Anthropogenic features of salt marsh flora with varying substrate salinity, human impact and abundance of halophytes

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Abstract. The paper presents an assessment of the degree of flora synanthropization of salt marshes along the Noteć Canal in the vicinity of the soda works in Mątwy and Janikowo, the salt mine in Góra, and at the salt works and spa in Inowrocław, vestern Kuyavia. Salt marshes were located mainly along pipelines that supply brine from the mine to industrial production, medical care and recreation and pipelines that carry saline industrial and municipal wastewater to places of its disposal and, after preliminary treatment, to the Vistula River.

In previous studies, we recorded the occurrence of 117 vascular plant species, which we assigned to geographical–historical groups. In this work, we present the results of further analysis, which includes the comparison of the salt marsh flora in terms of synanthropization indices with the flora of 55 natural and artificial sites from different regions of Poland.

The flora of the compared sites developed under varying substrate moisture, history of use and intensity of human impact. The range of variability of these factors was extensive, as these were both natural and degraded ecological systems, including those developed on artificial substrates. Both facultative and obligate, halophytes played an essential role in the floristic composition of many of these sites.

Numerical classification of a set of 56 floras characterised based on the values of 13 indices showed that, in terms of the degree of synanthropization, the flora of investigated salt marshes is most similar to the floras of meadows occurring in other regions of Poland, both to those in the vicinity of industrial plants and those of artificial biotopes. Numerical ordination, however, showed that the indices of permanent synanthropization and total synanthropization, as well as the index of apophytism of spontaneophytes, contributed most to the variability. Differences in the values of 13 indices of synanthropization of selected floras from the five main subgroups distinguished in the numerical classification and ordination are presented by the graphical method.

Keywords: flora, salt marshes, saline water, soil salinity, indices of flora synanthropization, numerical classification, ordination.

1. Introduction

The Kuyavia region is one of the main areas of salt marshes in Poland. They are distributed around sites associated with the extraction of saline water and its use in the production of salt in salt works, the production of soda in two large chemical plants, as well as in sanatorium treatment and recreation. A place with a widespread and abundant occurrence of halophytes is the western part of Kuyavia, where most mining, industrial and healthcare facilities are located. This area is also the site of intensive botanical research on the occurrence of halophytic vegetation. The history of research in this area has recently been described in detail by W. Karasińska et al. in *Ecological Questions* (Karasińska et al., 2021). In the following paper of this series (Karasińska et al., 2024), we presented the structure of plant communities formed at sites of leakage of brine extracted from the Góra mine and distributed through pipelines to industrial plants and hydrotherapy and sanatorium centers, as well as at sites of leakage of saline industrial wastewater piped from these centers to disposal sites and, after pretreatment, to rivers. We have designated the area encompassing the above-mentioned technical infrastructure and the salt marshes developing next to it, located in the Noteć River valley and by the Noteć Canal, as study area N.

In the latter work, we presented a numerical classification of 611 relevés taken on 215 salt marshes in the study area N in 1998–2001. The species composition of the 16 main groups of relevés distinguished by TWINSPAN (Hill, 1979; Hill & Šmilauer, 2005) was compared with the species composition of associations and plant communities characterised by Wilkoń-Michalska (1963) on salt marshes of the entire Kuyavia region, using the standard phytosociological method of Braun-Blanquet (1951).

In addition to syntaxonomic analyses, the cited work also presents a floristic analysis. A list of vascular plant species present in the set of relevés taken on the salt marshes was prepared and the affinity of species with geographical–historical groups distinguished according to the criteria defined by Kornaś (1968) and Mirek (1981) was determined. A geographical and historical classification, based on the origin and degree of domestication of the species: 1 – non-synanthropic spontaneophytes (native species, found exclusively on natural and semi-natural habitats); 2 – synanthropic spontaneophytes, or apophytes (i.e. native species, established in anthropogenic habitats); 3 – archaeophytes (species that arrived or originated before 1492, i.e. permanent domesticates); 4 – neophytes (also known as kenophytes, species that arrived or became established after 1492, i.e. permanent domesticates); 5 – diaphytes (plant species of alien origin, which are temporarily present in the flora of Poland and have failed to establish permanently). In the latter respect, two groups of plants are distinguished: ephemerophytes – temporarily adventive species, and ergaziophygophytes – species of cultivated plants that escaped from cultivation and became naturalized.

Quantitative relationships between the number of species in the five main historical–geographical groups can be used as a basis for assessing the degree of synanthropization of the flora. A method of making such an assessment based on calculating the values of 13 indices (see next chapter) was proposed by B. Jackowiak, who used it to assess the synanthropization of the flora in the city of Poznań (Jackowiak, 1990).

So far, the method has mainly been used to assess the flora of individual natural sites, and less frequently to make comparisons of indices between the flora of different areas. For example, Kamiński (2014) calculated the indices for the flora growing contemporaneously in historical areas of medieval earthworks located in the Chełmno Land and compared them with the values of indices calculated for analogous earthworks in Greater Poland based on floristic data published by Celka (1999). The former author also compared the values of indices obtained for earthworks with the values of the flora of other natural objects in the Chełmno Land and in Greater Poland with different legal protection status and varied impact of anthropogenic factors ("Płutowo" forest reserve, "Zbocza Płutowskie" xerothermic vegetation reserve, Greater Poland National Park, Gniezno Lake District). On the other hand, the assessment of changes in values of indices in time rather than space was made by Nienartowicz et al. (2010). The authors compared the values of indices for heaths growing on the Zadroże Dune near the city of Toruń in 1948 and for a pine forest developed 45 years after the dune was afforested in 1963. Comparisons of indices for agricultural areas were carried out by Kutyna and Malinowska (2011), who assessed values of indices for the flora of winter cereal crops and several years' old fallow land in Western Pomerania. In a broader scope, values of indices for floras of natural sites in Western Pomerania and Greater Poland were compared by Kutyna et al. (2013). On the basis of the comparisons made and the results obtained, the authors defined ranges of variability for the floras of areas with different conservation status and different intensity of human impact, and consequently with different land use and land vegetation cover.

So far, indices have not been calculated for the saltmarsh flora. The objective of the present study is to fill this gap by making such assessments and answering the following ecological questions:

1. What is the value of the synanthropization indices for the saltmarsh flora in the area of intensive extraction, use and processing of brine in the western part of Kuyavia?

2. To the floras of which areas with saline or non-saline substrate, protected or unprotected and with varying effects of human impact, does the set of indices of the flora we studied show the greatest similarity?
3. What are the differences in the values of indices calculated for the flora of salt marshes from different regions of Poland, especially inland salt marshes, usually occurring in the vicinity of industrial and urban areas, and for the flora of coastal salt marshes subjected to lesser human impact?
4. Which of the 13 indices analyzed contribute most to the variability of the sets of the natural sites compared?

