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ORGANIC CARBON AS AN INDICATOR OF VARIATIONS IN THE TROPHIC STATE OF TWO LAKES LOCATED IN THE UPPER REACHES OF THE ŁYNA RIVER (MAZURIAN LAKELAND, POLAND)

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ABSTRACT. Seasonal variations in the content of the dissolved (DOC) and particulate (POC) fractions of organic carbon were investigated in the waters of lakes Święte and Łańskie. The $SUVA_{260}$ parameter, which is the value of absorbance normalized against DOC, was used in the qualitative description of dissolved organic matter. The results of the investigations indicated that the concentration of organic carbon was higher in Lake Święte, which is evidence that this basin is more productive. High concentrations of DOC in summer accompanied by low $SUVA_{260}$ values indicate that the main source of organic matter in this basin is primary production. This is confirmed by the high chlorophyll content, low visibility, and oxygen over-saturation in the surface water layer. In accordance with the criteria proposed by Thurman (1985), while both of the studied lakes are mesotrophic, the range of DOC concentration in Lake Święte indicates that the eutrophication process there is more advanced.

Key words: TOC, DOC, POC, $SUVA_{260}$, TROPHY, LAKE

INTRODUCTION

Lakes are dynamic ecosystems that exhibit temporal changes. The development of lakes usually leads to their enrichment and intensified biological production. This phenomenon is accompanied by morphometric changes in the basins and transformations in the physical and chemical characteristics of the aquatic environment. Limnological succession generally runs its course harmoniously under natural conditions. As they gradually fill with sediments and vegetation grows, basins become shallower and slowly level and are thus transformed into swamps and peatbogs. The transformations occurring in lakes are clearly intensifying as a result of the progressing human exploitation of the environment. These changes are often of

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a discordant nature, and a variety of changes occur that are stimulated by the types of anthropogenic pressure placed on the lakes. As a consequence of these natural and anthropogenic conditions, lakes have varied abundances of the nutritive elements that play a decisive role in primary production and the content of organic material in waters and bottom sediments. Most frequently, the trophic state of lakes is evaluated based on the contents of total phosphorous and chlorophyll, visibility (Carlson 1977, Vollenweider 1989), the availability of compounds P and N for primary producers, which refers to the ratio of these elements (N/P) and the abundance and composition of phytoplankton (Hillbricht-Ilkowska and Kajak 1986). In the trophic classification of lakes, Vollenweider (1989) also considers the degree of oxygenation in the near-bottom water layer during the summer stagnation period. Measurements of concentrations of organic carbon and its fractions may also be a good indicator of the degrees of degradation and of surface water pollution (Thurman 1985, Barałkiewicz and Siepak 1994, Górniak 2001, Dunalska et al. 2006a). The applicability of using organic carbon measurements to assess lake trophic status was verified based on results from two lake-river systems located in the upper reaches of the Łyna River (northern Poland).

MATERIAL AND METHODS

The catchment basin of the upper Łyna River has an area of 506 km^2 and is located in the mesoregion of the Olsztyn Lakeland which, in turn, is located in the macroregion of the Mazurian Lakeland. There are 87 lakes and 146 post-glacial lakes with a combined total surface area of 4240 ha in this region. The mean lake percentage of this catchment is 8.4%, making it one of the largest in Poland (Maślanka et al. 1996). Lakes Święte and Łańskie are both located within this system. Tables 1 and 2 present the limnological characteristics and the variability of the physical and chemical parameters of their waters.

Water samples used to determine the contents of organic carbon were collected ten times in 2004 and 2005, beginning with spring circulation (April), through the summer stagnation to fall circulation (November). The samples were collected with a Toń-2 scoop in the deepest part of the lake from the surface and bottom layers as well as from the metalimnion during summer stagnation.

