Ecohydrology & Hydrobiology

Patterns of effects of land-use structure on lake water quality in coastal lake catchments of the southern Baltic Sea

--Manuscript Draft--

Manuscript Number:	
Article Type:	VSI: Hydro-Antropocene
Keywords:	land use; water quality; trophic state; coastal lake; catchment management; habitat heterogeneity
Corresponding Author:	Monika Szymańska - Walkiewicz POLAND
First Author:	Monika Szymańska - Walkiewicz
Order of Authors:	Monika Szymańska - Walkiewicz
	Mikołaj Matela
	Krystian Obolewski
Abstract:	This study investigated potential relationships between land-use structure in the catchments of six southern Baltic coastal lakes that differ in the level of hydrological connection with the sea and the lakes' trophic states. Our results indicate that three types of catchments can be distinguished, each of which has a high contribution of agricultural areas, plus: (i) considerable contributions of wetlands and water bodies (C1); (ii) a large contribution of wooded and seminatural habitats (C2); or (iii) a considerable contribution of artificial surfaces (C3). Correlations were analysed between land-use types and single-parameter Carlson's trophic state indices of lakes (TSIChl, TSITP, TSISD, TSITOC). Type C2 clearly differed from the others and was linked with the lowest trophic state index values. The other two catchment types were similarly related to the fertility of the coastal lakes. The results show that the analysed lakes' levels of connection with the sea do not affect the trophic state of their waters. Catchment structure, analysed using CORINE Land Cover data, is significantly linked with TP and TOC values, but it does not affect the Secchi depth or chlorophyll content of water in the lakes. Wetlands (especially peat bogs) in the catchment area most strongly reduced the phosphorus and organic carbon content of lake water. Furthermore, comparable contributions of natural vs. anthropogenic components (~1:1) are associated with a lower trophic state of water. The presented results may be important for shaping the proper management of various catchment types in the future, especially when implementing climate change mitigation strategies.
Suggested Reviewers:	

KAZIMIERZ WIELKI UNIVERSITY
IN BYDGOSZCZ

Faculty of Biological Sciences
Department of Hydrobiology
Chodkiewicz 30f Str., 85-064 Bydgoszcz, Poland
tel. +48(52) 3767913

Bydgoszcz, 10th January, 2023

Dear Editor,

This cover letter accompanies our paper "Patterns of effects of land-use structure on lake water quality in coastal lake catchments of the southern Baltic Sea". Our paper addresses the relationship between catchment land-use structure and the trophic status of six coastal lakes of the Baltic Sea that differ in their levels of connectivity to the sea. We believe this will be of interest to the readers of the Special Issue "Hydro-Antropocene" of *Ecohydrology & Hydrobiology*.

In our work, we searched for correlations between the catchment use structure of six coastal lakes and the quality of their waters as assessed by trophic indices and their mean Carlson Trophic State Index (CTSI). Analyses were conducted to determine the relationship in a specific hydrological catchment–lake–sea system, and to look for regularities in catchment structure that affect the trophic levels of the coastal lakes. According to our results, we conclude that there are three types of land use in the catchment areas of the studied coastal lakes. Although the lakes are characterized by high water trophy, depending on the share of each catchment component, patterns can be observed indicating that lakes with a high participation of forested and semi-natural areas, wetlands and water bodies in the catchment have a lower level of water trophy. Interestingly, the intensive intrusion of Baltic waters (=salinity level) included in the analyses was not confirmed to be important in improving the trophic level of lake waters, which indicates the predominance of the terrestrial factor over the marine factor.

We confirm that neither the manuscript nor any parts of its content are currently under consideration or published in another journal. All authors have approved the manuscript and agree with its submission to *Ecohydrology & Hydrobiology*.

We hope that you will consider this submission suitable for review, and we look forward to your response.

Yours faithfully,
Monika Szymańska-Walkiewicz (corresponding author)

Msc Monika Szymańska
Assistant of Dept. of Hydrobiology
e-mail: szymanska.monika@ukw.edu.pl

Patterns of effects of land-use structure on lake water quality in coastal lake catchments of the southern Baltic Sea

Monika Szymańska - Walkiewicz*, Mikołaj Matela, Krystian Obolewski

Kazimierz Wielki University, J.K. Chodkiewicza 30 Street, 85-064 Bydgoszcz, Poland

*corresponding author:

Monika Szymańska-Walkiewicz, Kazimierz Wielki University, J.K. Chodkiewicza 30 Street, 85-064 Bydgoszcz, Poland; szymanska.monika@ukw.edu.pl +48 52 37 67 912

Conflict of Interest:

None declared.

Ethical Statement:

The research was done according to ethical standards.

Acknowledgements:

The authors are grateful to Sylwia Ufnalska and Tim Brombley for comments on the manuscript. This study was supported by the Polish Minister of Education and Science under the program “Regional Initiative of Excellence” in 2019–2023 (Grant No. 008/RID/2018/19).

Funding Body:

Minister of Science and Higher Education (Poland)

Abstract: This study investigated potential relationships between land-use structure in the catchments of six southern Baltic coastal lakes that differ in the level of hydrological connection with the sea and the lakes' trophic states. Our results indicate that three types of catchments can be distinguished, each of which has a high contribution of agricultural areas, plus: (i) considerable contributions of wetlands and water bodies (C1); (ii) a large contribution of wooded and seminatural habitats (C2); or (iii) a considerable contribution of artificial surfaces (C3). Correlations were analysed between land-use types and single-parameter Carlson's trophic state indices of lakes (TSI_{Chl}, TSI_{TP}, TSI_{SD}, TSI_{TOC}). Type C2 clearly differed from the others and was linked with the lowest trophic state index values. The other two catchment types were similarly related to the fertility of the coastal lakes. The results show that the analysed lakes' levels of connection with the sea do not affect the trophic state of their waters. Catchment structure, analysed using CORINE Land Cover data, is significantly linked with TP and TOC values, but it does not affect the Secchi depth or chlorophyll content of water in the lakes. Wetlands (especially peat bogs) in the catchment area most strongly reduced the phosphorus and organic carbon content of lake water. Furthermore, comparable contributions of natural vs. anthropogenic components (~1:1) are associated with a lower trophic state of water. The presented results may be important for shaping the proper management of various catchment types in the future, especially when implementing climate change mitigation strategies.

Keywords: land use; water quality; trophic state; coastal lake; catchment management; habitat heterogeneity

1. Introduction

The Anthropocene is characterised by intensive changes in land-use structure within catchments and the gradual disappearance of natural habitats, to be replaced by transformed ones (e.g. Amiri & Nakane, 2009; Muchová & Tárníková, 2018). Currently, these trends are coinciding with global demographic, climatic, and socio-economic changes that often vary widely in the extent of their impact (Akasaka et al., 2010). It is also disturbing that the availability of usable fresh water is decreasing quickly as a result of inappropriate land use in catchment areas (Ding et al., 2016; Shi et al., 2017).

To prevent unfavourable changes, concepts for regulating the functioning of aquatic ecosystems have been developed to limit nutrient loads and the input of other pollutants into river systems, and thereby to limit the eutrophication and contamination of rivers, lakes and the World Ocean (Kiedrzyńska et al., 2015; Whitehouse et al., 2000). Many European countries, including those located around the Baltic Sea, are facing the need to reduce pollution loads from anthropogenic sources and to meet the requirements of the European Water Framework Directive (2000/60/EC) and Urban Waste Water Treatment Directive (91/271/EEC), so that freshwater quality can be improved. These efforts are aimed at, for example, further developing and protecting the network of Natura 2000 sites. Its priority habitat types include coastal lagoons and lakes (priority habitat 1150) with a high conservation value. Coastal lakes of the southern Baltic Sea are the last terrestrial components of catchments of major tributaries, but they vary in degree of connection with the sea (Cieśliński, 2018; Obolewski et al., 2018). Thanks to their hydrological connection with the sea, there is an exchange of matter between the ecosystems, which affects their ecological status depending on the dominance of marine or terrestrial influences (Astel et al., 2016; Mrozińska et al., 2021). As the inflow of water into coastal lakes slows sharply, organic matter is mineralised in them more quickly, and both allochthonous matter and autochthonous matter are deposited in bottom sediments (A. Jarosiewicz et al., 2015). For this reason, the water flowing through the lakes to the sea can be less strongly polluted with nutrients and organic matter (e.g. Mashkova, 2022; Stanford et al., 1988). Thus, coastal lakes act as sedimentation basins, reducing the flow of pollutants deriving from the catchment area

(Hatvani et al., 2017; Tian et al., 2017). However, the lakes are gradually overloaded with nutrients, which leads to the death of aquatic plants and animals living in them (Astel et al., 2016; Obolewski, 2009; Trojanowski et al., 1991). The reduction in biological components additionally limits the buffering capacity of lakes, and this in turn is a threat to the ecological status of the sea (A. Jarosiewicz et al., 2015; Teodoru & Wehrli, 2005). Hence, to improve lake condition, changes are necessary not only in them, but above all in their catchments, in accordance with Ecohydrological Nature-based Solutions (EH-NbS) (P. Jarosiewicz et al., 2022). Thus, one possible protective measure is to modify the land-use structure in coastal lakes' catchments to limit the pollution loads received by those lakes (Fernández-Alías et al., 2022).