2. Materials and methods

The baseline data for the analysis, i.e. the floristic list, was obtained from Table 1A provided in the Appendix to the paper by Karasińska et al. (2024). The floristic list for the salt marshes of the N area included 118 vascular plant species, each with a defined affinity to a specific geographic–historical group, as well as six cultivated plant species. To maintain the comparability of our data with the flora of other areas, cultivated plant species were omitted in the analysis. The cited article and the previous work by Karasińska et al. (2021) provide a detailed description of the study area referred to as study area *N*, including in particular its vegetation.

The affinity of species with geographical and historical groups was mainly based on the study by Chmiel (1993) and Celka (1999). To assess the degree of synanthropization of the studied flora, the coefficients defined by Jackowiak (1990) and used, among others, by Nienartowicz et al. (2010) and Kamiński (2014) were applied; they represent the percentage of specific geographical and historical groups calculated in relation to the entire analyzed flora.

The following indices were calculated:

total synanthropization index (*WSc*):

$$WSc = \frac{Ap+A}{Sp+Ap+A} \times 100\% \quad (1)$$

permanent synanthropization index (*WSt*):

$$WSt = \frac{Ap+M}{Sp+Ap+M} \times 100\% \quad (2)$$

total apophytization index (*WApc*):

$$WApc = \frac{Ap}{Sp+Ap+A} \times 100\% \quad (3)$$

permanent apophytization index (*WApt*):

$$WApt = \frac{Ap}{Sp+Ap+M} \times 100\% \quad (4)$$

spontaneophyte apophytism index (*WAp*):

$$WAp = \frac{Ap}{Sp+Ap} \times 100\% \quad (5)$$

total anthropophytization index (*WAnc*):

$$WAnc = \frac{A}{Sp+Ap+A} \times 100\% \quad (6)$$

permanent anthropophytization index (*WAnt*):

$$WAnt = \frac{M}{Sp+Ap+M} \times 100\% \quad (7)$$

total archaeophytization index (*WArc*):

$$WArc = \frac{Ar}{Sp+Ap+A} \times 100\% \quad (8)$$

permanent archaeophytization index (*WArt*):

$$WArt = \frac{Ar}{Sp+Ap+M} \times 100\% \quad (9)$$

total kenophytization index (*WKc*):

$$WKc = \frac{Kn}{Sp+Ap+A} \times 100\% \quad (10)$$

permanent kenophytization index (*WKt)*:

$$WKt = \frac{Kn}{Sp+Ap+M} \times 100\% \quad (11)$$

flora modernization index (*WM*):

$$WM = \frac{Kn}{M} \times 100\% \quad (12)$$

index of fluctuating changes (*WF)*:

$$WF = \frac{Df}{Sp+Ap+A} \times 100\% \quad (13)$$

The symbols used in the above equations denote the following species groups: *Sp* – non-synanthropic spontaneophytes; *Ap* – synanthropic spontaneophytes, or apophytes; *Ar* – archaeophytes; *Kn* – kenophytes; *Df* – diaphytes; *A* – anthropophytes (*Ar*+*Kn*+*Df*), *M* – metaphytes (*Ar*+*Kn*). Metaphytes (from the ancient Greek: μετα beyond something, φυτόν plant) represent those alien species (anthropophytes) that are permanently established in a given flora, i.e. successfully reproduce in that flora and are therefore able to survive in it for a long time (https://atlas-roslin.pl, 2023). The total number of species in the analyzed dataset was as follows: $T = Sp + Ap + Ar + Kn + Df = Sp + Ap + A$.

The flora of salt marshes occurring in the study area was compared by numerical taxonomy methods in terms of the 13 above-mentioned indices with the flora of 55 other natural sites, including 19 sites with varying but usually significant cover of saline vegetation and proportion of halophytes, both obligate and facultative. Twenty six sites selected for comparison lacked such vegetation. The large dataset comprised floras of ecological systems occupying different positions in gradients of salinity and soil moisture, as well as in gradients of naturalness and intensity of human impact. The latter gradient covered a series of sites ranging from natural and legally protected sites with high nature conservation status, through highly transformed agricultural and urbanized areas, to sites with almost entirely artificial substrate developed as a consequence of soda industry waste dumps in two distant regions of Poland. The selection of sites for the comparison was based on the principle that the set representing them should be large and diverse, and that the classification of the components of the flora of each site should be complete, i.e. include all categories of geographical and historical groups of species, and that these species should be distinguished according to the principles given in the works of florists from the Poznań academic center (Jackowiak, 1990; Chmiel, 1993; Celka, 1999). Following these principles made it possible to determine the range of values for each of the 13 indices of flora synanthropization for Poland, to compare the values of the indices for areas exposed to similar anthropogenic factors but located in different regions of Poland, and, above all, to find answers to the questions formulated in the introductory chapter of this paper.

The location, names and codes for all 56 floras compared are provided in Figure 1 and Table A1 in the Appendix to this work. The codes of floras with a significant contribution of halophytes contain a capital letter S. In contrast, the codes of floras in which halophytes were also present, but with lower frequency and abundance, contain a lower-case letter s.

Figure 1. Location of study area N and other 55 sites in Poland with floras included in the comparative analysis. Explanations: rectangle N denotes our study area, numbers in circles denote the location of floras from large areas, uncircled numbers denote the location of floras from small areas.