TABLE 1

Limnological characteristics of lakes Święte (A) and Łańskie (B)

Parameter	A	B
Surface area (ha)	59.4	1042.3
Volume (million m^3)	4.3	168.0
Max. depth (m)	40.8	53.0
Mean depth (m)	6.8	16.0
Max. length (km)	1.6	10.0
Max. width (km)	0.5	2.2
Shoreline length (km)	4.3	34.0
Shoreline development	1.6	2,99
Degree of lake stability*	IV	III

**according to the typology of Patalas (1960)*

TOC content was determined in unfiltered samples and DOC after filtration on 0.45 μm Millipore filters. POC was calculated as the difference between the TOC and DOC concentrations. The determinations were performed on a Shimadzu TOC-5000 organic carbon analyzer after the samples had been acidified with 2M HCl to about 2 pH in order to remove the CO_2.

The quality of the dissolved organic matter was determined as $SUVA_{260}$ (Abs 260/DOC). Specific ultraviolet absorbance (SUVA) is defined as the UV-absorbance of a water sample at a given wavelength normalized for DOC concentration. A Shimadzu UV-1601PC spectrophotometer was used to measure the UV-absorbance (260 nm) of the water samples.

RESULTS AND DISCUSSION

Lake Święte had a low water temperature (mean of 1.0°C; Table 2). The lowest temperatures were confirmed in both lakes in April 2005, at 3.4°C in Lake Święte and 3.3°C in Lake Łańskie. The more important factors shaping lake thermal regimes include exposure to wind and lake basin shape (Olszewski 1959, Patalas 1960). The size of the lakes investigated in the current study was the deciding factor in their temperature ranges. The large surface area of Lake Łańskie promoted the heating of the surface waters while the unconstrained impact of wind intensified the mixing process.

TABLE 2

Variability of physical and chemical parameters (range, mean ± SD) in lakes Święte (A) and Łańskie (B) in 2004-2005 (according to Zdanowski et al. 2006)

Parameter	A		B	
	range	mean ± SD	range	mean ± SD
Temperature (°C)	3.4-20.2	9.0 ± 5.4	3.3-21.2	10.0 ± 5.8
Oxygen (mg O_2 l^{-1})	0.0-18.9	6.0 ± 5.7	0.3-14.9	8.1 ± 4.2
Visibility (m)	1.1-2.7	1.8 ± 0.5	1.7-3.8	2.9 ± 0.8
Conductivity (μS cm^{-1})	273-340	312 ± 19	244-316	288 ± 17
pH	7.3-8.7	7.9 ± 0.3	7.3-8.4	8.0 ± 0.3
Ca^{2+} (mg l^{-1})	44.6-75.2	61.5 ± 7.6	41.7-70.5	56.6 ± 6.0
Mg^{2+} (mg l^{-1})	5.5-10.7	8.1 ± 1.4	5.8-17.7	8.1 ± 2.4
Na^{+} (mg l^{-1})	4.3-5.0	4.8 ± 0.2	4.5-4.9	4.7 ± 0.1
K^{+} (mg l^{-1})	1.5-1.9	1.7 ± 0.1	1.4-1.7	1.6 ± 0.1
Fe_{tot} (mg l^{-1})	0.001-0.060	0.024 ± 0.010	0.000-0.119	0.018 ± 0.020
CO_3^{2-} (mg l^{-1})	0.0-3.6	0.6 ± 1.2	0.0-9.0	1.4 ± 2.2
HCO_3^{-} (mg l^{-1})	0.0-222.0	160.9 ± 52.5	0.0-195.2	146.8 ± 49.0
Cl^{-} (mg l^{-1})	9.6-12.1	10.6 ± 0.6	8.4-9.6	8.6 ± 0.3
SO_4^{2-} (mg l^{-1})	23.8-29.3	26.7 ± 1.6	22.0-18.2	23.5 ± 1.4
NH_4-N (mg l^{-1})	0.03-1.40	0.36 ± 0.45	0.01-0.49	0.06 ± 0.10
NO_2-N (mg l^{-1})	0.000-0.089	0.009 ± 0.017	0.000-0.028	0.005 ± 0.006
NO_3-N (mg l^{-1})	0.00-0.40	0.08 ± 0.12	0.00-0.53	0.15 ± 0.17
$N_{org.}$ (mg l^{-1})	0.00-1.44	0.64 ± 0.36	0.07-3.48	0.68 ± 0.78
N_{tot} (mg l^{-1})	0.16-2.26	1.09 ± 0.49	0.36-3.67	0.90 ± 0.66
PO_4-P (mg l^{-1})	0.013-0.425	0.125 ± 0.136	0.007-0.135	0.058 ± 0.040
$P_{org.}$ (mg l^{-1})	0.000-0.168	0.050 ± 0.036	0.012-0.086	0.037 ± 0.019
P_{tot} (mg l^{-1})	0.063-0.472	0.175 ± 0.127	0.037-0.154	0.095 ± 0.035
TOC (mg l^{-1})	3.9-7.8	6.0 ± 0.9	3.9-6.4	5.2 ± 0.7
DOC (mg l^{-1})	3.1-5.4	4.2 ± 0.7	2.9-4.7	3.9 ± 0.6
POC (mg l^{-1})	0.7-2.7	1.8 ± 0.5	0.4-3.1	1.3 ± 0.6
$SUVA_{260}$ (cm^{-1} (g C)$^{-1}$ l)	22.3-43.0	32.5 ± 5.4	26.7-45.4	33.2 ± 5.2