In this study, we investigated relations between land-use structure in catchments of six coastal lakes and their water quality assessed using single-parameter trophic state indices (TSI_{Chl}, TSI_{TP}, TSI_{SD}, TSI_{TOC}) and mean Carlson's trophic state index (CTSI)(Carlson, 1977). Large-scale analyses were carried out for two reasons: (1) to determine relations in the hydrological system: catchment–lake–sea; (2) to search for catchment structure patterns affecting the trophic state of coastal lakes.

2. Materials and methods

2.1 Study areas

The study covers six Baltic coastal lakes (BCLs): Liwia Łuża, Resko, Kopań, Wicko, Gardno and Sarbsko. They are polymictic, with high trophic state index values (Astel et al., 2016; Obolewski, Glińska-Lewczuk, Szymańska, et al., 2018). The lakes were selected on the basis of published literature to reflect a salinity gradient, from the freshwater Lake Wicko (<0.12 PSU) to the most saline Lake Resko (>2.5 PSU) (Cieśliński, 2018; Mrozińska et al., 2021). Their catchments, located along the southern coast of the Baltic Sea, vary in area from 38.5 km^2 (Lake Kopań) to 907.2 km^2 (Lake Gardno) (Figure 1).

2.2. Water sampling

Samples were taken in these six BCLs (Figure 1) from May till September in 2019–20 to compare three seasons: spring, summer and autumn. In each lake, five sampling stations were located in both the littoral and pelagic zones (except the morphologically varied Lake Wicko, where seven sampling stations were selected). *In-situ* measurements of water transparency were taken using a Secchi disc. Simultaneously, water samples were collected to plastic containers (1L each) with the use of a Patalas sampler from the depth of 0.5–1.0 m. In this way, 192 lake water samples were taken for further laboratory analyses.

2.3. Laboratory procedure

Total phosphorus (TP) content was measured with a DR3900 spectrophotometer (Hach, USA) and assessed as recommended by Hashim et al. (2018). Total organic carbon (TOC) was analysed after filtering the samples through nitrocellulose membranes with pore size 0.45 μm (Millipore) using a QbD1200 analyser (Beckman Coulter, USA), which oxidises the organic carbon into carbon dioxide.

The water samples for chlorophyll-*a* analyses were kept in darkness until analysis (~4 h), to obtain the optimal fluorescence intensity. In the laboratory, water was poured into a glass 25-ml cuvette and analysed using a spectral AlgaeLabAnalyse (ALA) fluorimeter (BBE, Germany). For a detailed description, see Nguyen et al. (2015).

2.4. Trophic state

Carlson's trophic state index (TSI) is used to provide a single assessable index for classifying lakes according to the trophic state of the lake. Recently, Carlson's index has usually been accepted in the limnological community as a reasonable approach to this problem. It is used for assessing the trophic state of a marine body based on the following water quality factors: turbidity or transparency measured as Secchi disk depth (SD) and concentrations of total phosphorus (TP), chlorophyll-*a* (Chl-a) and total organic carbon (TOC). The spatial proration of the TSI data was recorded as the mean (CTSI) by a modified Kriging (Dunalska, 2011; M. El Zokm et al., 2018) as follows:

$$\mathrm{CTSI} = [\mathrm{TSI(Chl)} + \mathrm{TSI(SD)} + \mathrm{TSI(TP)} + \mathrm{TSI(TOC)}]/ 4,$$

The formulas for calculating TSI values from Chl-a, SD, TP and TOC are:

$$(1)\ \mathrm{TSI(Chl)} = 9.81 \ln(\mathrm{Chl}) + 30.6;$$

$$(2)\ \mathrm{TSI(SD)} = 60 - 14.43 \ln(\mathrm{SD});$$

$$(3)\ \mathrm{TSI(TP)} = 14.43 \ln(\mathrm{TP}) + 4.15;$$

$$(4)\ \mathrm{TSI(TOC)} = 20.59 + 15.71 \ln(\mathrm{TOC}),$$

where: ln is natural logarithm, TP is total phosphorus (µg L^{-1}), Chl-a is chlorophyll-*a* (µg L^{-1}), SD is Secchi depth (m), and TOC is total dissolved carbon (µg L^{-1}).

Vollenweider’s method for assessing a water body’s trophic state was also applied, which is based on the average values of selected parameters (Vollenweider et al., 1998). On Carlson’s scale, a water body is classified as oligotrophic if TSI is <30, mesotrophic from 30 to 50, eutrophic from 50 to 70, and hypereutrophic >70.

2.5. Land-cover data

The land-use structure of the catchment areas was analysed using the CORINE Land Cover (CLC) database created by the EU and coordinated by the EEA (CLC, 2018). Its major sources of information are images taken by Landsat 7 satellite (spatial resolution 30 m), followed by IRS and Spot 4. The images are interpreted using aerial photographs and topographic maps. The area was divided into five main categories of land use (level 1) and 44 detailed classes of land cover (level 3). The analyses of land-use structure of total catchments were made in the GIS environment, with a minimum cartographic unit of 25 hectares, on the basis of visual interpretation of high-resolution satellite images. Next, we estimated areas covered by individual land-use categories and classes (CLC levels 1 and 3) characteristic of the studied catchment areas (Figure 1). Both the main CLC categories and detailed classes were used for factor analysis to assess the influence that land use in the direct and total catchments had on the trophic state of the studied coastal lakes, which are the last mainland components of the catchments before the water flows into the sea.

2.6. Patterns of the influence of land-use types on the trophic state of BCLs

On the basis of CLC analysis results, we attempted to identify patterns of the influence of catchments on the trophic state of the selected BCLs. For this purpose, we calculated the ratio of the total percentage contribution of natural and semi-natural habitats to the total contribution of anthropogenic components for individual catchment types:

$$\mathrm{N}_{(FSNA+WB+W)} : \mathrm{A}_{(AA+AS)},$$

where: $\mathrm{N}_{(FSNA+WB+W)}$ is the sum of the natural components (FSNA – forests and semi-natural areas; WB – water bodies; W – wetlands); and $\mathrm{A}_{(AA+AS)}$ is the sum of anthropogenic components (AA – agricultural areas; AS – artificial surfaces).

Finally, N:A ratios were compared with the CTSI values of the coastal lakes in the studied catchments to assess the influence of land-use structure on the trophic state of the BCLs.

2.7. Statistical analysis

First, Spearman rank correlation analysis was conducted to detect correlations between each single-parameter trophic state index (TSI) and percentage contributions of the main land-use categories in the total catchment (level 1). The procedure was repeated using detailed land-cover classes (level 3). All the analyses were conducted using Statistica v.13 software (TIBCO Software Inc.).

Next, we classified the studied coastal lakes in respect of land-use structure assessed using CLC analysis. For this purpose, we applied agglomerative hierarchical clustering (AHC), followed by principal component analysis (PCA) to investigate the dispersion of data on percentage contributions of the main land-use categories in the studied catchments and values of single-parameter trophic state indices of lake water (TSI_{SD}, TSI_{TP}, TSI_{Chl} and TSI_{TOC}). Both procedures were carried out using XL_{STAT} software (Addinsoft 2021).

Finally, the significance of differences in mean Carlson's index (CTSI) of coastal lakes between the distinguished catchment types and between seasons was assessed using permutational analysis of variance (PERMANOVA) on Euclidean similarity matrix (999 permutations) with the Monte-Carlo test. Values of the predictor (CTSI) were earlier normalised, and all the analyses were conducted using PRIMER 7 software according to the procedure of Clarke & Gorley (2015)

3. Results

3.1. Trophic state

Mean Carlson's index values (CTSI) indicate that most of the lakes are eutrophic, except for Liwia Łuża and Kopań, where they exceed 70, which is characteristic of a hypertrophic state (Table 1). Among the single-parameter trophic state indices, TSI_{TP} reached the highest values, on average >80, characteristic of hypertrophic waters. In individual lakes, values of this index were highest in spring and lowest in autumn, except at Lake Resko. Values of TSI_{SD}, calculated on the basis of Secchi depth, reached on average 77 (hypertrophic). In all the analysed lakes, its values were highest in summer. TSI_{TOC} values were slightly lower, only slightly exceeding 60 on average, indicating a eutrophic state of the studied BCLs. They were highest in summer, as was TSI_{SD}. The mean level was lowest for TSI_{Chl} (below 60), indicating a eutrophic state. During this study, values of this index were higher in spring and summer than in autumn (Table 1).

3.2. Catchment structure of coastal lakes

Land-use structure in the catchments of individual BCL was characterised by a dominance of agricultural areas (AA) or forests and semi-natural habitats (FSNA), which belong to the main CLC categories (level 1). The highest contributions of AA were found in the catchments of lakes Liwia Łuża and Resko, at 77.8% and 73.2%, respectively (Figure 2). A very different land-use structure was found in the catchments of lakes Sarbsko and Gardno, where agricultural areas accounted for 44.9% and 50.9%, respectively. Simultaneously, these two catchments had the highest percentage contributions of FSNA: 48.0% in Sarbsko and 42.4% in Gardno. As for water bodies (WB), their contribution was the greatest in the catchment of Lake Kopań (20.0%) but negligible in the case of Liwia Łuża (<1%). The catchments of all the studied BCLs had relatively low contributions of artificial surfaces (AS), ranging from 2.7% (Gardno) to 5.1% (Wicko), and wetlands (W), varying from 0% (Liwia Łuża and Resko) to 4% (Kopań) (Figure 2).

