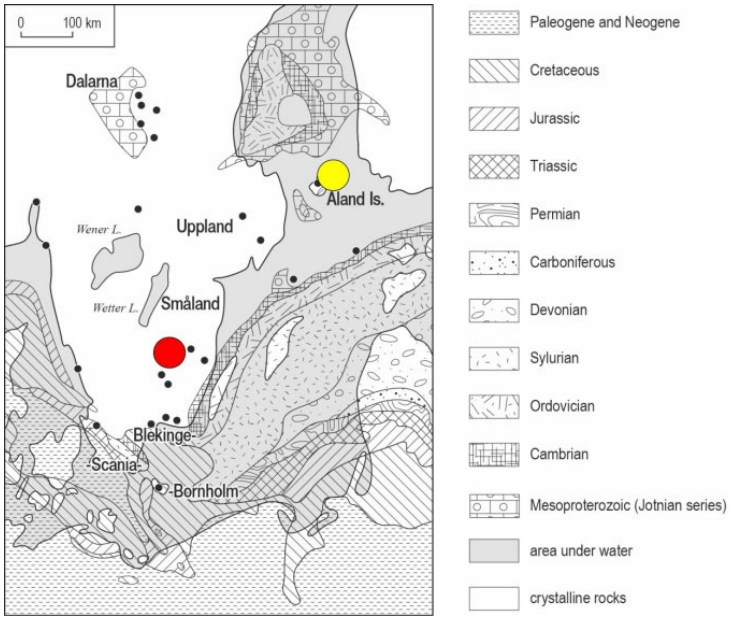


Figure 17. Scandinavian alimentation regions of indicator erratics within all glacial boulders of the Połaniec Basin discussed in this text: Småland granites (Nos.: 4, 5, 13, 14). Åland granites rapakivi (Nos.: 10, 11).

It is important at this stage to consider the influence of the successive morphogenetic environments in which the erratics were located, and it can be seen that one of the studied boulders shows traces of a subglacial environment in the form of glacial striations (No. 5). Meanwhile, three others (Nos. 4 (Figure 18), 10 (Figure 19), 11) exhibit rounded corners and edges, indicating high-energy conditions in sub/inglacial tunnels through which the boulders were transported, providing regulation and knowledge services.

Table 3. Characteristics of erratic boulders studied in the Połaniec Basin.

No of the Boulder	Site	Coordinates	Vol. [m^3], Weight [t], Age [Ga]	Petrographical Type, Kind of an Erratic	Specific Features of the Boulder Morphology	Currently Secured Geosystem Services
4	Rytwiany, Forest Hermitage of Our Lady of Fatima	50.525528 21.235333	0.44 1.21 1.75-1.5	Igneous, indicator erratic, Småland granite	Coarse-grained granite, rounded corners	Regulation, provisioning, cultural and knowledge services
5			0.29 0.79 1.75-1.5	Igneous, indicator erratic, Småland granite	Coarse-grained granite, strongly exfoliated, with slightly visible glacial scratches	Regulation, support, provisioning, cultural and knowledge services
7	Pliskowola	50.526389 21.370889	1.13 3.11 difficult to assess	Metamorphic, gneiss	Gneiss with veins, located in the bushes behind the local forest district sign, anthropogenically damaged - there are four smaller fragments of this boulder nearby	Regulation, support, provisioning and knowledge services
10	Wiśniowa	50.58896 21.25804	0.96 2.64 1.7-1.54	Igneous, indicator erratic, Åland rapakivi granite	The granite lies centrally in the lawn in front of the property on the roadside, surrounded by flowering plants, with parts of its surface eolian polished, showing signs of exfoliation	Regulation, support, provisioning, cultural and knowledge services
11			0.22 0.61 1.7-1.54	Igneous, indicator erratic, Åland rapakivi granite	The smaller granite lies on the side of the residential building, with glacially rounded corners and edges	Regulation, provisioning, cultural and knowledge services
13	Kopanina	50.595361 21.169000	2.25 6.2 1.46-1.35	Igneous, indicator erratic, Småland granite	Weathered granite, heavily eolised, with distinct corrasive micro-relief in places, exfoliation present on fragments of the surface; intentionally transported from the immediate vicinity to the property	Regulation, provisioning, support and knowledge services
14	Kotuszów	50.603607 21.056708	1,19 3.27 1.75-1.5	Igneous, indicator erratic, Småland granite	Granite shows strong weathering	Support, provisioning and knowledge services

The estimated volume of the boulder was calculated using the formula of Schulz (1964): 0.523 × length × width × height, and the weight of the boulder was determined, assuming that 1 m^3 = 2.75 tons. The age of the rock is given according to the work of Górska-Zabielska (2008).