The oxygen content of the basins studied ranged from 0.0 to 18.9 mg O_2 l^{-1} (Table 2). During the summer stagnation period, trace amounts of oxygen were noted in the near-bottom waters of Lake Święte, while in August 2005 a total lack of oxygen was noted. The highest oxygen content, however, was noted in the surface layers in April 2004 (14.4 mg O_2 l^{-1}) and 2005 (18.9 mg O_2 l^{-1}). The lowest oxygen content was

observed in Lake Łańskie only in August at 0.4 mg O_2 l^{-1} in 2004 and 0.3 mg O_2 l^{-1} in 2005, while the maximum value (14.9 mg O_2 l^{-1}) was noted during the spring circulation cycle in 2005.

The Secchi disc visibility in Lake Święte ranged from 1.1 to 2.7 m and was always lower than that in Lake Łańskie (range – 1.7 to 3.8 m; Table 2). The electrolytic conductivity in the studied lakes was similar at a mean of 312 μS cm^{-1} in Lake Święte and 288 μS cm^{-1} in Lake Łańskie, and the value of this parameter in the near-bottom layers was higher (a mean of approximately 30 μS cm^{-1}) in comparison to that in the surface layers. The mean pH value in both lakes was similar at 7.9 in Lake Święte and 8.0 in Lake Łańskie. The lowest value of this parameter (pH – 7.3) in each of the lakes was noted in August near the bottom. Slight differences were recorded in the maximum values. The highest value (pH – 8.7) was recorded in Lake Święte in April 2005, while that in Lake Łańskie (pH – 8.4) was noted in June 2004. In summer, the pH of the surface water layer of Lake Święte did not fall below 8.3, while that in Lake Łańskie ranged from 7.9 to 8.4. The waters of the studied lakes had different concentrations of the principle ions. In both lakes the dominant cations were calcium ions, while the dominant anions were hydrogen carbonates. The concentration of calcium ions in Lake Święte ranged from 44.6 to 75.2 mg l^{-1}, while that in Lake Łańskie was from 41.7 to 70.5 mg l^{-1} (Table 2). Similarly to the calcium ions, the concentration of hydrogen carbonates (a mean of 14.1 mg l^{-1}) was slightly higher in Lake Święte.