The numbering of sites with the name of the corresponding region, site name and code (written in brackets) is as follows: 1 – Western Kuyavia, 'Źródła rzeki Gąsawki' nature reserve (P1f); 2 – Tuchola Forest, 'Uroczysko Kiełpinek' ecological site (E1); 3 – Pomerania, Słowińskie Coast, Słowiński National Park and Biosphere Reserve (P2s); 4 – Greater Poland (Wielkopolska), planned nature reserve 'Łąki Pyzdrskie' (M1s); 5 – Greater Poland, Wielkopolska National Park (P3); 6 – Pomerania Baltic coast, coastal halophyte communities (S1); 7 – Pomerania Baltic coast, coastal salt marshes fed by brine (S2); 8 – Southern Kuyavia, vegetation of hydrogenic soils, anthropogenic origin (K1w); 9 – NE Greater Poland, all nature reserves (P4); 10 – Pomerania Baltic coast near Gdynia city, 'Mechelińskie Łąki' nature reserve (P5s); 11– Pomerania, Chełmno Land, 'Zbocza Płutowskie' nature reserve (P6x); 12 – Greater Poland, the village of Folusz, planned nature reserve of xerothermic vegetation (X1); 13 – Greater Poland, Gniezno Lakeland, total flora (V1); 14 – Western Pomerania, small water bodiesin agricultural landscape (K2w); 15 – Western Kuyavia, 'Ostrów Małe Rudy' habitat in the Noteć river valley, xerothermic flora (X2); 16 – Western Kuyavia, Gopło Millennium Landscape Park (P7s); 17 – Pomerania, Żuławy Wiślane, banks of the Wisła Królewiecka River and the estuary of Szkarpawa River (G1s); 18 – Western Kuyavia saline meadows in the Noteć river Valley (S3); 19 – Pomerania and Kuyavia, small water bodies in agricultural landscape – kettleholes (K3w); 20 – Pomerania, western coast of the Bay of Puck (V2s); 21 – Kuyavia, Gniewkowo terrain depressions, shores of periodic floodplains in agricultural landscape (K4w); 22 – NE Greater Poland, flora of protected areas (P8); 23 – Poland, flora of salt marshes (S4); 24 – Eastern Kuyavia, Zgłowiączka river valley (M2s); 25 Pomerania, south-eastern shore of the Vistula Lagoon (G2s); 26 – Pomerania, Słowiński National Park, flora of former military area (R1t); 27 – Greater Poland, Główna River catchment, total flora (V3); 28 – Greater Poland, flora of nonprotected areas (O1v); 29 – Pomerania, Żuławy Wiślane, estuarine section of Vistula (W1); 30 – Greater Poland, Główna River catchment, 'Bogdanka I' and 'Bogdanka II' ecological sites (E2); 31 – Greater Poland, Główna River catchment, litoral flora of water reservoirs (W2); 32 – Kuyavia, halophytic communities of Kuyavia (S5); 33 – Pomerania, South Baltic Lakeland, shores of water bodies and ponds in agricultural landscape (K5w); 34 – Greater Poland, Główna River catchment, flora of humid grasslands (M3); 35 – Kuyavia, 'Ciechocinek' nature reserve of halophytes in 1954-1965 (P9s); 36 – Lesser Poland, Kraków, meadows in Wieliczka flooded by brine (S6); 37 – Pomerania Lower Vistula Valley Landscape Park, synanthropic flora (P10); 38 - Pomerania, Żuławy Wiślane, flora of bank protection structures of the Wisła Śmiała River (W3s); 39 - Greater Poland, Główna River catchment, anthropogenic biotopes with aquatic and reed vegetation (W4); 40 – Lesser Poland, Kraków, meadows near the 'Bonarka' superthomasine factory (M4); 41 – Western Kuyavia, salt marsh vegetation on the banks of the Noteć River and the Noteć Canal (N-S7); 42 – Greater Poland, Główna River catchment, biotopes with herbaceous, meadow, grasland and rural vegetation (M5); 43 – Greater Poland, Główna River catchment, mesophilous meadows and grasslands (M6); 44 – Pomerania, Żuławy Wiślane, segetal flora of the entire region and ruderal flora of villages (A1); 45 – Western Pomerania, the town of Maszewo, flora of gravel pit (I1); 46 – Greater Poland, Konin Brown Coal Basin, *Plantaginetalia majoris* plant communities (I2s); 47 – Kuyavia, Aleksandrów, Nieszawa and Włocławek, ruderal plant communities of three towns ((U1); 48 – Greater Poland, the town on Nowy Tomyśl, synanthropic flora of the city (U2); 49 – Western Kuyavia, the village of Małe Rudy, segetal weed flora of root crops (A2); 50 - Western Pomerania, several years old old fallowland (A3); 51 – Greater Poland, Główna River catchment, flora of fallowland ((A4); 52 – Greater Poland, Główna River catchment, flora of synanthropic flora of rural and urban settlements (U3); 53 – Western Pomerania, flora of winter cereal crops (A5); 54 – Greater Poland, Główna River catchment, flora of arable fields; 55 – Western Kuyavia, Mątwy and Janikowo towns, limestone heaps and salty lime sludge deposits (H1s); 56 – Lesser Poland, Kraków, flora of settling ponds of Cracow soda plants (H2s).

The directions of changes in the synanthropization indices within individual floras and Numerical classification of the dataset comprising a total of 56 floras was carried out using the minimum variance method with the Euclidean distance and the ordination was carried out using the method of principal components. The MVSP program (Kovach, 1993; Piernik, 2008) was used in the classification. Ordination was performed using Canoco 5 software package (ter Braak & Šmilauer, 2012). The resulting dendrogram and ordination diagram show the main groups of sites outlined with colored ellipses.

The similarities and differences between the floras were also presented using the graphical method proposed by Jentys-Szaferowa (1970) for biometric analyses. The method consists of calculating the quotients of the values of individual indices of each flora by the arithmetic means M_i of the consecutive 13 indices (i = 1, 2, 3,…., 13) obtained for the set of all 56 analyzed floras. The quotient values are plotted on the graph as deviations from the vertical straight line representing the quotients of the arithmetic means of the consecutive indices of the entire analyzed set. When plotted on the diagram, the quotient values obtained for the subsequent indices form broken lines that can be compared against the straight line and against the course of broken lines drawn for other sites. The arithmetic mean values of the indices for the entire dataset and the quotient values for the selected sites are presented in Table A2 in the Appendix.

3. Results

3.1. Conservation status and transformation indices for the flora of the study area

The total synanthropization index for the salt marsh flora in the study area N in the western part of Kuyavia, comprising 22 species of spontaneophytes, 73 apophytes, 16 archaeophytes and six kenophytes, reached the value of *WSc* = 81.20%. This value indicates a considerable degree of synanthropization of the studied flora. With the cultivated plants excluded from the calculations and the number of diaphytes equal to 0 (zero) in the analysis of the flora we studied, five pairs of indices calculated in the total and permanent version obtained equal values. These were the following pairs of indices: *WSc* = *WSt* = 81.20%; *WApc* = *WApt* = 62.39%; *WAnc* = *Want* = 18.80%; *WArc* = *Wart* = 13.68%; *WKnc* = *WKnt* = 5.13%. The absence of diaphytes meant that the fluctuation change index of the studied flora was equal to zero (*WF* = 0.00%). Table 1A presents the values of all 13 indices of the analyzed flora. The table also contains data on the state of the flora of 55 other sites with varying degrees of naturalness and intensity of human impact located in different regions of Poland. Halophytes were a frequent component in 20 out of all 56 analyzed floras.