Figure 18. Småland granite (No. 4, Rytwiany), with a profile indicating glacial transport (rounded edges and corners), provides regulatory, supporting, and knowledge services; its aesthetic value, manifested in the intensity of red and blue quartz crystals, gives the recipient great aesthetic satisfaction, providing them with cultural services.



Figure 19. The Åland rapakivi granite (No. 10) in Wiśniowa provides the hostess with great aesthetic satisfaction (cultural service), but unfortunately reflects her low ecological awareness—the boulder was intentionally relocated from its in situ position; nevertheless, it still ensures regulatory, supportive, and knowledge services.

In the context of a cold desert, wind–sand–snow streams have been observed to have a destructive impact on abandoned erratic boulders. Their morphogenetic influence was identified on two erratic boulders (Nos. 10 (Figure 19) and 13 (Figure 20)), in the form of, respectively, the polishing of a fragment of their surface and strongly expressed aeolisation, manifested as corrasion relief (=eolian ribs) (providing regulation and knowledge services). Three boulders (13 (Figure 21), 14 and 10 (Figure 22)) exhibited significant weathering (providing support and knowledge services), while the surface of four others (4 (Figure 18), 5, 10 (Figure 19), 13 (Figure 21)) underwent erosion in the form of exfoliation of the outer,

near-surface rock layer (providing support and knowledge services). The processes of weathering and exfoliation are and remain closely related to the colonisation of erratic boulders by epiliths (e.g., No. 7; Figure 23) (providing support and knowledge services).



Figure 20. On a small surface of Småland granite (No. 13; village of Kopanina), already affected by aeolisation, micro-corrugations (=eolian ribs) are beginning to emerge; the boulder provides regulatory, supporting, and knowledge services.



Figure 21. General view of Småland granite (No. 13, Kopanina) reveals fragments of rock undergoing exfoliation, i.e., surface peeling; in this way, it provides regulatory, supporting, and knowledge services. Its exposure on a private property provides (unfortunately, only to the owner) cultural services.

In the vicinity of Staszów, erratic boulders provide a valuable resource for local residents. Two boulders (10 [Figure 19] and 11) in Wiśniowa and one boulder (13 [Figure 21]) in Kopanina provide sentimental services to the local inhabitants, belonging to the group of cultural services. The landowners, captivated by the imposing nature of these boulders, have deliberately relocated three of them from a nearby forest and a village situated 8 km away, positioning them in strategic locations such as a flower bed in front of their residences and on their property. This action has not only enhanced the aesthetic appeal of their immediate surroundings but also underscores the cultural significance these boulders hold

for the local community. However, the limited ecological awareness of these individuals, evidenced by their lack of knowledge regarding the boulders, has resulted in the disruption of the original ecological balance of the boulders' depositional environment. Furthermore, the boulders, in their original, unchanged position since the time of glacial deposition, fulfil an important cognitive need within the group of knowledge services. However, the intentional relocation of these boulders results in the irreversible loss of their scientific significance. Access to these boulders is subject to variation: in Wiśniowa, access is unrestricted; in Kopanina, access is permitted within the property boundaries, though not visible from the footpath or road. However, the landowner has expressed a willingness to permit interested parties access to the property.



Figure 22. Details of the structure and texture of the weathered fragment of Åland rapakivi granite (No. 10) in Wiśniowa.



Figure 23. Three fragments of the same gneiss (No. 7) in Pliskowola (the Połaniec Basin) currently provide regulatory and supporting services, and, for experts, knowledge; the unused potential for cultural and knowledge services for laypeople visiting the nearby forestry lodge is immense.

Boulder No. 7 (Figure 23), which has been irreversibly destroyed by anthropogenic activity, having been broken into three fragments, is located in proximity to the forest lodge. It is surprising that people who are connected with the forest on a daily basis are not interested in the services these rocks already provide and could additionally meet the cognitive (knowledge service) and aesthetic (cultural service) needs of visitors/tourists/passers-by.

It can be hypothesised that the two remaining erratic boulders (4, 5), which have been placed near a local spring by human activity, contribute to an increased aesthetic satisfaction. This contributes to the provision of cultural geosystem services.