The content of total phosphorous in Lake Święte ranged from 0.063 to 0.472 mg l^{-1}, while in Lake Łańskie it was decidedly lower within the range of 0.037 to 0.154 mg l^{-1}. The highest levels in both of the lakes were observed in summer near the bottom. The dominant form of phosphorous was orthophosphate, which comprised 71% of the total phosphorous fraction in Lake Święte and 61% in Lake Łańskie. The mean concentration of total nitrogen in each of the lakes was similar at about 1 mg l^{-1}. Distinct differences occurred with regard to extreme concentrations; in Lake Święte these values ranged from 0.16 to 2.26 mg l^{-1}, and in Lake Łańskie from 0.36 to 3.67 mg l^{-1}. Differences were also noted in the percentages of the particular fractions of total nitrogen. Organic nitrogen, ammonium nitrate, and nitrate nitrogen comprised 58.7, 32.7, and 7.6% in Lake Święte and 75.2, 7.0, and 17.1% in Lake Łańskie, respectively.

The total content of organic carbon was 1.2 mg l^{-1} higher, on average, in Lake Święte (Table 2). In both lakes the highest concentrations in the surface water layers

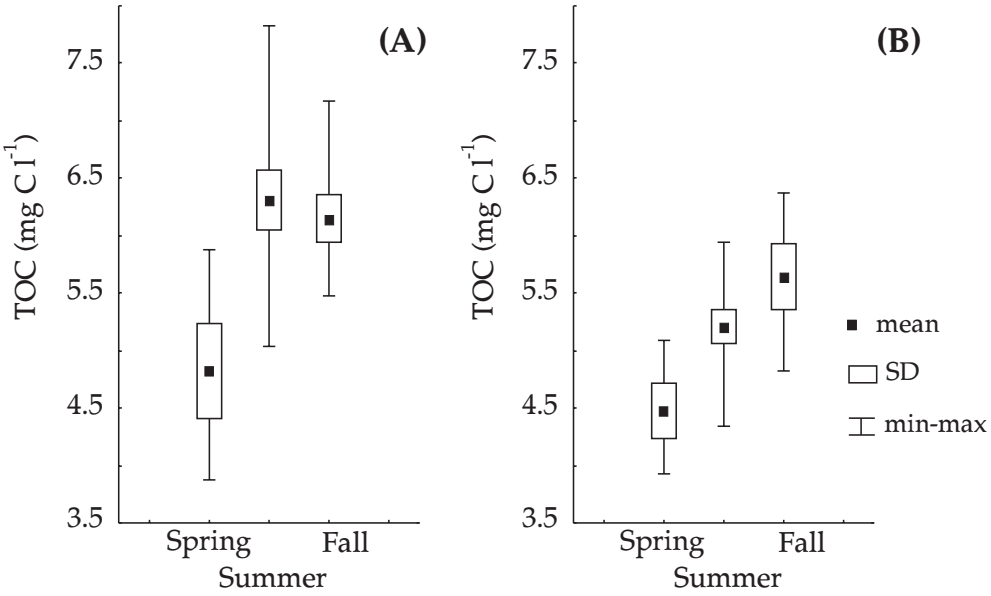

Fig. 1. Seasonal variability in the TOC contents in lakes Święte (A) and Łańskie (B) in the 2004-2005 period.

were noted in the second half of the summer stagnation period (7.8 mg l^{-1} in Lake Święte and 6.4 mg l^{-1} in Lake Łańskie). The dominant form of organic carbon was dissolved organic carbon, which comprised 70 and 75% of the total organic carbon in lakes Święte and Łańskie, respectively.