3.2. Comparison of flora synanthropization indices in the study area and at other sites

The compared sites were ranked according to the increase in the indices of total synanthropization (*WSc*) and permanent synanthropization (*WSt*). Using this criterion, indices expressing the state of flora on saline soil in the vicinity of brine extraction and salt and soda production sites in Western Kuyavia were included in the column numbered 41 and marked with code N-S7. The indices of total and permanent synanthropization of this area reached the value of *WSc* = *WSt* = 81.20%. Slightly lower values (*WSc* = 77.14%; *WSt* = 78.64%) were obtained by Świeboda (1970) for meadows located around the "Bonarka" superthomasine factory in Kraków (No. 40, code M4 in Table 1A). Artificial biotopes with tall-herb, meadow, grassland and ruderal vegetation in the drainage basin of the Główna River in Greater Poland (code M5), analyzed by Ratyńska (2003), ranked 42 in this comparison. The flora of this site, comprising 367 species of vascular plants, scored *WSc* = 83.11% and *WSt* = 82.58%.

The analysis of the whole range of variability of the above parameters showed that the lowest values, below 40%, were obtained for ecological systems with the highest degree of naturalness – the spring area of the Gąsawka valley (*WSc* = 36.44%; *WSt* = 36.16%) and "Uroczysko Kiełpinek" ecological land use (*WSc* = *WSt* = 36.90%). The highest values were obtained for the flora of heaps and settling ponds of lime sludge at the soda works in Janikowo and Mątwy in the western part of Kuyavia, which was studied by Wilkoń-Michalska and Sokół (1969), and the flora of heaps and settling ponds at the soda works in Kraków, which was studied by Trzcińska-Tacik (1966). At both of these sites, the vegetation developed on the artificial substrate and the indices of total synanthropization and permanent synanthropization reached 100%. Slightly lower values of less than 3% were obtained for floras of winter cereal crops in Western Pomerania and arable fields in Greater Poland (Table 1A).

The values of the *WSc* and *WSt* indices of the flora analyzed in our study remained within the range typical of meadow and riparian communities, usually developing in the vicinity of industrial plants, disturbed by economic activity and the presence of waste disposal sites and technical infrastructure, such as bank reinforcements, but also by farming operations typical of meadows, such as grazing and mowing.

Of the ecological systems whose flora contains halophytes, the most approximate, though higher values of both indices were obtained for carpet communities in the Konin Coal Mining Region (study site No. 46 with symbol I2s). Similar, but lower values compared to the indices obtained for the flora analyzed in our study were obtained for the flora of bank fortifications at the mouth of the Śmiała Wisła and the Vistula Canal (in Polish: *Przekop Wisły*; site No. 38; W3s), the meadows in the vicinity of the Wieliczka salt mine inundated by brine (No. 36; S6), the flora of the "Ciechocinek" halophytic reserve established in the 1960s, i.e. in the period when the meadows near the graduation towers were flooded with brine (No. 35; P9s), and the flora of halophytic communities (No. 32; S5) studied by Wilkoń-Michalska (1963).

The analysis of the data in Table 1 shows that the lowest values of the *WSc* and *WSt* indices were obtained for the floras containing halophytes in the Słowiński National Park (No. 3; P2s), the planned "Łąki Pyzdrskie" nature reserve in Greater Poland (No. 4; M1s), the legally protected and unprotected coastal salt marshes (No. 6; S1 and 7; S2) and the "Mechelińskie Łąki" nature reserve on the Baltic coast (No. 10; P5s).

The data in Table 1 can also lead to a general conclusion that the degree of synanthropization of coastal salt marshes in Poland is clearly lower compared to inland salt marshes. Indeed, the *WSc* indices calculated on the basis of Piotrowska's (1974) data on the flora of salt marshes occurring on the Polish Baltic coast and Piernik's (2014) data on the flora of inland salt marshes from the whole territory of Poland were 0.33% and 66.67%, respectively.

A comparison of all 56 sites using the minimum variance agglomerative hierarchical classification method on the basis of the values of 13 indices is presented in Figure 2. The flora of the salt marshes in our study area (code N-S7) was placed in the main (i.e. upper) branch of the dendrogram (Fig. 2) together with the floras of the 15 most anthropogenically transformed areas. At the lower aggregation levels, they formed two subsets – consisting of nine and seven items, marked on the dendrogram with blue and red ellipses, respectively. Our flora was included in the former subset together with the flora of artificial biotopes with tall-herb, meadow, grassland and ruderal vegetation (M5) and fresh (mesic) meadows (M6) from the catchment area of the Główna River, the flora of lime waste heaps at the soda factories in Mątwy and Janikowo (H1s), the flora of waste heaps in the vicinity of Krakowskie Zakłady Sodowe (H2s), the synanthropic flora of the city of Nowy Tomyśl (U2), the flora of rural and urban settlements in the drainage basin of the Główna River in Greater Poland (U3), the flora of a gravel pit in Maszewo near Stargard (I1), and the flora of several years old fallows after winter cereal cultivation in Western Pomerania (A3). The latter subset was dominated by segetal floras of various field crops (A1, A2, A4–A6). There was also a ruderal flora of towns and cities in Kuyavia (U1) and carpet communities with facultative halophytes in the Konin Coal Mining Region (I2s).

The distance of the cluster from the subset of the remaining 40 floras from the sites with much lower human impact was considerable. In this subset of sites, a group of four floras from the most natural and legally protected sites was clearly distinguished – the flora of the Słowiński National Park marked with code P2s (with a small number and abundance of halophytes in the total number of 865 vascular plant species), the "Uroczysko Kiełpinek" ecological site (E1), the "Źródła rzeki Gąsawki" nature reserve with the dominance of forest species (P1f) and the Wielkopolska National Park (P3). This group is marked with a yellow ellipse in the dendrogram (Fig. 2).

Of the group of 36 sites, a cluster of nine floras located in the upper part of the dendrogram was distinguished, comprising i.a. the flora of the halophytic communities in Kuyavia (S5), the flora of meadows in the vicinity of the Wieliczka salt mine (S6), the flora of "Ciechocinek" reserve of halophytes in Kuyavia (P9s) and the meadows around the former "Bonarka" superthomasine factory in Kraków (M4).

These four floras forming a distinct cluster are connected at a low level of distance with five floras of littoral vegetation developing around ponds in the agricultural landscape and on river banks, including those reinforced by technical infrastructure (sites: K5w, M3, W2, W3s, W4). The cluster comprising nine sites is marked with a dark green ellipse on the dendrogram (Fig. 2).