5.2.4. Epilithic Biota of Erratic Boulders of the Połaniec Basin Area

An average of six epilithic species each were found on the seven boulders analysed in study area II. The highest diversity, with 11 species each, was found on the boulders of Småland granite Nos. 13 (Figure 21) and 14 (Table S2). These boulders were found in sunny locations close to roads, and like the boulders of Småland granite from study area I, they also were overgrown with both typical acidophilous epilitic lichens, e.g., *Porpidia crustulata*, and lichens using nitrogen-rich habitats, e.g., *Physcia tenella*. Only on one boulder, No. 13, was interesting lichen—*Xanthoparmelia conspersa*—found.

Boulders of Småland granite Nos. 4 and 5, and gneiss No. 7 were situated in a forest environment, which was reflected by the lichens colonising them. Alongside typical acidophilic, shade-loving epilithic species such as *Porina chlorotica*, which thrive on rocks in forested settings, there were species more commonly found on tree bark, like *Bacidina modesta*, and on decaying wood, such as *Cladonia coniocraea* and *Micarea viridileprosa*. These latter species typically inhabit forested areas, growing on rotting wood and tree bases.

6. Discussion

The erratic boulders from both study areas currently fulfil many important roles, despite providing only a limited number of geosystem services to their recipients. However, they possess the potential to provide geosystem services across all groups: regulation, support, provisioning, cultural, and knowledge [1,13]. The utilisation of these services is contingent upon the ecological awareness of the beneficiaries, who stand to benefit from the comprehensive range of services that Scandinavian erratic boulders can offer in enhancing their quality of life and promoting the sustainable development of their immediate environment.

Irrespective of whether the erratic boulders under scrutiny are exposed or constitute part of household waste, they provide geosystem services within the regulatory and support categories. These are intrinsic functions/services of the rock material. Indeed, these boulders participate in geomorphological processes, including the breakdown and weathering of the rock. They contribute to the support service by facilitating soil formation processes and providing habitats for living organisms.

In accordance with the theory of geosystem services, the erratic boulders also provide provisioning services by serving as substrates for epiliths, which colonise the appropriately prepared surfaces of the boulders. All erratic boulders, along with external factors, create a variety mosaic of microhabitats, which are used in different ways by living organisms. Erratic boulders can support a wide variety of lichen morphological forms, as well as interesting species. Depending on their location—such as forest surroundings, proximity to fields, or within the vicinity of roads—specific microhabitats are formed. These microhabitats allow for the occurrence of species typical of both open, sunlit sites and those characteristic of damp, heavily shaded environments. Lowland rock exposures, including erratic boulders, are very important for extending the geographical range of many lichen species, such as the mountain-specific species found in the study area, e.g., *Acarospora*

privigna, *Acarospora versicolor*, *Rhizocarpon distinctum*. The conducted research provides novel insights into the species diversity of living organisms, which is of crucial importance for deepening our understanding of biodiversity. The results obtained offer valuable baseline data and can serve as a reference point for future research or further methodological developments. Similar results, indicating that the species diversity of lichens on erratic boulders is shaped individually under the influence of existing habitat conditions, were obtained in earlier studies conducted in the northern part of Poland [94,106–108]. Those studies also recorded up to dozen lichen species per boulder and emphasised that these rocks provide critical substrate for many high-mountain taxa, thereby extending their distribution. This role is especially important for very rare and endangered species [94].

The erratic boulders that are currently exposed in both study areas provide geosystem services in the cultural and knowledge categories. The following functions are fulfilled by these boulders:

1. Scientific: These boulders represent a specific petrological type that serves as a hallmark of the geological processes that led to their formation. Furthermore, they stand as a testament to various geomorphological processes that transpired during the early stages in Scandinavia, followed by their transportation to the glacial deposition areas in the Małopolska Upland, and finally during the retreat of the San II Glaciation (MIS 12) [115] and the Odranian Glaciation (MIS 6) [115] of the Middle Polish Glaciations Complex in the study area. Among the studied objects are indicator erratics that point to the area of their glacial alimentation.
2. Geoethical/cultural: These boulders cultivate a sense of place among the local community, which selected five erratic boulders from the Radom Plain (29, 66c, 84a, 66c, 66e) and the Połaniec Basin (66c, 66e, 75b, 85b, 92b) to erect a monument with an informational plaque. This initiative serves as a wayfinding tool and, in a sentimental role, commemorates the times of land development on private properties. Geoethics should be integral to everyone who values nature, as a sense of place is a predictor of pro-environmental behaviours.
3. Pro-environmental/educational: This study found that several boulders, among the 25 studied, triggered sensitivity to non-living nature among the local residents, leading to a commitment to preserve and care for these objects. Such behaviours and beliefs, once internalised, will guide informed recipients towards decisions about legal protection for the geological object. At the time of writing this article, one of the boulders (No. 10 in Wiśniowa, near Staszów) is undergoing a process of legal protection according to the decision of its owners.
4. Aesthetic: The erratic boulder from Wiśniowa mentioned above has been exposed by its owners in a prominent place on their property. Its strategic placement within a flowerbed has also been noted, contributing to the owners' overall sense of aesthetic satisfaction. A similar function is served by boulder No. 90c in Chomętów-Socha, which adorns the village's relaxation area.