The quality of the dissolved organic matter differed slightly as is indicated by the range of variability in the $SUVA_{260}$ parameter. In Lake Święte the magnitude of this parameter varied from 22.3 to 43.0 cm^{-1} $(g\ C)^{-1}$ l, while in Lake Łańskie it was from 26.7 to 45.4 cm^{-1} $(g\ C)^{-1}$ l. The concentration of TOC was lower in spring, while in Lake Święte it increased distinctly in summer and then decreased again in fall (Fig. 1). In Lake Łańskie the increasing tendency was sustained from spring to fall. In spring the concentration of TOC was determined primarily by dissolved organic matter, the source of which was inflow from the catchment area which is evidenced by the highest values of $SUVA_{260}$ (Fig. 2). Increased values of this indicator are connected with the increase of the polar functional group present in the DOM molecules, increases in the molecular weight, and aromaticity (Symons and Zheng 1996, Dunalska and

Zdanowski 2004). The high value of $SUVA_{260}$, including the high share of rings in the molecule, is characteristic for material of terrestrial origin. The export of organic elements in spring is connected with intense filtration of melt waters through the soil profile as well as the runoff from increased atmospheric precipitation (Eckhardt and Moore 1990, Chróst 1995, Górniak and Zieliński 1999). The manner in which a catchment area is exploited has a significant impact on the quality of the organic

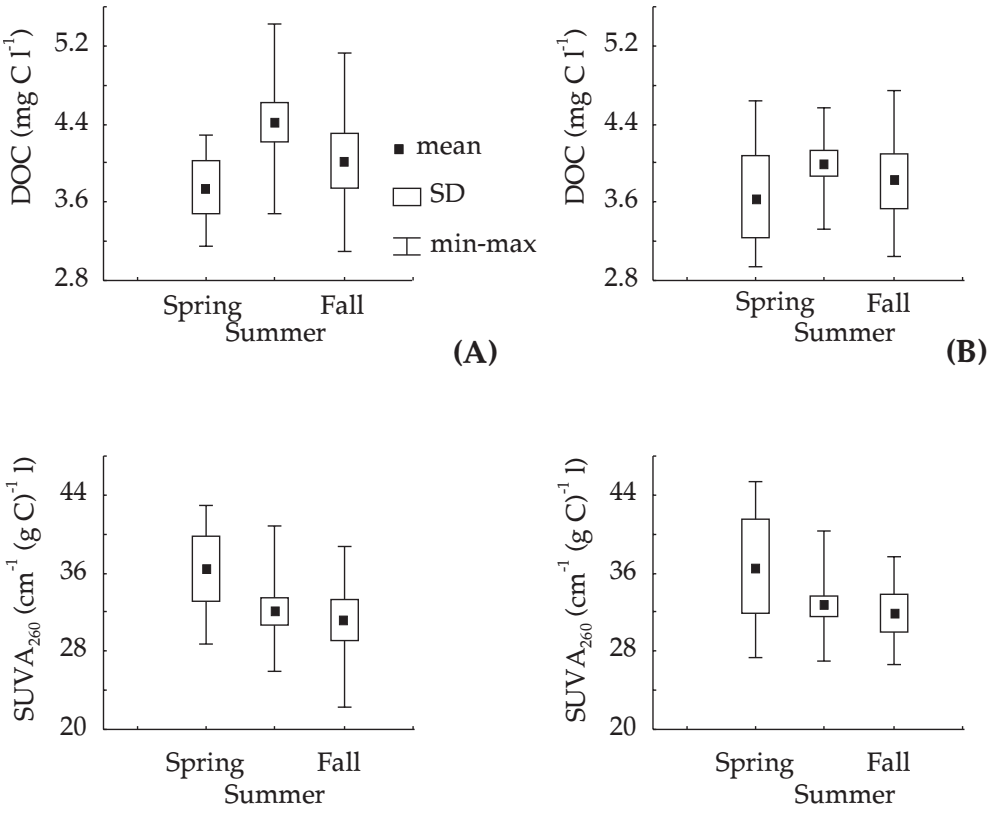

Fig. 2. Seasonal variability in the DOC contents and the values of the SUVA parameters in lakes Święte (A) and Łańskie (B).