The remaining 27 floras formed a large cluster in the central part of the dendrogram, marked with a light green ellipse. It includes eight floras with halophytes: S1 – the flora of coastal salt marshes studied by Piotrowska (1974); S2 – the flora of coastal salt marshes infiltrated by saline water analyzed by Bosiacka (2011) and Bosiacka et al. (2011); S3 – salt marshes in the Noteć River valley described by Wilkoń-Michalska (1957); S4 – inland salt marshes analyzed by Piernik (2012); M1s – halophytic meadows of the planned "Łąki Pyzdrskie" nature reserve in Greater Poland described by Brzeg (1998); M2s – a section of the Zgłowiączka River valley according to the study by Pisarek (1995); P5s – the flora of the "Mechelińskie Łąki" nature reserve located by the Baltic Sea, described by Meissner et al. (2004) and Żółkoś et al. (2007); and V2s – the flora of various ecosystems located on the western margins of Puck Bay surveyed by Wszałek-Rożek and Markowski (2010). This group also includes floras of grasslands with a small proportion of semi-halophytic species growing near the mouths of the Wisła Królewiecka and Szkarpawa rivers (G1s) and on the south-eastern margins of the Vistula Lagoon (G2s) and the Gopło Millennium Landscape Park (P7s). Other sites include floras of protected areas, especially large protected areas (P4, P8, P10), nature reserves and ecological sites (P6x, E2), as well as areas that are not protected (O1, V1, V3), floras along the shores of field, small bodies of water, like ponds (K1w, K2w, K3w, K4w), rivers (W1), xerothermic meadows (X1, X2) and ruderal flora developed after the introduction of technical infrastructure to environmentally valuable areas (R1t).

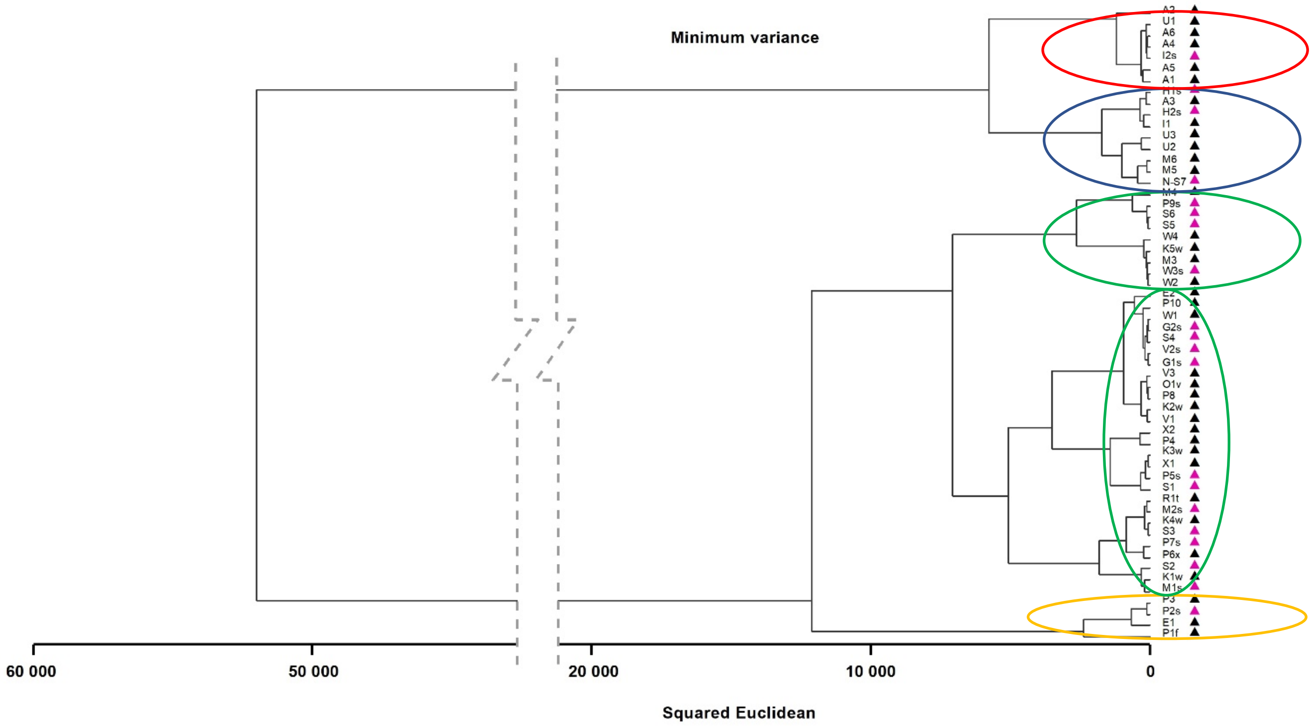

Figure 2. Hierarchical agglomerative classification of 56 floras from different regions of Poland based on the values of 13 indices proposed by Jackowiak (1990). Codes of the compared sites as in captions to Figure 1; magenta triangles indicate floras with halophytes.

The five main groups of sites with the above-mentioned composition were also clearly distinguished in the ordination diagram produced by the PCA method (Fig. 3). In the plane defined by the first and second ordination axes, which account for respectively 67.7% and 16.3% of the variance in the studied set of 56 floras, the subset of nine sites to which our site N-S7 was classified was located on the left side of the diagram. The surface of the ellipse encompassing this subset (blue) is intersected by vectors showing the directions of interactions of the synanthropization (*WSc* and *WSt*, respectively), apophytism of spontaneophytes (*WAp*) as well as the total and permanent anthropophytization (*WApc* and *WApt*, respectively). The first of these vectors, *WSc*, is most strongly (negatively) correlated with axis I, followed by the *WSt* vector, which is only slightly less correlated.