It is noteworthy that other georesources, not yet exhaustively studied, have the potential to address unarticulated needs within the local community. The authors propose the following potential roles for these rock objects:

5. Educational: This would necessitate the installation of an informative plaque with comprehensible text for all visitors to the erratic boulder. The dissemination of knowledge could be facilitated by a geointerpreter, such as a teacher, guide, or local nature enthusiast. Each of these individuals could highlight details on the boulder that demonstrate its petrological type, as well as the recorded signs of processes from different stages of the boulder's "life." For instance, a geography teacher could facilitate a discussion on the various types of rock and glacial activities, an art teacher

could lead an outdoor drawing session, a mathematics teacher could offer a lesson on measurements and calculations related to the volume and weight of the rock block, a chemistry teacher could highlight minerals and teach their chemical formulas, and a Polish language teacher could assign writing tasks, such as an essay. The educational function of erratic boulders in proximity to a school has the greatest potential for success: the collection of geo-objects would provide a safe and eagerly awaited outdoor lesson for students.

6. Geoethical: The promotion of awareness among the local community of their distinctive position on Earth has the capacity to counteract atomistic behaviours and re-establish the environmental equilibrium necessary to guarantee the sustained delivery of geosystem services. This would pave the way for a more sustainable and resilient future.
7. Cultural: It is noteworthy that only one of the 25 erratic boulders under scrutiny is associated with a local legend, namely "The Wooden Stone" (No. 33 in Kowala, the Radom Plain). The largest boulders (Nos. 75b in the Radom Plain and 13 in the Połaniec Basin) could be assigned unique names through a local competition involving nearby residents. The erection of an obelisk at significant historical sites within the region, as exemplified by boulder No. 75b in Bardzice, or utilising the boulder as a pedestal for a sculpture symbolising a figure of regional importance, would further enhance the cultural significance of these boulders.
8. Pro-environmental/educational: Boulder No. 90c (currently located in Chomętów-Socha) and other currently unused boulders (No. 66a, 70, 89a, 90a, 96b, 96c in the Radom Plain and No. 7 in Pliskowola and No. 14 from Kotuszów in the Połaniec Basin) could be relocated to frequently visited locations. Accompanying these boulders should be an informational plaque that aims to raise awareness among passersby of the role and significance of the abiotic component of the surrounding nature in maintaining ecological balance, and consequently human well-being.
9. Geoenvironmental: All erratic boulders provide geosystem services (i.e., goods and services performed by nature) for the benefit of both humans and nature. However, the authors did not find any platform where these important functions, essential to human economic activities, were publicly disseminated. In the event that the local community is aware of these benefits, there is a strong likelihood that they would utilise erratic boulders in a manner that would enhance the well-being of the residents to a considerable extent. In order to benefit from these services, ensuring a better quality of life for the future, the population would engage with geoheritage in a sustainable way, maintaining ecological balance in their immediate surroundings.
10. Geoconservation: It is posited that if residents of both study areas adhered to geoethics and calotropy (surrounding themselves with beauty and goodness), legal protection would have been ensured for some of the studied erratic boulders in accordance with the [116]. Only two of the erratic boulders in the study areas are currently legally protected as inanimate nature monuments, and none are listed on [111].
11. Aesthetic: The residents of the Radom Plain and the Połaniec Basin could experience an enhancement in their quality of life if they recognised the potential of erratic boulders to improve the aesthetic quality of their properties or the nearby squares. For instance, utilising funds from a municipal budget, they could propose the establishment of pocket gardens in lieu of neglected, undeveloped plots situated within their villages or towns. This approach would create a mutually beneficial scenario, wherein the neglected areas would be revitalised aesthetically, while the exposed erratic boulders would serve a geoenvironmental function. This initiative would not only enhance

the local environment but also garner positive evaluations from residents and visitors alike, thereby fostering a sense of community pride and engagement.