All detailed information about percentage contributions of land-use categories and classes (CLC levels 1 and 3, respectively) in the catchment of each lake is given in the supplementary material (Table 2).

3.3. Catchment cover structure vs. trophic state

The analysis of Spearman's rank correlations between single-parameter trophic state indices and CLC categories (level 1) shows that they were significant only for TSI_{TP} and TSI_{TOC} (Table 3).

Significant contributions of artificial surfaces (AS) in the lake catchments were positively correlated with TSI_{TP} values (r_s=0.46), whereas large contributions of forests or semi-natural areas (FSNA) were negatively correlated with TSI_{TOC} values (r_s=-0.48). A more detailed analysis of relations between values of trophic state indices and percentage contributions of CLC classes (level 3) showed the importance of specific forms of land use in the catchment on values of TSI_{TOC} and TSI_{TP} (Table 4). Increased contributions of discontinuous urban fabric are linked with higher values of these indices (in both cases, r_s =0.42), as are, in the case of TSI_{TOC}, pastures (r_s=0.42). Simultaneously, a decrease in TSI_{TOC} is associated with growing contributions of coniferous forest (r_s=-0.56), mixed forest (r_s=-0.48), land principally occupied by agriculture with significant areas of natural vegetation (r_s=-0.44), and peat bogs (r_s=-0.40). Increasing TSI_{TP} values were significantly correlated with decreasing contributions of peat bogs (r_s=-0.43). Spearman's rank correlation matrix did not show any significant correlations of CLC classes (level 3) with TSI_{SD} and TSI_{Chl} values (Table 4). We did not find any significant influence of degree of connection with the sea on values of trophic state indices in the study lakes.

3.4. Classification of BCL catchments

Considering the results of CLC analysis and using agglomerative hierarchical clustering (AHC), three types of BCL catchment were distinguished: (C1) lakes Wicko and Kopań; (C2) lakes Sarbsko and Gardno; and (C3) lakes Liwia Łuża and Resko (Figure 3A). They differed in percentage contributions of individual CLC categories (level 1) in the direct catchment.

A comparison of catchment structure (CLC level 1) with values of trophic state indices of the BCLs was subjected to principal component analysis (PCA) (Figure 3B). In total, axes F1 and F2 explained 54.66% of variance. F1 was affected mostly by contributions of agricultural areas (AA) and of forests and semi-natural areas (FSNA), and F2 by contributions of water bodies (WB) and wetlands (W). Only high contributions of FSNA in type C2 were linked with low values of trophic state indices in BCLs (Figure 3B).

All the distinguished catchment types had low percentage contributions of artificial surfaces (AS) and wetlands (W) (Table 5). Simultaneously, all catchments included large contributions of agricultural areas (AA), which in type C3 accounted for three quarters of the catchment. In type C2, contributions of agricultural areas were similar to those of forests and semi-natural areas, whereas in type C1, all CLC categories (level 1) were considerably represented (Table 5).

In all the distinguished catchment types, the coastal lakes were classified as hypertrophic on the basis of total phosphorus content. On average, TSI_{TP} reached 89 in C1 and C3 and 79 in

C2. Furthermore, the low transparency of water in the study lakes resulted in high TSI_{SD} values, also classifying the BCLs as hypertrophic (Table 5). The other trophic state indices (TSI_{Chl} and TSI_{TOC}) exhibited values corresponding to a eutrophic state (Table 3). Their values were lowest in type C2. The mean CTSI values indicated that the water quality (hypertrophic) was lowest in catchments of types C1 and C3, but slightly better (eutrophic) in type C2.

Permutational analysis of variance (Table 6) revealed significant differences between the distinguished catchment types on the basis of CTSI values for the study lakes (p=0.001). Pair-wise tests showed that CTSI values of lake water in C2 significantly differed from those in the other types (in each case with p=0.01). In contrast, no significant difference in CTSI values was found between lakes in C1 and C3 (p=0.25). Additionally, PERMANOVA did not detect any significant differences in CTSI between seasons (spring vs. summer vs. autumn)

3.5. Patterns of the influence of land-use types

The percentage contribution of natural and semi-natural areas (N=FSNA+WB+W) compared to anthropogenic areas (A=AA+AS) in catchments affected the trophic state index values of the lakes located in them. Only in the case of similar contributions of N and A (~1:1), as in the case of type C2, was the lake water eutrophic. In the other catchment types, the trophic state index values of the coastal lakes were not improved. In C1, the N:A ratio was ~1:2, while for C3 it was ~1:4. In both cases, CTSI values markedly exceeded the threshold for hypertrophic conditions.

4. Discussion

Coastal ecosystems are open systems whose functioning depends on the supply of matter from their catchment areas but periodically also from the sea, during seawater intrusion (e.g. Astel et al., 2016; Malone & Newton, 2020; McQuatters-Gollop et al., 2009). In general, like in other shallow lakes, eutrophication is caused mostly by phosphorus, slightly by nitrogen, and only exceptionally by carbon (Stigebrandt et al., 2014; Withers et al., 2014; Zhou et al., 2022). Our results confirm this conclusion, as the major predictor of poor water quality was phosphorus (Table 1). However, the capacity to decrease its supply to the lakes is greatly limited by the current land-use structure in the individual catchments (Figure 2). Among the analysed land-cover categories (CLC level 1), none showed an ability to accumulate phosphorus in their areas (Table 3). Only the detailed analysis of land-cover classes (CLC level 3) indicated that the presence of peat bogs in catchments can limit phosphorus migration towards coastal lakes (Table 4). Simultaneously, this class of land cover can reduce the migration of organic carbon. This also happens even if its percentage contribution to the total area of the direct catchment is small, as it reached up to only ~0.05% in the analysed catchments (Table 2). Clerici et al. (2014) and Zalewski (2020) reported that wetlands are components limiting the intensity of erosion and the migration of nutrients to the lowest point of catchment. The ability for wetlands to remove nutrients from waters is based on the interception of sediments and removal of excess nutrient loads by the rich plant and animal communities living in them (DeBusk, 1999; Obolewski, 2011). Thus, they apparently act as the “kidneys” of a catchment, constituting the principal component protecting water bodies and watercourses (e.g. Amoros & Bornette, 2002; Brooks et al., 2013). For this reason, much attention has recently been paid to the protection and restoration of natural wetlands as well as the construction of artificial substitutes (Lee et al., 2005; Obolewski et al., 2018).

If the contribution of anthropogenic components (AS + AA) to the total catchment area increases, then a deterioration in lake water quality can be expected, even to the hypertrophic level. In the case of the BCLs, the major category of transformed components of catchments are agricultural areas (AS), accounting for 45–78% of the total area (Figure 2). However, their influence on the trophic state of BCLs is revealed only when detailed land-use classes are analysed (CLC level 3). Their negative impact concerns the presence of pastures (13%), which are linked with an increase in organic carbon content of water in the BCLs (Table 4). Pastures are characterised by a relatively low ability to bind organic substances under conditions of continuous grazing (Cardoso et al., 2009). They are also treated as an element of traditional farming responsible for increased nutrient concentrations in surface runoff (e.g. Haidary et al., 2013; Johnson et al., 2013; Ongley et al., 2010; Zhang et al., 2014). Simultaneously, the presence of abandoned agricultural areas (old fields, etc.) can significantly reduce organic carbon loads received by lakes (Sánchez-Sánchez et al., 2014). This effect is observed, though the mean contribution of this CLC class is only ~2% (Table 2). Thus, in the analysed catchments, it can be assumed that, in AA, the production and reduction of organic carbon are balanced.

The identified types of BCL catchments differed in land-use structure in respect of its main categories (CLC level 1, Figure 3, Table 5). Type C1 had the highest contributions of wetlands and water bodies (in total 17.4%) but, despite this, very high TSITP and TSISD values. It appears that wetlands and aquatic ecosystems in the catchment are not capable of assimilating the amounts of phosphorus and organic matter produced in areas transformed by human activity. Similarly, an unfavourable catchment structure is found in type C3, where areas of these land-cover categories are absent or negligible (Table 5). The situation is slightly improved by the presence of forests in the catchment (<20%), which can bind part of TOC (Table 3). However, most of the pollution will be deposited in the BCLs, leading to hypertrophic conditions, implying intensive phytoplankton growth (Obolewski et al., 2018) Only larger contributions of forests and semi-natural areas (FSNA) comparable with those of agricultural areas (type C2) are linked with significantly lower values of trophic state indices of BCLs (Table 5). The presence of broad-leaved and mixed forests significantly limits carbon migration, which may lead to decreased primary production in the lakes (Olson et al., 2020). This is confirmed by lower values of TSI_{Chl} in catchments of type C2 than in the other types (Table 5). Krzemińska et al. (2006) and Staniszewski et al. (2017) showed that such a catchment structure creates a buffer zone, increasing the resistance of lakes to degradation, even of those particularly prone to eutrophication, e.g. shallow coastal water bodies (Trojanowski et al., 1991). Trophic state index values of lake water in C2 significantly differed from those in C1 and C3 (Table 6). Surprisingly, seasonal variation did not influence CTSI, although changes in plant activity are obvious during the growing season. Additionally, it is noteworthy that salinity level, reflecting hydrological connection with the sea, did not significantly affect the trophic state of the study lakes. It is commonly assumed that seawater intrusion to coastal water bodies temporarily lowers the trophic state of water and improves its ecological status (Djihouessi et al., 2021; M. El Zokm et al., 2018; Paturej, 2008). However, it seems that, in the BCLs, the intensity of intrusion of brackish water from the Baltic Sea is insufficient to influence markedly their CTSI values. In the interplay of influences of terrestrial and marine waters, the former prevail, but this may change if the water level in the World Ocean rises as a result of global climate change (Prange et al., 2020). However, to limit the current eutrophication of coastal lakes, we need to undertake protective measures within the catchment. In this context, it is advisable to attempt to balance the contributions of natural and anthropogenic components of the catchment (Figure 4). The presented results indicate that, when their contributions are similar (ratio ~1:1), then the land-cover structure allows the eutrophic state to be maintained, which is natural for coastal lakes (Trojanowski et al., 1991). Obviously, it is impossible to eliminate agricultural areas and artificial surfaces from catchments, so to improve water quality in coastal lakes we need to introduce changes according to the ecohydrological concept, close to nature.