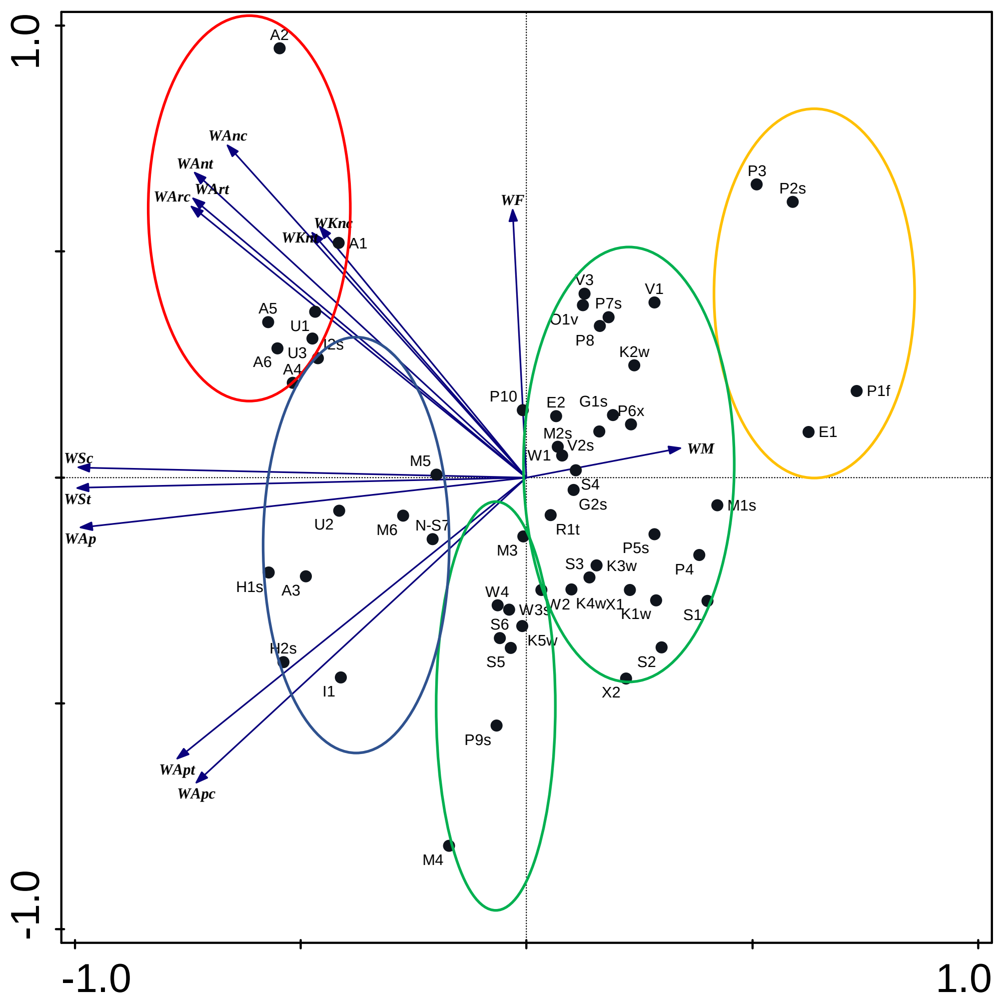

Figure 3. Results of Principal Components Analysis. The ordination diagram shows the position of 56 floras from different regions of Poland, characterized based on 13 indices proposed by Jackowiak (1990), in the dimensions of axis I (67.7%) and axis II (16.3%). Codes of the compared sites and vectors of the indices as in Fig 1 and Table 1A in Appendix.

Above the blue ellipse there is a red ellipse covering seven sites, mainly segetal and synanthropic floras of rural and urban settlements. This ellipse is joined by vectors indicating the directions of effects of the total and permanent anthropophytization (*WAnc* and *WAnt*), archaeophytization (*WArc* and *WArt*) and kenophytization (*WKnc* and *WKnt*), with the length of the last two vectors being noticeably shorter than the four preceding them, indicating a lesser effect of these indices on the variability of the analyzed floristic dataset. The *WM* vector of the flora modernization index is much shorter than the *WKnc* and *WKnt* vectors and is positively correlated with axis I with the opposite direction to the impact of the *WSc* index (Fig. 3). The impact of the *WM* index on the variability of the analyzed floristic dataset is therefore the smallest among all 13 traits included in the analysis.

The red ellipse is shifted, relative to the location of the blue ellipse, toward higher values on axis II, with which the *WF* vector is most strongly correlated. It is only slightly shorter than the kenophytization vectors (*WKnc* and *WKnt*). The subsets of sites within the blue and red ellipses, lying close to each other in the ordination diagram, formed together a 16-item cluster, i.e. one of the two main ones that occurred at the highest level of merging in the hierarchical agglomeration classification.

The three subsets distinguished on the second main branch of the dendrogram also formed disjoint point clouds in the ordination diagram. Outlined with yellow and light and dark green ellipses, they are arranged along axis I according to increasing values of the *WSc* index and other indices strongly negatively correlated with this axis, i.e. *WSt* and *WAp* (Fig. 3). Along axis II, these three ellipses are shifted relative to each other according to increasing values on axis II, with the dark green ellipse being the lowermost, covering, among others, the flora of the "Ciechocinek" reserve of halophytes, the salt marshes of Kuyavia and the saline meadows near the Wieliczka salt mine, and the yellow ellipse, covering the flora of four protected areas, being the uppermost.

The elongated, elliptical shape of the contours of all five subsets indicates their internal differentiation, which is most often influenced by the values of the flora fluctuation change index, *WF*, strongly correlated with the second ordination axis.

The directions of changes in the values of the indices, as indicated by their vectors in the ordination diagram, were also clearly repeated in the analysis carried out using the graphical method. Figures 4A and 4B show broken lines for eight selected floras from sites characterized by a high proportion of salt marshes in their land cover. These floras were selected so as not to miss any subgroup distinguished in the numerical classification and ordination. Strongly negatively correlated with ordination axis I, the indices *WSc*, *WSt* and *WAp* of the flora from site P2s of high conservation status (Słowiński National Park) scored values significantly lower than the arithmetic means of the entire dataset, as represented by the vertical line with a quotient value of 1.0. The points corresponding to these three indices lie to the left of this line at a considerable distance from it (Fig. 4A). The points of floras S1 and P5s functioning under similar conditions of relatively low salinity and high soil moisture (these are the coastal salt marshes and the "Mechelińskie Meadows" nature reserve, respectively) also lie to the left, but much closer to the vertical line than the points on line P2s. In contrast, the points of more saline sites S5 and S6 (inland salt marshes in the region of Kuyavia and saline meadows in the vicinity of the Wieliczka salt mine near Kraków, respectively) lie on the vertical line or slightly to the right of it (Fig. 4B). Significantly higher values of the three compared indices than the arithmetic means correspond to the course of the lines determined successively for the flora of the Noteć River and Noteć Canal meadows studied by us, degraded by the soda industry, and for the flora of lime stone heaps and salty lime sludge deposits of this industry (lines N-S7 and H1s in Fig. 4B, respectively). The quotient values obtained for the *WSc*, *WSt* and *WAp* indices of the flora growing on slightly saline soils near mines in the Konin Brown Coal Basin (site I2s in Fig. 4A) are somewhat lower compared to those obtained for the flora of heaps and deposits at site H1s (Fig. 4B).