material in the basins themselves (Dunalska et al. 2006b). The studies of Zieliński and Górniak (1999) indicated that in catchment areas with a high degree of forestation (> 60%), the surface waters are characterized by high levels of dissolved organic matter and high aromaticity. Despite increased $SUVA_{260}$ values, no high concentrations of DOC were confirmed in the lakes studied in the current investigation (Fig. 2). The outflow of water from a forested catchment is less than that from a deforested one, which, calculated as water volume units, delivers a smaller load of DOC to the lacustrine ecosystem. In the case of lakes Święte and Łańskie, the share of forests in the immediate catchment vicinity (over 90%) means that in spring the organic material in both lakes is of a similar structure as is evidenced by identical $SUVA_{260}$ levels. Simultaneously, the fact that the DOC concentration was low in comparison to the remaining vegetation seasons indicates that the forests protect the lakes from intense inflows of allochthonous organic material. Along with a limited inflow from the catchment, the quantity and tempo of the transformation of organic material will be decided mainly by the primary production in a basin, which concurs with research Dunalska et al. (2006a). The clearly low DOC/POC ratio in spring in Lake Święte in comparison with that in Lake Łańskie, along with the simultaneously similar values of DOC, attests to the significant role of particulate organic matter in this lake (Fig. 3).

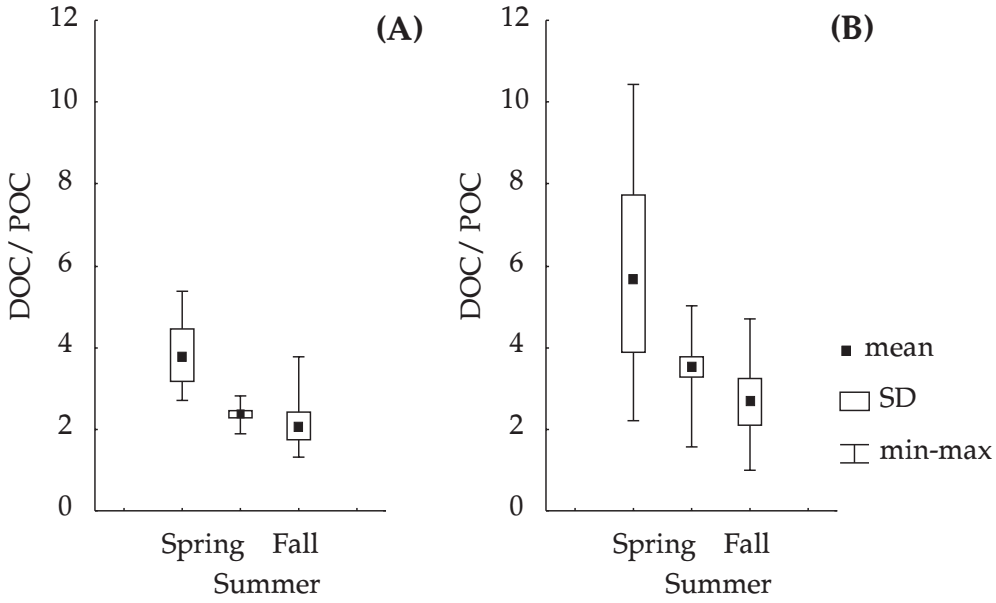

Fig. 3. Ratio of the DOC to POC contents in lakes Święte (A) and Łańskie (B) in the 2004-2005 period.