Large-scale changes in land-use structure, such as deforestation, the creation of artificial surfaces in catchments, and the straightening of shorelines and river banks, increases the transfer of nutrients and pollutants along the river–water body–sea system (Zalewski, 2020).

A crucial component of the recommended form of catchment management is the protection, restoration or construction of wetlands to limit the migration of phosphorus and organic carbon (Table 4). Its limitation can be intensified by creating buffer zones, such as wooded patches among fields, green belts or forests (Silva & Williams, 2001). In areas transformed by human activity, over-engineering should be minimised, while the contribution of grassy pitches, parks and squares should be increased to neutralise the phosphorus produced by cities and towns (Di Capua et al., 2022). Continuing to manage coastal lake catchments without properly developed protection plans based on Ecohydrological Nature-Based Solutions (EH-NbS) would lead to the disappearance of the lakes and a noticeable loss of biodiversity in the catchment.

5. Conclusions

Coastal lakes can be sites for monitoring the migration of water pollution towards the sea. They are prone to degradation, as reflected in a high trophic state of lake water. This is caused by transformations in catchments dominated by agricultural areas. Despite this, if the contributions of arable fields and forests or semi-natural habitats are balanced, then the coastal lakes within the catchments have a lower trophic state. This indicates that proper management of catchment areas can reduce human impact on its aquatic components and limit the resultant degradation of the Baltic Sea.

Coastal lakes are subject to continuously opposing terrestrial and marine influences. In this context, it is surprising that the presented results do not confirm the importance of seawater intrusion from the Baltic Sea (salinity) on the trophic state of the study lakes. It seems that the importance of intrusion is a specific feature of coastal lakes connected with saltwater seas (whereas the Baltic Sea is brackish). For this reason, in other analyses of the trophic state of coastal lakes, both the marine and terrestrial influences should be taken into account, aiming to promote harmonious cooperation between various components of the environment (catchment–lake–sea). The results of this study may be useful for shaping future procedures for catchment management in a broader system than in the case of coastal areas. Quantification of the problems of land-cover structure in catchment areas may help to develop EH-NbS programmes reducing the threats to the accessibility of high-quality water.

References

Akasaka, M., Takamura, N., Mitsuhashi, H., & Kadono, Y. (2010). Effects of land use on aquatic macrophyte diversity and water quality of ponds. *Freshwater Biology*, *55*(4), 909–922. https://doi.org/10.1111/j.1365-2427.2009.02334.x

Amiri, B. J., & Nakane, K. (2009). Modeling the Linkage Between River Water Quality and Landscape Metrics in the Chugoku District of Japan. *Water Resources Management, 23*(5), 931–956. https://doi.org/10.1007/s11269-008-9307-z

Amoros, C., & Bornette, G. (2002). Connectivity and biocomplexity in waterbodies of riverine floodplains: Connectivity and biocomplexity in riverine floodplains. *Freshwater Biology*, *47*(4), 761–776. https://doi.org/10.1046/j.1365-2427.2002.00905.x

Astel, A. M., Bigus, K., Obolewski, K., & Glińska-Lewczuk, K. (2016). Spatiotemporal assessment of water chemistry in intermittently open/closed coastal lakes of Southern Baltic. *Estuarine, Coastal and Shelf Science*, *182*, 47–59. https://doi.org/10.1016/j.ecss.2016.09.010

Brooks, K. N., Ffolliott, P. F., & Magner, J. A. (2013). *Hydrology and the management of watersheds* (4th ed). Wiley-Blackwell.

Cardoso, E. L., Silva, M. L. N., Moreira, F. M. de S., & Curi, N. (2009). Atributos biológicos indicadores da qualidade do solo em pastagem cultivada e nativa no Pantanal. *Pesquisa Agropecuária Brasileira, 44*(6), 631–637. https://doi.org/10.1590/S0100-204X2009000600012

Carlson, R. E. (1977). A trophic state index for lakes1: Trophic state index. *Limnology and Oceanography*, *22*(2), 361–369. https://doi.org/10.4319/lo.1977.22.2.0361

Cieśliński, R. (2018). Changes in hydrological, physical and chemical properties of water in closed/open coastal lakes due to hydrotechnical structures. *Oceanological and Hydrobiological Studies*, *47*(4), 345–358. https://doi.org/10.1515/ohs-2018-0033

Clarke, K., & Gorley, R. N. (2015). PRIMER v7: User manual/tutorial. PRIMER-E. *Plymouth*.

Clerici, N., Paracchini, M. L., & Maes, J. (2014). Land-cover change dynamics and insights into ecosystem services in European stream riparian zones. *Ecohydrology & Hydrobiology*, *14*(2), 107–120. https://doi.org/10.1016/j.ecohyd.2014.01.002

CORINE Land Cover. (2018). *European Environment Agency, from Copernicus Servisces.* https://land.copernicus.eu/pan-european/corine-land-cover/clc2018

DeBusk, W. F. (1999). Nitrogen Cycling in Wetlands. *Institute of Food and Agricultural Sciences. University of Florida*.

Di Capua, G., Coumou, D., van der Hurk, B., Weissheimer, A., Turner, A. G., & Donner, R. V. (2022). *Validation of boreal summer tropical-extratropical causal links in seasonal forecasts* [Preprint]. Dynamical processes in the tropics, incl. tropical–extratropical interactions. https://doi.org/10.5194/wcd-2022-48

Ding, J., Jiang, Y., Liu, Q., Hou, Z., Liao, J., Fu, L., & Peng, Q. (2016). Influences of the land use pattern on water quality in low-order streams of the Dongjiang River basin, China: A multi-scale analysis. *Science of The Total Environment*, *551–552*, 205–216. https://doi.org/10.1016/j.scitotenv.2016.01.162

Djihouessi, M. B., Tigo, B. A., & Aina, M. P. (2021). The use of nutrient budget approach for informing eutrophication management in urbanised shallow coastal lakes: A case study from Lake Nokoué in Benin. *Ecohydrology & Hydrobiology*, *21*(2), 341–353. https://doi.org/10.1016/j.ecohyd.2020.11.003

Dunalska, J. (2011). Total organic carbon as a new index for monitoring trophic states in lakes. *Oceanological and Hydrobiological Studies*, *40*(2), 112–115. https://doi.org/10.2478/s13545-011-0022-7

Fernández-Alías, A., Montaño-Barroso, T., Conde-Caño, M.-R., Manchado-Pérez, S., López-Galindo, C., Quispe-Becerra, J.-I., Marcos, C., & Pérez-Ruzafa, A. (2022). Nutrient overload promotes the transition from top-down to bottom-up control and triggers dystrophic crises in a Mediterranean coastal lagoon. *Science of The Total Environment*, *846*, 157388. https://doi.org/10.1016/j.scitotenv.2022.157388

Haidary, A., Amiri, B. J., Adamowski, J., Fohrer, N., & Nakane, K. (2013). Assessing the Impacts of Four Land Use Types on the Water Quality of Wetlands in Japan. *Water Resources Management*, *27*(7), 2217–2229. https://doi.org/10.1007/s11269-013-0284-5

Hashim, K. S., Adeola Idowu, I., Jasim, N., Al Khaddar, R., Shaw, A., Phipps, D., Kot, P., Ortoneda Pedrola, M., Alattabi, A. W., Abdulredha, M., Alwash, R., Teng, K. H., Joshi, K. H., & Hashim Aljefery, M. (2018). Removal of phosphate from River water using a new baffle plates electrochemical reactor. *MethodsX*, *5*, 1413–1418. https://doi.org/10.1016/j.mex.2018.10.024

Hatvani, I. G., Clement, A., Korponai, J., Kern, Z., & Kovács, J. (2017). Periodic signals of climatic variables and water quality in a river – eutrophic pond – wetland cascade ecosystem tracked by wavelet coherence analysis. *Ecological Indicators*, *83*, 21–31. https://doi.org/10.1016/j.ecolind.2017.07.018

Jarosiewicz, A., Obolewski, K., & Ożgo, M. (2015). Long-term trends in nutrient concentrations in Polish coastal rivers. *Ocean & Coastal Management*, *118*, 37–46. https://doi.org/10.1016/j.ocecoaman.2015.04.007

Jarosiewicz, P., Fazi, S., & Zalewski, M. (2022). How to boost Ecohydrological Nature-Based Solutions in water quality management. *Ecohydrology & Hydrobiology*, *22*(2), 226–233. https://doi.org/10.1016/j.ecohyd.2021.11.005

Johnson, R. C., Jin, H.-S., Carreiro, M. M., & Jack, J. D. (2013). Macroinvertebrate community structure, secondary production and trophic-level dynamics in urban streams affected by non-point-source pollution: Macroinvertebrate response to urban non-point-source pollution. *Freshwater Biology*, *58*(5), 843–857. https://doi.org/10.1111/fwb.12090

Kiedrzyńska, E., Kiedrzyński, M., & Zalewski, M. (2015). Sustainable floodplain management for flood prevention and water quality improvement. *Natural Hazards*, *76*(2), 955–977. https://doi.org/10.1007/s11069-014-1529-1

Krzemińska, A., Adynkiewicz-Piragas, M., & Kazimierska, R. (2006). *Assessment of oxygen conditions in lower course of the Smortawa river as the basis for evaluation of self-purification of waters with regards to the Water Framework Directive requirements.* 67–76.