In the course of the curves representing the selected floras, exceptionally high or low values of the indices were also evident in the floras lying close to the vectors of these indices' impact. Indeed, the flora of site H1s scored the highest values of the indices of total apophytization *WAp*c and permanent apophytization *WApt*. The values of these indices of the flora of the N-S7 Noteć meadows we studied (location close to the initial part of the *WAp*c and *WApt* vectors on the ordination diagram; Fig. 3) are slightly lower (Fig. 4B). On the other hand, the values of the *WAnc*, *WAnt, WArc WArt* and *Knc* and *Knt* indices for the floras of site I2s located in the directions of the anthropophytization and archaeophytization vectors and the short kenophytization vectors in the ordination diagram (Fig. 3) were significantly higher than the arithmetic means of the entire analyzed set (Fig. 4A). The flora from the P2s protected areas lying in the ordination diagram in the direction of the *WF* vector is characterized by the highest values of this index compared to other cases presented in Figure 4.

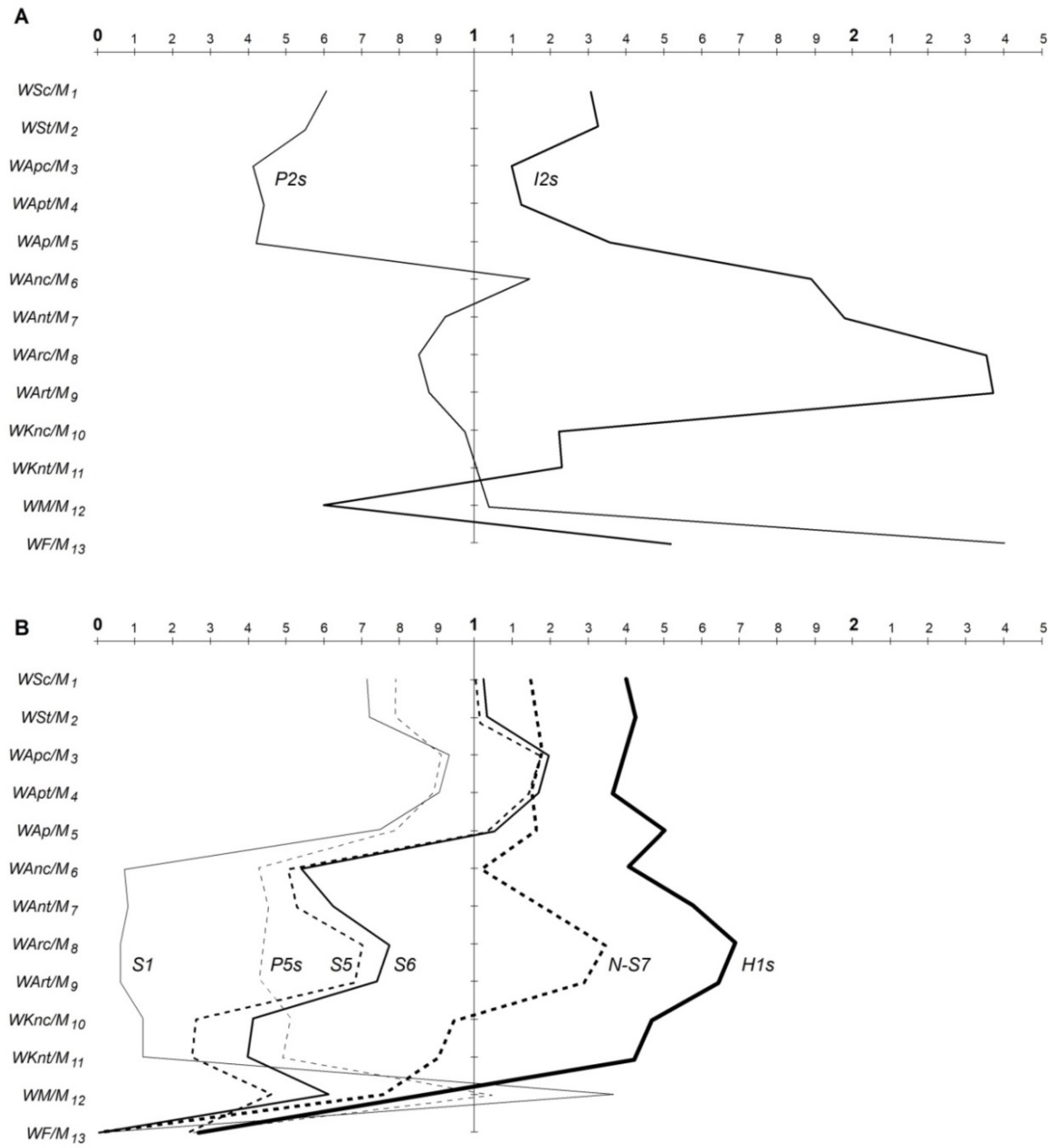

Figure 4. Comparison of the eight selected floras using the graphical method. A – two floras from the extreme subgroups distinguished in the dendrogram and along axis I in the numerical ordination, B – six floras from the three groups distinguished in the middle of axis I in the numerical ordination. Explanation of flora symbols: P2s – Słowiński National Park and Biosphere Reserve in Baltic coast; I2s – Konin Brown Coal Basin, *Plantaginetalia majoris* plant communities; S1 – Baltic coastal halophytic plant communities; P5s – 'Mechelińskie Łąki' nature reserve near Gdynia city in Baltic coast; S5 – halophytic plant communities of Kuyavia; S6 – meadows flooded by brine in Wieliczka near Kraków; N-S7 salt marsh vegetation on the banks of the Noteć River and the Noteć Canal; H1s –lime stone heaps and salty lime sludge deposits in Mątwy and Janikowo towns.

4. Discussion

The ordination analysis of the floras performed with the PCA method confirmed our hypothesis that the total synanthropization index, *WSc*, expressing the percentage of synanthropic spontaneophytes (apophytes) and anthropophytes in the total species richness, is one of the main factors accounting for the variability within the analyzed set of nature sites. The position and length of the *WSc* vector in the ordination diagram (Fig. 3) indicates that this index accounts for a large percentage of the variability in the studied floras and is most strongly correlated with the first ordination axis, which represents 67.7% of the variability in the studied floristic dataset. The *WSt* and *WAp* indices also had a strong influence on the variability of the studied dataset, however, the deviation of the spontaneophyte apophytism vector (*WAp*) from the first ordination axis is greater than that of the *WSc* vector.