According to Lange and Maślanka (1997), the variability of particulate concentrations in water is one of the ways to identify the delivery and production of organic material. The content of autochthonous seston (phytoplankton, zooplankton, detritus) is primarily responsible for determining visibility in lakes as well as the range of the light zone (Kajak 1998). In the lakes from the current study the source of POC was primary production, which intensified during the spring-summer period in Lake Święte and

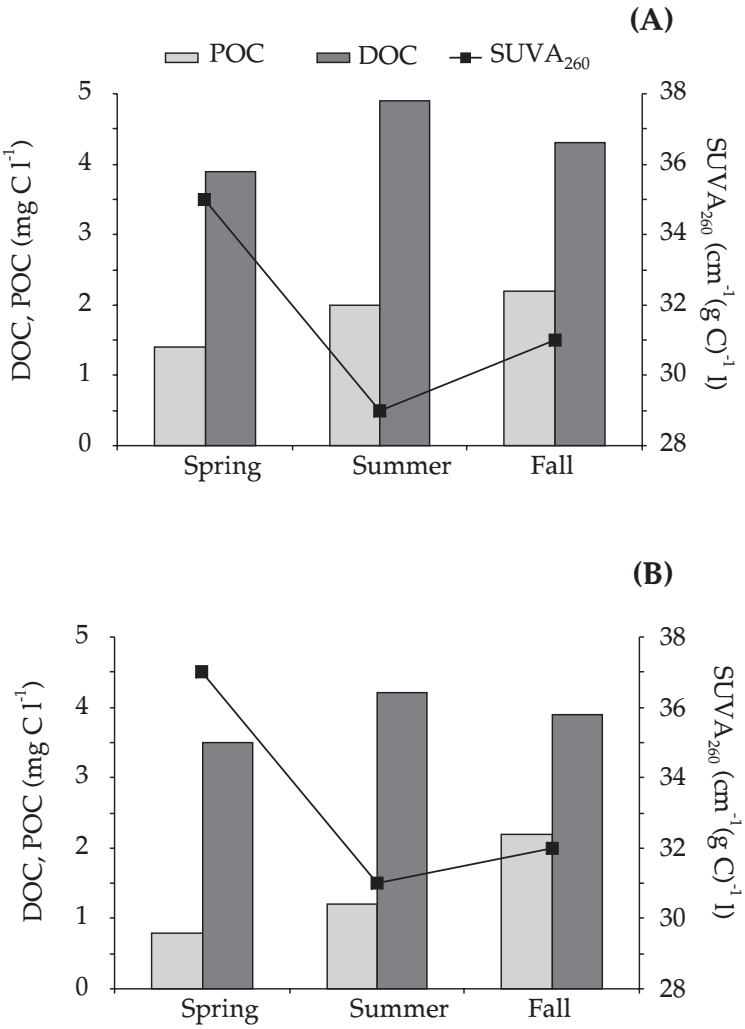

Fig. 4. Seasonal variability in the contents of DOC and POC as well as the value of SUVA in the surface layers of lakes Święte (A) and Łańskie (B).

during the summer in Lake Łańskie, which is also confirmed by other physical and chemical parameters. In Lake Święte in April 2005 the following parameters were noted: oxygen oversaturation in the surface water layer to values of 153.7%; visibility of 1.5 m; chlorophyll concentration 4.6 g l^{-1}; pH = 8.7, which was the highest value obtained throughout the investigation season. Primary production processes were not observed to intensify in Lake Łańskie until June, when the lowest visibility (1.7 m) and the highest pH (8.4) were noted. Water oxygen saturation remained at a level of 105.4%.

The concentrations of phosphorous and total nitrogen also provide evidence of the varied advancement of the studied lakes' trophic levels. The concentrations of these elements in Lake Święte were higher by means of 0.08 mg for P l^{-1} and 0.19 mg for N l^{-1}. With regard to organic carbon as a trophic indicator, the mutual ratio between the contents of DOC and POC and the value of the $SUVA_{260}$ parameter are significant. Increases in the concentration of DOC in summer in relation to that in spring along with a simultaneous decrease in the value of $SUVA_{260}$ indicate the accumulation of autochthonous organic material in both basins (Fig. 4). The source of this is the decomposition process of molecular matter, the products of photosynthesis, and autolysis. Meanwhile, the higher concentrations of both DOC and POC in Lake Święte in comparison to those in Lake Łańskie attest to the greater productivity in the former basin (Fig. 4). This concurs with the studies of Wetzel (1990) and Górniak (1996), which both indicated that levels of DOC and POC increase as tropic status increases.