Lee, B.-A., Kwon, G.-J., & Kim, J.-G. (2005). The Relationship of Vegetation and Environmental Factors in Wangsuk Stream and Gwarim Reservoir: I. Water Environments. *The Korean Journal of Ecology*, *28*(6), 365–373. https://doi.org/10.5141/JEFB.2005.28.6.365

M. El Zokm, G., R.Z. Tadros, H., A. Okbah, M., & H. Ibrahim, G. (2018). Eutrophication assessment using TRIX and Carlson’s indices in Lake Mariout Water, Egypt. *Egyptian Journal of Aquatic Biology and Fisheries*, *22*(5), 331–349. https://doi.org/10.21608/ejabf.2018.23918

Malone, T. C., & Newton, A. (2020). The Globalization of Cultural Eutrophication in the Coastal Ocean: Causes and Consequences. *Frontiers in Marine Science*, *7*, 670. https://doi.org/10.3389/fmars.2020.00670

Mashkova, I. (2022). Study of the trophic status and ecological state of the coastal zones of the natural monuments of the Chelyabinsk Region (Russia) of the Turgoyak and Uvildy Lakes. *International Journal of GEOMATE*, *23*(97). https://doi.org/10.21660/2022.97.2900

McQuatters-Gollop, A., Gilbert, A. J., Mee, L. D., Vermaat, J. E., Artioli, Y., Humborg, C., & Wulff, F. (2009). How well do ecosystem indicators communicate the effects of anthropogenic eutrophication? *Estuarine, Coastal and Shelf Science*, *82*(4), 583–596. https://doi.org/10.1016/j.ecss.2009.02.017

Mrozińska, N., Glińska-Lewczuk, K., & Obolewski, K. (2021). Salinity as a Key Factor on the Benthic Fauna Diversity in the Coastal Lakes. *Animals*, *11*(11), 3039. https://doi.org/10.3390/ani11113039

Muchová, Z., & Tárníková, M. (2018). Land cover change and its influence on the assessment of the ecological stability. *Applied Ecology and Environmental Research*, *16*(3), 5169–5182. https://doi.org/10.15666/aeer/1603_21692182

Nguyen, T., Roddick, F. A., & Fan, L. (2015). Impact of green algae on the measurement of *Microcystis aeruginosa* populations in lagoon-treated wastewater with an algae online analyser. *Environmental Technology*, *36*(5), 556–565. https://doi.org/10.1080/09593330.2014.953212

Obolewski, K. (2009). Using macrozoobenthos to assess the ecological condition of the estuary lake Jamno. *Ochrona Środowiska*, *31*, 17–24.

Obolewski, K. (2011). Composition and density of plant-associated invertebrates in relation to environmental gradients and hydrological connectivity of wetlands. *Oceanological and Hydrobiological Studies*, *40*(4), 52–63. https://doi.org/10.2478/s13545-011-0041-4

Obolewski, K., Glińska-Lewczuk, K., Bąkowska, M., Szymańska, M., & Mrozińska, N. (2018). Patterns of phytoplankton composition in coastal lakes differed by connectivity with the Baltic Sea. *Science of The Total Environment*, *631–632*, 951–961. https://doi.org/10.1016/j.scitotenv.2018.03.112

Obolewski, K., Glińska-Lewczuk, K., Szymańska, M., Mrozińska, N., Bąkowska, M., Astel, A., Lew, S., & Paturej, E. (2018). Patterns of salinity regime in coastal lakes based on structure of benthic invertebrates. *PLOS ONE*, *13*(11), e0207825. https://doi.org/10.1371/journal.pone.0207825

Olson, C. R., Solomon, C. T., & Jones, S. E. (2020). Shifting limitation of primary production: Experimental support for a new model in lake ecosystems. *Ecology Letters*, *23*(12), 1800–1808. https://doi.org/10.1111/ele.13606

Ongley, E. D., Xiaolan, Z., & Tao, Y. (2010). Current status of agricultural and rural non-point source Pollution assessment in China. *Environmental Pollution*, *158*(5), 1159–1168. https://doi.org/10.1016/j.envpol.2009.10.047

Paturej, E. (2008). Estuaries – types, role and impact on human life. *Baltic Coastal Zone. Journal of Ecology and Protection of the Coastline*, *12*, 21–37.

Prange, M., Wilke, T., & Wesselingh, F. P. (2020). The other side of sea level change. *Communications Earth & Environment*, *1*(1), 69. https://doi.org/10.1038/s43247-020-00075-6

Sánchez-Sánchez, Á., Suárez-García, F., Martínez-Alonso, A., & Tascón, J. M. D. (2014). Influence of Porous Texture and Surface Chemistry on the CO $_2$ Adsorption Capacity of Porous Carbons: Acidic and Basic Site Interactions. *ACS Applied Materials & Interfaces*, *6*(23), 21237–21247. https://doi.org/10.1021/am506176e

Shi, P., Zhang, Y., Li, Z., Li, P., & Xu, G. (2017). Influence of land use and land cover patterns on seasonal water quality at multi-spatial scales. *CATENA*, *151*, 182–190. https://doi.org/10.1016/j.catena.2016.12.017

Silva, J. J. R. F. da, & Williams, R. J. P. (2001). *The biological chemistry of the elements: The inorganic chemistry of life* (2nd ed). Oxford University Press.

Stanford, J. A., Hauer, F. R., & Ward, J. V. (1988). Serial discontinuity in a large river system: With 3 figures and 1 table in the text. *SIL Proceedings, 1922-2010*, *23*(2), 1114–1118. https://doi.org/10.1080/03680770.1987.11899780

Staniszewski, R., Jusik, S., Andrzejewska, B., & Frankowski, P. (2017). Water quality parameters of a small midforest watercourse receiving domestic sewage after treatment. *Acta Scientiarum Polonorum Formatio Circumiectus*, *1*, 161–171. https://doi.org/10.15576/ASP.FC/2017.16.1.161

Stigebrandt, A., Rahm, L., Viktorsson, L., Ödalen, M., Hall, P. O. J., & Liljebladh, B. (2014). A New Phosphorus Paradigm for the Baltic Proper. *AMBIO*, *43*(5), 634–643. https://doi.org/10.1007/s13280-013-0441-3

Teodoru, C., & Wehrli, B. (2005). Retention of Sediments and Nutrients in the Iron Gate I Reservoir on the Danube River. *Biogeochemistry*, *76*(3), 539–565. JSTOR.

Tian, Z., Zheng, B., Wang, L., Li, H., & Wang, X. (2017). Effects of river-lake interactions in water and sediment on phosphorus in Dongting Lake, China. *Environmental Science and Pollution Research*, *24*(29), 23250–23260. https://doi.org/10.1007/s11356-017-9873-9

Trojanowski, J., Trojanowska, Cz., & Korzeniewski, K. (1991). Trophic state of coastal lakes. *Polskie Archiwum Hydrobiologiczne*, *38*(1), 23–34.

Vollenweider, R. A., Giovanardi, F., Montanari, G., & Rinaldi, A. (1998). Characterization of the trophic conditions of marine coastal waters with special reference to the NW Adriatic Sea: Proposal for a trophic scale, turbidity and generalized water quality index. *Environmetrics*, *9*(3), 329–357. https://doi.org/10.1002/(SICI)1099-095X(199805/06)9:3<329::AID-ENV308>3.0.CO;2-9

Whitehouse, R., Soulsby, R., Roberts, W., & Mitchener, H. (2000). *Dynamics of estuarine muds: A manual for practical applications*. Thomas Telford Publishing. https://doi.org/10.1680/doem.28647

Withers, P. J. A., Sylvester-Bradley, R., Jones, D. L., Healey, J. R., & Talboys, P. J. (2014). Feed the Crop Not the Soil: Rethinking Phosphorus Management in the Food Chain. *Environmental Science & Technology*, *48*(12), 6523–6530. https://doi.org/10.1021/es501670j

Zalewski, M. (2020). *Ekohydrologia*. Wydawnictwo Naukowe PWN, Warszawa.