Similar to the work by Kutyna et al. (2013), our analyses also generally revealed marked differences in the values of the *WSc*, *WSt* and *WAp* indices between the floras of legally protected areas and areas not covered by legal protection. Sites with the highest protection status, i.e. national parks and nature reserves, showed particularly low values of the total and permanent synanthropization indices and the index of spontaneophyte apophytism, i.e. a high degree of naturalness. In our analysis, however, such a relationship did not occur in the case of the "Ciechocinek" halophyte reserve. The indices of total synanthropization and permanent synanthropization obtained for the flora of this site were only slightly lower than the values calculated for meadows located in the vicinity of industrial facilities and healthcare centers in Kuyavia, as well as those near the Wieliczka salt mine, whose operations resulted in the inundation of neighboring areas with saline waters. From the consequences presented, it follows that the persistence of the salt marsh in Ciechocinek, which was granted the status of a nature reserve in 1963, is conditioned by anthropogenic factors, as reflected in the geographical and historical structure of the flora. In recent years, with the reduced inundation of meadows with saline water, halophytes are withdrawing from the "Ciechocinek" reserve and glycophytes tolerating low salinity of substrate play an increasingly important role (Wilkoń-Michalska, 1970; Warot & Nienartowicz, 2001; Nienartowicz, 2007; Piernik et al., 2015; Hulisz et al., 2020; Lubińska-Mielińska et al., 2022). On the other hand, values of these indices for inland salt marshes, the duration of which is contributed to by natural saltwater infiltration and not by anthropogenic inundation, such as the meadows in the Zgłowiączka river valley in Kuyavia included in our comparisons, are clearly lower compared to those calculated for the "Ciechocinek" nature reserve from the 1960s. For example, the value of the total synanthropization index *WSc* for the saline meadows in the Zgłowiączka valley is 67.14% and that for the "Ciechocinek" nature reserve is 73%. The state of the flora of both compared sites is also well reflected by the flora naturalness index proposed by Kutyna et al. (2013), the value of which is complementary to 100% of the total synanthropization index *WSc* expressed as a percentage of spontaneophytes in the examined flora. For meadows in the Zgłowiączka valley and the "Ciechocinek" nature reserve, the index of naturalness is 32.86% and 27%, respectively.

Even lower values of the *WSc* index and a much higher index of naturalness were obtained for the salt marshes on the Baltic coast, located on Chrząszczewska Island and in the city of Kołobrzeg, but conditioned by saltwater infiltration. Their total synanthropization index is 51.72% and their index of naturalness is 48.28%.

The environmental disturbance, often accompanied by an increase in substrate salinity, leads to the encroachment of apophytes and anthropophytes and consequently contributes to an increase in the *WSc* index and a decrease in the index of naturalness. The total synanthropization index and the naturalness index obtained for the saltmarsh flora of our study plot *N* were 81.2% and 18.8%, respectively. The values of these indices for the carpet communities with a small proportion of halophytes occurring in the Konin Coal Mining Region and its periphery are 93.3% and 6.7%, respectively. For the floras of the limestone sludge settling ponds at the two soda works in Kuyavia and at the Kraków Soda Works, after recognizing all spontaneophytes as apophytes due to their occurrence on man-made (not natural) substrates, the values of the total synanthropization index reach the maximum value of 100% and the naturalness indices reach the minimum value of 0%.

The floristic lists, used to calculate the 13 indices for the 56 natural sites, were prepared using two methods – either by exploring the entire site or by compiling a common list of species from all synoptic tables presenting the vegetation variability of the area under consideration. Thus, in the second method, only species occurring at the sites where relevés were taken were factored in. For this reason, differences in the number of species and the geographic–historical structure of the flora of the same area for each method can be significant. Attempts were made to minimize these differences by selecting source materials with a large (as complete as possible) number of syntaxonomic units and a large number of relevés used to distinguish and present each type of plant community.

The same main groups of objects (floras) were distinguished in the numerical analyses, both for the classification method and the ordination method used, and such consistency of results obtained with such different computational techniques does not often occur. The result obtained by numerical taxonomy methods in the form of a dendrogram or ordination diagram summarizes the similarity or difference of the analyzed flora with respect to each flora of another area compared to it. It is determined on the basis of all the characteristics taken into account in the analysis and expressed by the location of the point corresponding to that flora in the ordination diagram, or the location in a specific branch of the dendrogram. The graphical method used in this study allowed for a more comprehensive presentation of the similarities between the degree of synanthropization of the compared floras by demonstrating the differences of each of the 13 features taken into account, i.e. synanthropization indices. The comparison of broken lines allows for a more accurate interpretation or verification of the results of numerical classification and ordination.

Based on the analyses carried out, we conclude that the comparisons presented in this work for the dataset of 56 natural sites from different regions of Poland indicate that the indices of anthropogenic transformation of flora proposed by Jackowiak (1990), and supplemented by Kutyna et al. (2013) with indices of flora naturalness, provide a good representation of the state of natural sites developing under conditions of human impact, and can be used in comparative numerical analyses as features of the vegetation present there.

5. Conclusions

1. The total synanthropization index for the salt marsh flora in the study area *N* in the western part of Kuyavia, represented by 22 species of spontaneophytes, 73 apophytes, 16 archaeophytes and six kenophytes, reached the value of *WSc* = 81.20%, which indicates a considerable degree of synanthropization of the studied flora.

2. The synanthropization indices of the saltmarsh flora in the study area *N* in the vicinity of Inowrocław, Janikowo and Góra in the western part of Kuyavia reach the values most similar to those obtained by other authors for meadows subjected to strong human impact, both those occurring in the vicinity of industrial plants, such as in the neighborhood of the 'Bonarka' phosphate factory in Kraków, and those less affected by human impact, such as meadows in the agricultural landscape of the Główna River catchment in Greater Poland, or anthropogenic biotopes with herbaceous, meadow, grass and ruderal vegetation occurring in this area. The obtained values of the indices may serve as reference values for further comparisons in time and space.

3. The data in Table 1 allow for the general conclusion that the degree of synanthropization of coastal salt marshes in Poland is clearly lower than that of inland salt marshes.

4. The ordination analysis of the 56 floras corroborated our hypothesis that the total synanthropization index *WSc* and the permanent synanthropization index *WSt* are the main factors accounting for the variability within the studied set of natural sites. The contribution of the other indices of floristic variability is much smaller.

5. Since the indices of anthropogenic transformation of the flora differentiate well between the states of natural sites with different conservation status and developing under conditions of

varying intensity of human impact, their values can be used as vegetation characteristics in comparative numerical analyses.

6. The graphical method originally proposed for biometric studies can also effectively support methods of numerical classification and ordination when comparing the degree of synanthropization of floras by presenting the deviations of subsequent features of each of the analyzed objects from the same reference points.

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