According to the trophic state index (TSI) by Carlson (1977), based on water transparency (TSI_{SD}) and chlorophyll content (TSI_{Chl}), Lake Święte is eutrophic and Lake Łańskie is mesoeutrophic (Zdanowski et al. 2006). Similar assessments of trophic status were derived using methods proposed by Hillbricht-Ilkowska and Kajak (1986) and Vollenweider (1989). According to the DOC concentration range reported by Lampert and Sommer (1996), both lakes can be classified as basins in which there is a paucity of humic substances since the concentration of DOC was within the range of 2 – 25 mg l^{-1}. In accordance with the criteria proposed by Thurman (1985), Lake Łańskie is mesotrophic (mean value of DOC 3.9 mg l^{-1}; range 2.9 – 4.7 mg l^{-1}). Lake Święte should also be classified as mesotrophic (mean value of DOC 4.2 mg l^{-1}; range 3.1 – 5.4 mg l^{-1}); the variability of DOC concentrations does indicate, however, that this lake is more eutrophic.

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STRESZCZENIE

WĘGIEL ORGANICZNY JAKO WSKAŹNIK RÓŻNICUJĄCY TROFIĘ DWÓCH JEZIOR GÓRNEGO BIEGU ŁYNY (POJEZIERZE MAZURSKIE, POLSKA)

Celem badań było prześledzenie sezonowej zmienności oraz dynamiki węgla organicznego, a na tej podstawie określenie produktywności wód jezior Święte i Łańskie (tab. 1). Badania prowadzono w latach 2004 i 2005, począwszy od cyrkulacji wiosennej (kwiecień), poprzez stagnację letnią do cyrkulacji jesiennej (listopad). Analizowano zawartość całkowitego węgla organicznego (TOC) oraz jego frakcji rozpuszczonej (DOC) i zawieszonej (POC). Jakość rozpuszczonej materii organicznej określono wartością absorbancji znormalizowanej względem DOC (parametr $SUVA_{260}$). Charakterystykę fizyko-chemiczną wód zbadanych zbiorników podano w tabeli 2.

Wyniki badań wykazały wyraźne zróżnicowanie w ilości ogólnego węgla organicznego (TOC) w zbadanych jeziorach. Wyższe stężenia (średnio o 1,2 mg l^{-1}) oznaczono w Jeziorze Święte (rys. 1). W obu zbiornikach dominującą formą TOC był rozpuszczony węgiel organiczny (DOC). W Jeziorze Święte stanowił on 70%, a w Jeziorze Łańskie 75% jego ogólnej zawartości. Materia organiczna w obu zbiornikach miała podobną strukturę jakościową, o czym świadczą zbliżone wartości wskaźnika $SUVA_{260}$ (rys. 2). Jej głównym źródłem była autochtoniczna materia organiczna. Wyraźnie wyższą zawartość POC oraz DOC, a tym samym intensywniejszą produkcję pierwotną, stwierdzono w Jeziorze Święte (rys. 3, 4). Potwierdzają to wyższe wartości chlorofilu, niska widzialność oraz przetlenienie powierzchniowych warstw wody. Zgodnie z kryteriami zaproponowanymi przez Thurmana (1985), Jezioro Łańskie ma charakter mezotroficzny (śr. wartość DOC 3,9 mg l^{-1}; zakres 2,9-4,7 mg l^{-1}). Jezioro Święte należy również zaliczyć do typu mezotroficznego (śr. wartość DOC 4,2 mg l^{-1}; zakres 3,1-5,4 mg l^{-1}). Zmienność zawartości DOC wskazuje jednak na większy stopień eutrofizacji tego jeziora.