Zhang, Y., Li, F., Zhang, Q., Li, J., & Liu, Q. (2014). Tracing nitrate pollution sources and transformation in surface- and ground-waters using environmental isotopes. *Science of The Total Environment*, *490*, 213–222. https://doi.org/10.1016/j.scitotenv.2014.05.004

Zhou, J., Leavitt, P. R., Zhang, Y., & Qin, B. (2022). Anthropogenic eutrophication of shallow lakes: Is it occasional? *Water Research*, *221*, 118728. https://doi.org/10.1016/j.watres.2022.118728

Figure captions

Figure 1. Location of the studied Baltic coastal lakes and outlines of their catchments (area in km^2)

Figure 2. Land-use structure in the studied lake catchments, determined by the percentage contributions of CORINE land cover (CLC) categories (level 1)

Figure 3. (A) Dendrogram resulting from agglomerative hierarchical clustering (AHC) of catchments of Baltic coastal lakes, based on the dissimilarity matrix of Euclidean distances (Ward's method of agglomeration) for percentage contributions of land-cover categories (CLC level 1). (B) Principal component analysis (PCA) for percentage contributions of land-cover categories (CLC level 1) in the study lake catchments and single-parameter trophic state indices (TSI)

Figure 4. (A) Functioning of coastal lakes with current level of human impact and catchment structure; (B) Method of changing catchment structure to diminish human impact and reduce nutrient loading of lakes

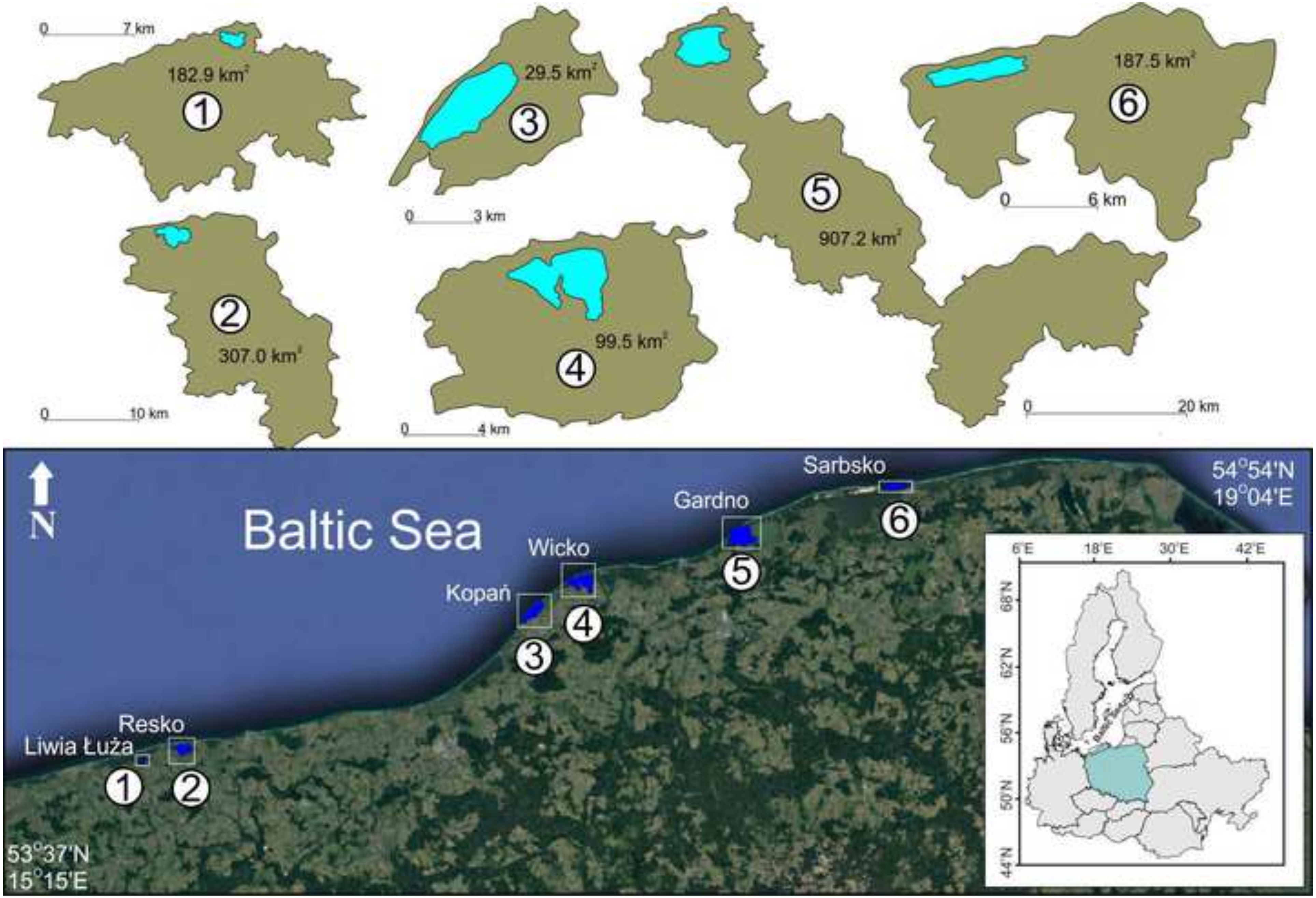
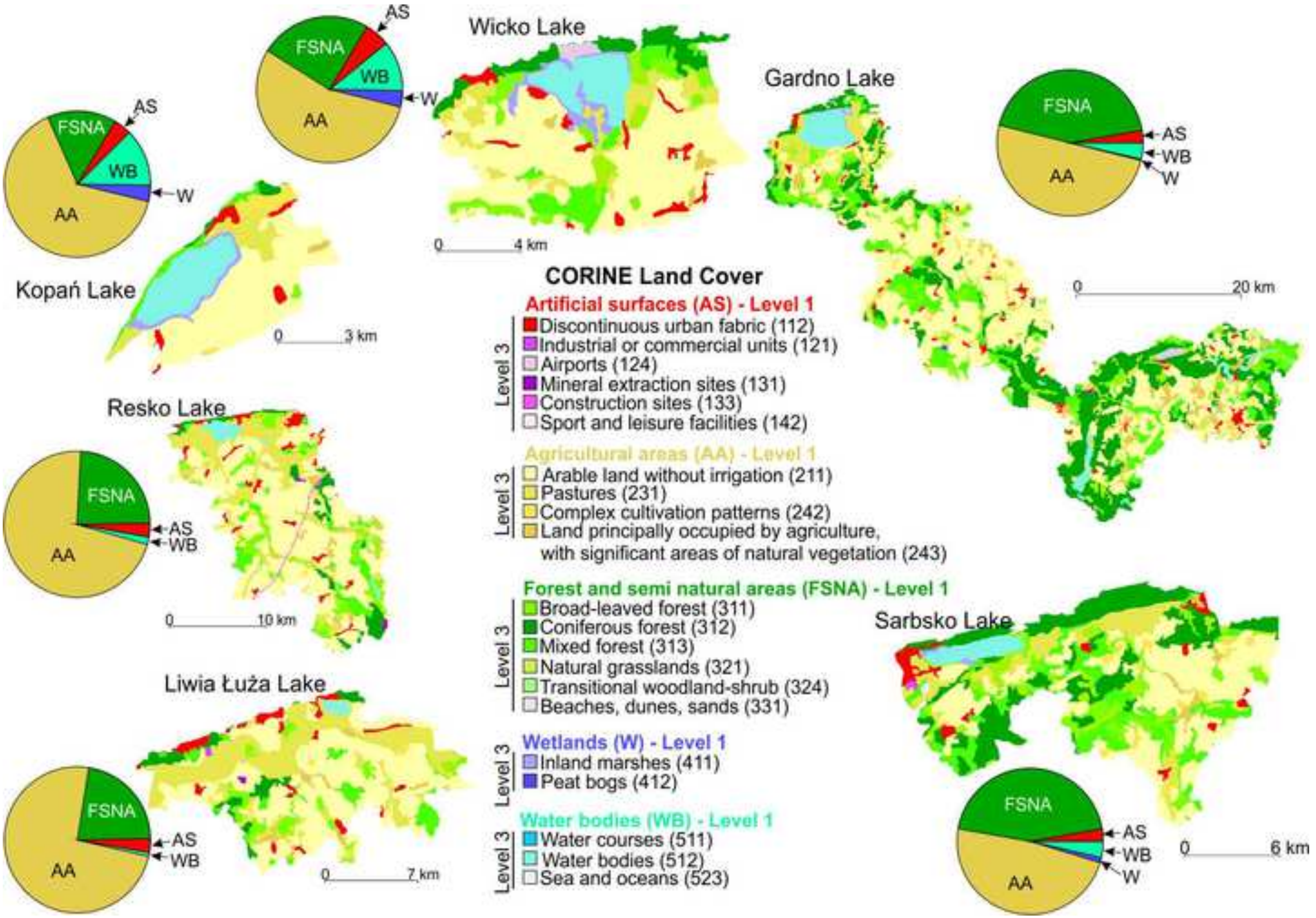

0 7 km
182.9 km²
①
29.5 km²
③
0 3 km
⑤
907.2 km²
187.5 km²
⑥
0 6 km
②
307.0 km²
0 10 km
99.5 km²
④
0 4 km
0 20 km
N
Baltic Sea
Sarbsko
54°54'N
19°04'E
Gardno
Wicko
Kopań
Resko
Liwia Łuża
53°37'N
15°15'E
6°E
18°E
30°E
42°E
68°N
62°N
56°N
50°N
44°N
Baltic Sea