As demonstrated in a number of international case studies (e.g., [117–119]), these functions have been utilised in the context of geotourism. The potential of erratic boulders for advancing geotourism has been addressed in several of the author's previous works (i.e., [39,40,101,104]). However, it is only in her recent publications [4,10,11,62] that the focus has shifted towards the geosystem benefits provided by Scandinavian erratic boulders. The contributions in [59–61] toward emphasising the value of the ecosystem services concept in tourism should also be recognised, as it demonstrates tangible advantages derived from natural environments.

Erratic boulders, as observed in the present study and in other regions (e.g., [8–11]), have the potential to generate economic benefits for all stakeholders involved in their exposure and geointerpretation. This encompasses the initiators of the concept, landscape architects, transport and crane operators, designers and producers of informational panels and labels, as well as geointerpreters and conservation staff responsible for protecting the objects (such as eco-patrols, cleaning rock surfaces from graffiti) and ensuring the safety of geotourists. It is imperative to acknowledge that effective knowledge dissemination necessitates the presence of a skilled geointerpreter [22], and a series of panels that convey information in a manner commensurate with the expertise of the intended recipient [120,121]. According to a recent study [122], there is a need to improve engagement and adopt more interactive and inclusive communication approaches. It is also recommended that contemporary trends in science communication, including for local communities, be emphasised.

7. Conclusions

In the contemporary era of tourism, where there is an increasing demand for a diversified tourism offer driven by increasingly sophisticated societal needs, erratic boulders provide a wide range of geosystem services. The glacial heritage of the Radom Plain areaand the Połaniec Basin area in central Poland, exemplified by Scandinavian erratic boulders, provides benefits derived from the inherent properties of the rocks, irrespective of public interest in them. The inherent characteristic of rocky material is its involvement in geomorphological processes; weathered rock fragments act as water filters, thereby regulating water quality. These functions fall under the category of ecosystem services. It is evident that the erratic boulders studied by the authors support pedogenetic processes through weathering and soil profile development, and provide habitats for epiliths. The boulders also provide provisioning services for all epilithic lichens.

The erratic boulders analysed in the current research procedure have a very underutilised potential for geosystem services related to knowledge. However, the geological resources studied offer knowledge services (scientific function) to experts. The cultural services provided by the analysed erratic boulders are much more extensively utilised. A significant proportion of these boulders, 14 in total, are utilised in the context of geoethical and culture-building functions, while several others are employed for their environmental and educational significance.

The presence of such a geo-object among the 25 erratic boulders of the two study areas, which were selected to provide provisions for the local population, is challenging to ascertain. Due to the methodological assumptions of this study, the focus was on individual erratic boulders rather than the Scandinavian material used for construction purposes.

It is hoped that the currently limited utilisation of erratic boulders will be adopted by the local community when their ecological awareness has been enhanced, allowing them to better appreciate the inanimate nature that surrounds them, beyond the current level

of engagement. The adage "necessity is the mother of invention" is particularly pertinent in this context, as it underscores the importance of recognising these specific geosources as a means of achieving economic benefits that would enhance the quality of life of the local community. Indeed, these geosources have significant potential to attract geotourists, thereby contributing to local economic development. However, there is a necessity to disseminate these findings to a broader audience. The Central Register of Geosites of Poland [102], which is administered by the Polish Geological Institute—National Research Institute, can be considered to be in an optimal location. It is unfortunate that none of the 25 erratic boulders surveyed have been registered there as of yet.

Finally, when local government units understand that erratic boulders can become a driving force for sustainable development in local communities, in accordance with legal regulations, municipal plans and development strategies, we can look to the future with optimism.

The authors propose that the detailed characterisation of 25 erratic boulders will initiate similar projects on a larger scale. The accompanying knowledge transfer is expected to facilitate the sustainable utilisation of these remarkable natural heritage objects for regional development, with geotourism (e.g., [123]) being a viable strategy.

The authors believe that this article will engage readers who are passionate about geology or geography, teachers of geography, or geointerpreters, as well as other individuals who may see for the first time the interest and significance of erratic boulders, which serve as "elements of the non-living part of the ecosystem" (cf. [66,124]).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources14060099/s1, Table S1: List of lichens growing on erratic boulders of the Radom Plain area; Table S2: List of lichens growing on boulders of the Połaniec Basin area.

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