Figure 2


Wicko Lake
Gardno Lake
Kopań Lake
Resko Lake
Liwia Łuża Lake
Sarbsko Lake
FSNA
AA
AS
WB
W
0 4 km
0 20 km
0 3 km
0 10 km
0 7 km
0 6 km
CORINE Land Cover
Artificial surfaces (AS) - Level 1
Level 3
Discontinuous urban fabric (112)
Industrial or commercial units (121)
Airports (124)
Mineral extraction sites (131)
Construction sites (133)
Sport and leisure facilities (142)
Agricultural areas (AA) - Level 1
Level 3
Arable land without irrigation (211)
Pastures (231)
Complex cultivation patterns (242)
Land principally occupied by agriculture, with significant areas of natural vegetation (243)
Forest and semi natural areas (FSNA) - Level 1
Level 3
Broad-leaved forest (311)
Coniferous forest (312)
Mixed forest (313)
Natural grasslands (321)
Transitional woodland-shrub (324)
Beaches, dunes, sands (331)
Wetlands (W) - Level 1
Level 3
Inland marshes (411)
Peat bogs (412)
Water bodies (WB) - Level 1
Level 3
Water courses (511)
Water bodies (512)
Sea and oceans (523)

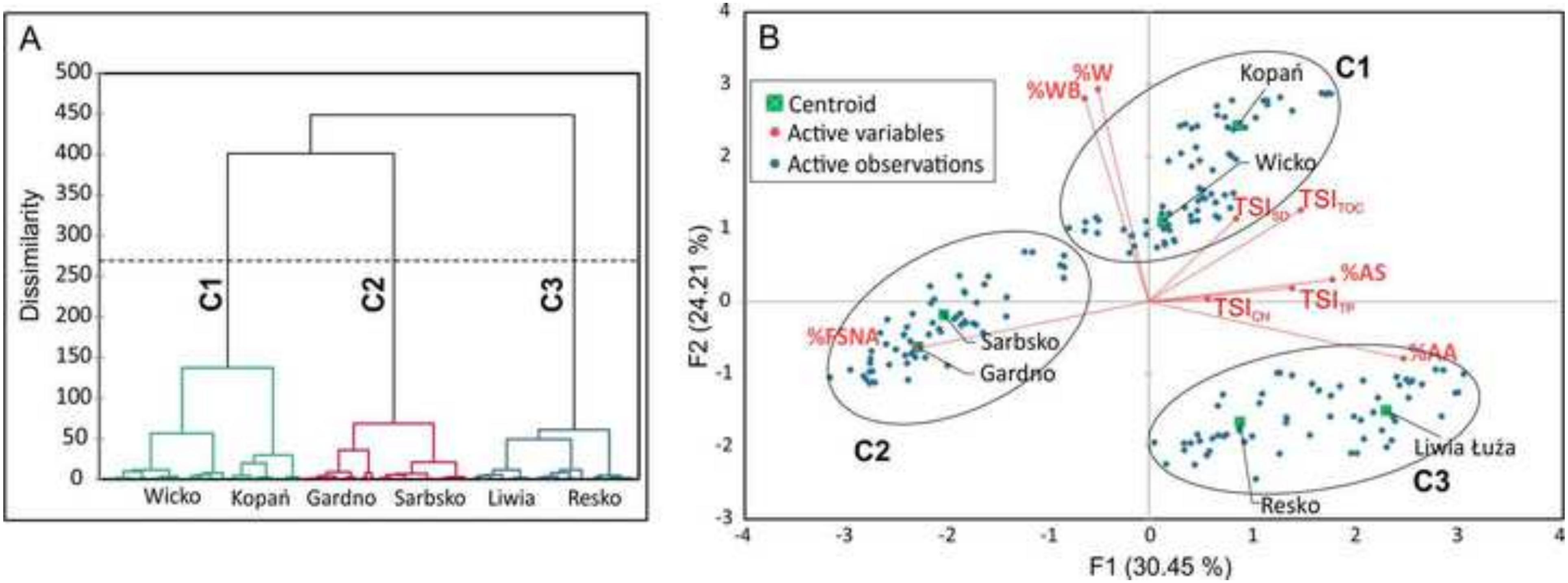

A
Dissimilarity
500
450
400
350
300
250
200
150
100
50
0
C1
C2
C3
Wicko
Kopań
Gardno
Sarbsko
Liwia
Resko
B
Centroid
Active variables
Active observations
%W
%WB
Kopań
C1
Wicko
TSI$_{SD}$
TSI$_{TOC}$
%AS
TSI$_{TP}$
TSI$_{CH}$
%FSNA
Sarbsko
Gardno
%AA
C2
Liwia Łuża
C3
Resko
F2 (24.21 %)
F1 (30.45 %)
4
3
2
1
0
-1
-2
-3
-4
-3
-2
-1
0
1
2
3
4

Figure 4

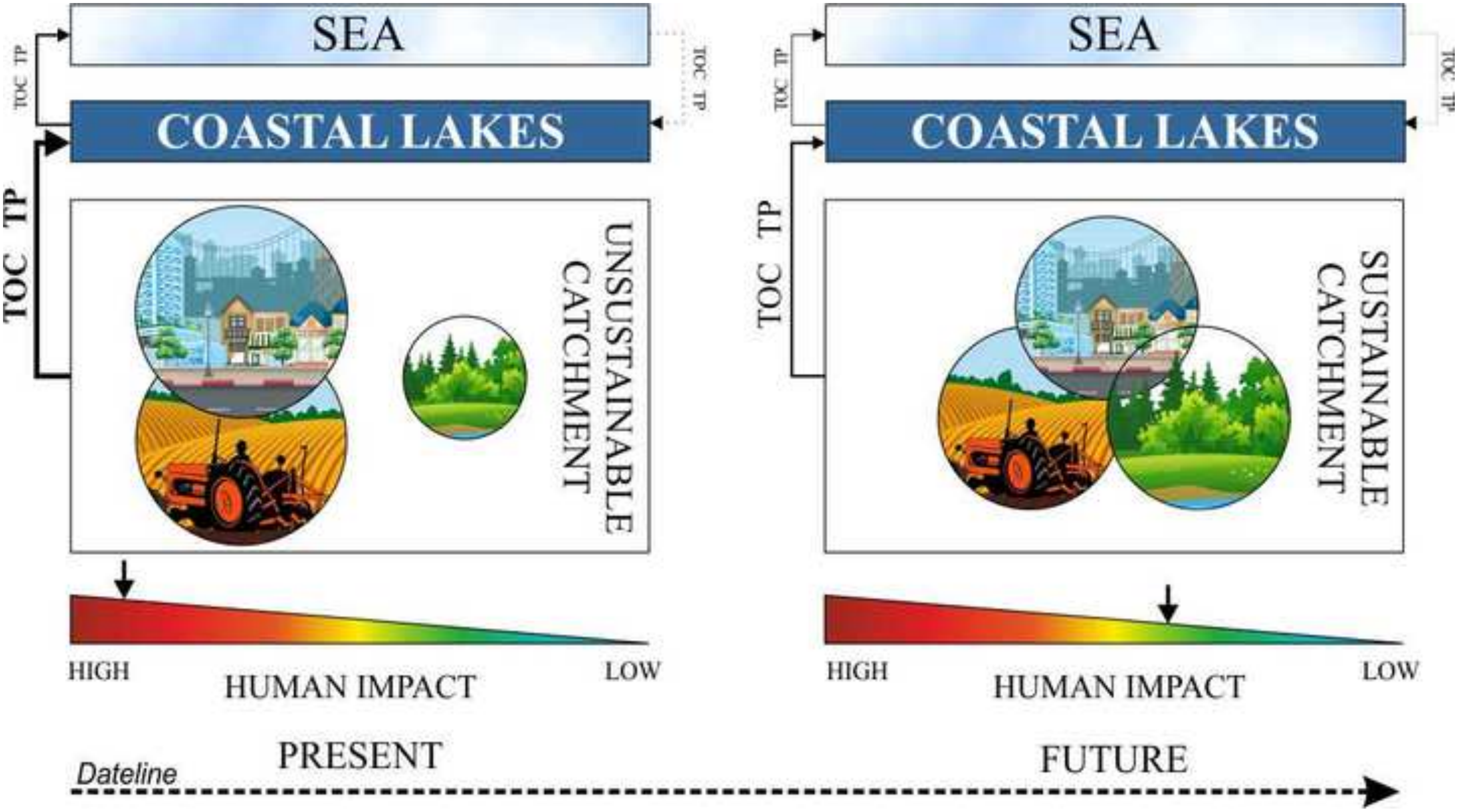

SEA
TOC TP
COASTAL LAKES
TOC TP
TOC TP
UNSUSTAINABLE CATCHMENT
HIGH
HUMAN IMPACT
LOW
SEA
TOC TP
COASTAL LAKES
TOC TP
TOC TP
SUSTAINABLE CATCHMENT
HIGH
HUMAN IMPACT
LOW
Dateline
PRESENT
FUTURE

Table 1. Seasonal variation in mean (±SD) values of single-parameter trophic state indices and mean Carlson's trophic state index (CTSI) for the studied Baltic coastal lakes (total n=192).

Lake	Season	Trophic state indices				CTSI
		TSI$_{SD}$	TSI$_{TP}$	TSI$_{Chl}$	TSI$_{TOC}$	
Liwia Łuża	Spring	73±2	96±10	60±14	65±6	73^{H}±5
n=30	Summer	84±3	88±7	57±12	73±7	75^{H}±4
	Autumn	71±24	78±28	54±22	60±20	66^{E}±23
	Total	**76±16**	**87±15**	**57±16**	**66±11**	**71^{H}±11**
Resko	Spring	73±3	88±7	55±11	57±4	68^{E}±4
n=30	Summer	79±4	89±9	60±11	62±8	72^{H}±5
	Autumn	76±4	89±8	57±13	59±5	70^{E}±6
	Total	**76±4**	**89±8**	**57±11**	**59±6**	**70^{E}±5**
Kopań	Spring	75±6	91±5	58±11	66±4	72^{H}±3
n=30	Summer	82±2	85±8	58±11	72±6	74^{H}±5
	Autumn	75±25	76±27	53±21	69±24	68^{E}±23
	Total	**77±11**	**84±13**	**56±14**	**69±11**	**71^{H}±10**
Wicko	Spring	70±20	88±25	58±21	54±15	67^{E}±19
n=42	Summer	78±2	85±12	60±15	64±3	72^{H}±7
	Autumn	73±20	86±25	57±20	59±17	69^{E}±20
	Total	**74±14**	**86±21**	**58±19**	**59±12**	**69^{E}±15**
Gardno	Spring	77±5	79±4	56±8	52±8	66^{E}±4
n=30	Summer	77±6	72±13	55±8	58±6	66^{E}±5
	Autumn	64±21	67±23	51±19	51±18	58^{E}±20
	Total	**73±11**	**73±13**	**54±11**	**54±11**	**63^{E}±10**
Sarbsko	Spring	70±2	85±8	62±16	58±10	69^{E}±6
n=30	Summer	79±2	81±17	63±17	59±6	71^{H}±7
	Autumn	75±25	75±27	56±24	61±21	67^{E}±23
	Total	**75±10**	**80±17**	**60±19**	**59±12**	**69^{E}±12**

Note: E – eutrophy; H – hypertrophy

Table 2. Percentage contributions of land-use classes (CLC levels 3) in the catchment of each lake.

		Type of catchment					
		C1		C2		C3	
		Wicko	Kopań	Sarbsko	Gardno	Liwia Łuża	Resko
AS%	Discontinuous urban fabric	3.98	3.85	3.29	2.27	4.48	3.56
	Mineral extraction sites	0.00	0.00	0.00	0.04	0.14	0.27
	Industrial or commercial units	0.00	0.00	0.17	0.03	0.17	0.00
	Sport and leisure facilities	0.00	0.00	0.14	0.06	0.00	0.00
	Construction sites	0.00	0.00	0.00	0.00	0.00	0.72
	Airports	1.09	0.00	0.00	0.31	0.00	0.00
FSNA%	Coniferous forest	7.69	1.68	22.97	24.10	5.03	5.35
	Mixed forest	6.46	4.40	13.42	10.87	4.72	5.70
	Broad-leaved forest	6.26	0.50	6.98	5.17	5.91	7.21
	Transitional woodland-shrub	2.86	0.00	4.38	2.15	0.77	1.94
	Beaches, dunes, sands	0.17	0.00	0.22	0.10	0.00	0.00
AA%	Non-irrigated arable land	48.12	50.50	31.79	39.22	46.92	50.88
	Pastures	9.16	9.94	9.57	6.74	27.82	18.63
	Land principally occupied by agriculture	1.11	0.72	1.38	3.95	2.18	3.08
	Complex cultivation patterns	0.49	4.50	2.15	0.99	0.91	0.56
W%	Inland marshes	3.80	3.95	0.40	0.18	0.00	0.00
	Peat bogs	0.00	0.00	0.00	0.05	0.00	0.00
WB%	Water bodies	8.80	19.96	3.16	3.79	0.96	2.07

Table 3. Spearman's rank correlation coefficients between the single-parameter trophic state indices and CORINE land cover (CLC) categories (level 1). (Correlation coefficients marked with asterisks are statistically significant with $p<0.05$; those in bold are the most significant).

CLC categories (level 1)	Trophic state indices			
	TSI_{SD}	TSI_{Chl}	TSI_{TP}	TSI_{TOC}
Artificial surfaces (AS)	0.06	0.06	**0.46**	0.18
Agricultural areas (AA)	0.11	0.02	0.30*	0.33*
Forests and semi-natural areas (FSNA)	-0.21	0.00	-0.25	**-0.48**
Wetlands (W)	0.15	-0.03	0.04	0.21
Water bodies (WB)	0.09	-0.06	-0.02	0.08

Table 4. Spearman's rank correlation coefficients between the single-parameter trophic state indices and CORINE land-cover (CLC) classes (level 3). (Correlation coefficients marked with asterisks are statistically significant with $p<0.05$; those in bold are the most significant).

CLC categories (level 1) and classes (level 3)		Trophic state indices			
Level 1	Level 3	TSI$_{\text{SD}}$	TSI$_{\text{Chl}}$	TSI$_{\text{TP}}$	TSI$_{\text{TOC}}$
AS	Airports	-0.13	-0.03	0.01	-0.33
	Construction sites	-0.11	-0.03	0.11	-0.22
	Discontinuous urban fabric	0.17	0.07	**0.42**	**0.42**
	Industrial or commercial units	-0.02	0.07	-0.23	0.00
	Mineral extraction sites	-0.12	-0.01	-0.01	-0.16
	Sport and leisure facilities	-0.12	-0.00	-0.39	-0.29
	Beaches, dunes, sands	-0.10	0.03	-0.10	-0.28
FSNA	Broad-leaved forest	-0.14	0.04	0.16	-0.29
	Coniferous forest	-0.24	-0.02	-0.31	**-0.56**
	Mixed forest	-0.21	0.00	-0.25	**-0.48**
	Transitional woodland-shrub	-0.16	0.03	-0.07	-0.39
AA	Complex cultivation patterns	0.14	-0.02	-0.28	0.26
	Agriculture with areas of natural vegetation	-0.24	-0.02	-0.26	**-0.44**
	Non-irrigated arable land	0.06	-0.04	0.29	0.13
	Pastures	0.15	0.06	0.26	**0.42**
W	Inland marshes	0.15	-0.03	0.04	0.21
	Peat bogs	-0.18	-0.07	**-0.43**	**-0.40**
WB	Sea and ocean (=hydrological connectivity)	0.13	0.05	0.36	0.35
	Water bodies	0.09	-0.06	-0.02	0.08

Table 5. Mean percentage (±Standard Deviation) contributions of CORINE land cover categories (CLC level 1) and trophic state index values in catchment types of Baltic coastal lakes (C1–3).

		CATCHMENT TYPE		
		C1	**C2**	**C3**
CLC	AS (%)	4.6	3.2	4.7
	AA (%)	61.7	47.9	75.5
	FSNA (%)	16.4	45.2	18.3
	W (%)	3.9	0.3	0
	WB (%)	13.5	3.5	1.5
TSI_{SD}	mean	78^H	76^H	77^H
	±SD	4	6	5
	range	69–83	65–88	67–87
TSI_{TP}	mean	89^H	79^H	89^H
	±SD	9	11	9
	range	67–104	54–105	72–111
TSI_{Chl}	mean	60^E	59^E	58^E
	±SD	12.23	12.90	12.15
	range	47–93	47–94	48–84
TSI_{TOC}	mean	66^E	58^E	64^E
	±SD	7	8	7
	range	53–87	39–75	45–91
CTSI	mean	73^H	68^E	72^H
	±SD	5	6	5
	range	63–84	58–86	63–86

Note: E – eutrophy; H – hypertrophy

Table 6. Permutational analysis of variance (PERMANOVA) results testing the effects of catchment types (C1, C2 and C3) and seasons (spring, summer and autumn) on mean Carlson's trophic state index (CTSI) in Baltic coastal lakes, based on the Euclidean similarity matrix, *p*(MC); *p*-value obtained with Monte Carlo permutation test. Bold values indicate significance (p<0.05).

	Source of variation	df	SS	MS	Pseudo *F*-values	*p*(MC)
CTSI	Type of catchment	2	909.0	454.5	14.827	**0.001**
	Season	2	82.1	41.1	1.340	0.25
	Type x season	4	93.7	23.4	0.765	0.58
	Residual	183	5609.7	30.7		
Pair-wise test						
Catchment types compared						
	C1 x C2				5.163	**0.001**
	C1 x C3				1.184	0.25
	C2 x C3				3.776	**0.001**

Conflict of Interest:

None declared.

Ethical Statement:

The research was done according to ethical standards.

Acknowledgements:

The authors are grateful to Sylwia Ufnalska and Tim Brombley for comments on the manuscript. This study was supported by the Polish Minister of Education and Science under the program “Regional Initiative of Excellence” in 2019–2023 (Grant No. 008/RID/2018/19)

Funding Body:

Minister of Science and Higher Education (Poland)

Author Agreement Statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. She is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs

Signed by all authors as follows:

Bydgoszcz, 12th January 2022

Szymańska - Walkiewicz
…………………………………………
Monika Szymańska-Walkiewicz
Correspondig author

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: