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THE INFLUENCE OF MINERAL FERTILIZATION ON PHYTOPLANKTON PRODUCTION IN LAKES OF VARIOUS TROPHIC TYPES

ABSTRACT: Investigations were carried out during the 1970–1974 period on the influence of mineral fertilization on phytoplankton production in four lakes differing trophically and morphometrically. Greatest changes in the chemism of water were noted in two dystrophic lakes. Change in the trophism of these lakes led to a growth of phytoplankton production during the first two years of fertilization. Fertilizing of the lakes during following years did not influence an increase in the level of their eutrophication.

Contents

1. INTRODUCTION

One of the methods used in investigating eutrophication of lakes consisted of experimental studies on changes in the lakes under the influence of fertilization. In conditions of controlled nutrient intake efforts were principally made to determine the circulation of salts introduced into the lakes in the form of fertilizers or of elements labelled with radioactive isotopes, limited as a rule to two basic components, namely nitrogen and phosphorus compounds (Einsele 1941, Lackey and Sawyer 1945, Hutchinson and Bowen 1947, Hasler and Einsele 1948, Smith 1948, Coffin et al. 1949, Hayes and Coffin 1951, Hayes et al. 1952). At the same time observations were conducted on changes in the environment, in order to determine the optimal limits of eutrophication favourable from the point of view of fish production and water quality. A precise review of the literature referring to this problem is given by Abrosov (1967), Stewart and Rohlich (1967), and Winberg and Lachnowicz (1968). Most of the studies noted that changes in lakes under the influence of fertilization consisted of an abundant development of phytoplankton, chiefly of filamentous algae and macrophytes, and of the rapid removal from the water of the introduced nutrients (Ball 1950, Nelson and Edmondson 1955, Weatherley and Nichols 1955, Berge 1969, Kočevych 1972). The mentioned changes are at times accompanied by a disruption of the equilibrium between primary production of the epilimnion and oxygen supplies in the hypolimnion, leading in effect to the occurrence of oxygen deficit in the hypolimnion, and in extreme cases to the appearance of winter fish kill (Ball 1950). Likewise changes in the dominance and growth of phytoplankton, zooplankton and bottom fauna numbers were observed under the influence of fertilization, as also improvement in the growth condition of introduced or naturally occurring fish (Nelson and Edmondson 1955, Smith 1955, Weatherley and Nichols 1955).

In determining trends of changes under conditions of controlled eutrophication processes, and utilization of results obtained for fishery requirements, it is necessary to carry out long term experimental studies. With this in mind complex investigations are being conducted since 1970 by the Inland Fisheries Institute in Olsztyn, the Institute of Ecology of the Polish Academy of Sciences in Dziekanów Leśny, and by the Zoological Institute of the Warsaw University in Warsaw on four lakes differing from a trophic and morphometric aspect. Mineral fertilization was applied to these water bodies, creating a model situation of accelerated eutrophication in the lakes. The present study constitutes a part of the mentioned complex studies, and was aimed at determining changes in phytoplankton production under the influence of mineral fertilization.

2. METHODS

2.1. General characteristics of lakes under study

Four lakes differing with respect to trophic and morphometric character were selected for investigation: lakes Smolak, Piecek, Dgał Mały and Czarna Kuta (Masurian Lakes' Region). Description and limnological characteristics are given in Table I.

Lake Smolak. An inter-forest water body deprived of water inflow and outflow, very low pH (around 4.5) and low calcium content (Patalas 1960c, Korycka 1969, Sosnowska 1974). On the basis of Stangenberg's (1936) criteria the lake is classified as an extremely dystrophic body characterized, according to studies by Patalas

Table I. General characteristics of investigated lakes

Parameters				Smolak*	Piecek*	Dgał Mały**	Czarna Kuta*
Surface in ha				5.3	23.3	14.3	25.2
Depth in m	maximum			5.1	8.4	15.8	3.6
	average			2.4	3.4	4.3	1.3
Volume in m^3 (thousands)				129.8	788.7	619.3	345.7
Maximal width in m				160	280	340	550
Maximal length in m				500	1,500	650	1,000
Development of shore line				1.50	1.60	1.28	1.50
Depth of epilimnion in m				1.5–4	2–5	4–6	up to the bottom
Temperature in summer (June-Aug.) in ^{o}C	in the layer	surface	highest	26.3	27.6	27.0	27.1
			lowest	18.2	17.4	17.0	16.3
		bottom	highest	20.4	12.0	7.6	27.0
			lowest	12.4	8.8	5.6	16.8
	annual average		surface	14.4–17.6	12.4–17.3	12.9–17.8	12.6–17.3
			bottom	11.5–13.1	7.8–10.0	5.4–7.1	11.8–16.0
Length of stagnation			summer	May-Aug.	May-Sept.	May-Oct.	no stagnation
			winter	Jan.-March	Jan.-March	Jan.-March	Jan.-March
Oxygen conditions			epilimnion	5.0 mg O_2/l up to 4 m	5.0 mg O_2/l up to 4 m	5.0 mg O_2/l up to 4 m	oxygen up to the bottom with periodic deficits
			matalimnion	drop of oxygen, strong deficits in the year of fertilization	deficits of oxygen	deficits of oxygen	–
			hypolimnion	–	–	no oxygen, H_2S	–
Trophic type				highly dystrophic	dystrophic/ /eutrophic	eutrophic	highly eutrophic

*According to Kondracki and Szostak (1960). ** According to morphometric data of Inland Fisheries Institute (1970).

(1960c, 1960d), as having a very low content of mineral salts and lowest primary production from among 44 lakes of the Masurian Lakes' Region investigated by this author. Only trace amounts of nitrates and phosphates occur, and calcium concentration was around 2.0 mg/l in summer and 6.0 mg/l in winter. Lake Smolak is a stratified water body (epi- and metalimnion), dimictic, representing the II grade of lake stability (P a t a l a s 1960a). The catchment basin of the lake consists of a coniferous forest supplying it with considerable amounts of organic matter and humic acids. The shores are overgrown with *Carex* sp. and *Sphagnum* sp., forming overhangings penetrating the lake. Formation of a littoral is lacking (P i e c z y ń s k a 1972). Bottom sediments are brown and gelatinous with a large admixture of allochthonous plant parts. Lake Smolak is characterized by very low numbers of phytoplankton, zooplankton and fish (Z a w i s z a 1961, P a t a l a s 1963, S o s n o w s k a 1974).

L a k e P i e c e k. According to S t a n g e n b e r g's (1936) typology this lake is classed between dystrophy and low eutrophy. It is a stratified water body (epi-, metalimnion), dimictic, representing the IV grade of lake stability (P a t a l a s 1960a). Chemical properties of the water are not typical. At a very low calcium, sodium and magnesium content potassium content was high reaching around 3–8 mg/l (P a t a l a s 1960c, K o r y c k a 1969). The species composition of higher plants is likewise untypical (lack of submerged vegetation). Sixty per cent of the shoreline is overgrown with vegetation occurring in eutrophic lakes (*Typha latifolia* L., *T. angustifolia* L., *Acorus calamus* L. and *Phragmites communis* Trin.), while the remaining shows species characteristic for dystrophic lakes (*Calla palustris* L., *Menyanthes trifoliata* L.). The littoral of around 1 m in width occupies 10% of the area of the water body. Inflows and outflows are lacking. Lake Piecek is characterized by low numbers of zooplankton, bottom fauna and fish (Z a w i s z a 1961, P a t a l a s 1963, L e s z c z y ń s k i 1969).

L a k e D g a ł M a ł y. This water body is located in a deep valley surrounded by sandy hills overgrown with a coniferous forest. It is distinguished by the greatest depth and a very stable thermal condition (epi-, meta- and hypolimnion), and in summer by a high oxygen deficit in the metalimnion. It is a dimictic and eutrophic body (S t a n g e n b e r g 1936). The area at the inflow from Lake Dgał Wielki and outflow to Lake Dargin is lower and wet. The littoral 1–3 m in width occupies 22% of the area of the lake. It is mainly overgrown with *Phragmites communis* (21.6% of the littoral) and *Ceratophyllum demersum* L. (65.5%) (B e r n a t o w i c z 1965, G e r l a c z y ń s k a 1973).

L a k e C z a r n a K u t a. This is a polymictic water body (W i s z n i e w s k i 1953, O l s z e w s k i and P a s c h a l s k i 1959), highly eutrophic (S t a n g e n b e r g 1936) due to inflowing sewage from the village Kuta located above the lake (north-eastern affluent). The southern affluent carries waters from nearby lying pastures and meadows, while a stream constitutes the outflow into Lake Głęboka Kuta. Sands covered with a coniferous forest make up the water basin. The highly boggish littoral occupies some 10% of the area of the lake (P i e c z y ń s k a 1972). As concerns vegetation *Phragmites communis*, *Acorus calamus*, *Carex* sp., *Typha latifolia*, *Batrachium circinatum* Sibth (Fr.), *Myriophyllum spicatum* L., *Potamogeton compressus* L. and *P. perfoliatus* L. are dominant.

2.2. Field operations

Observations carried out on the above mentioned lakes over the period 1970–1974 include the year preceding fertilization (1970), treated as a control, and four years of investigations during which the lakes were fertilized. Nitrogen-phosphorus fertilization was effected on each lake at three periods in each year – in May, June and July. For this purpose pulverized 35% ammonium nitrate and 28% super-Thomas slag was applied. Pulverized 50% potassium salts were applied in May of each year on three lakes, Lake Piecek being an exception. Lake Piecek was not fertilized with the last mentioned component in view of similar supplies of potassium as compared to the eutrophic lakes (P a t a l a s 1960c, K o r y c k a 1969). The dystrophic lakes (Smolak and Piecek) were given calcium once each year in winter in the form of 34% agricultural limestone (1971–1972), while during the years 1973–1974 the littoral belt and not the pelagial was fertilized. In addition ammonia water was given to Lake Smolak during the winter of 1971 (625 kg/ha).

Table II. Type and total amounts (kg/ha) of fertilizers introduced into the investigated lakes in 1971–1974
In parentheses single doses of fertilizers introduced each time

Lake	Potassium salt 50%	Ammonium nitrate 34%	Thomas slag 28%	Agricultural lime 35%
Smolak*	980.0 (245.0)	578.4 (48.2)	233.9 (19.5)	15,840.0 (3,960.0)
Piecek	–	1,167.4 (106.2)	281.5 (25.6)	19,880.0 (4,970.0)
Dgał Mały	980.0 (245.0)	839.4 (70.0)	197.1 (16.4)	–
Czarne Kuta	556.0 (139.0)	475.9 (39.6)	111.8 (9.3)	–

*In February, 1971, 625 kg/ha of ammonia liquor were introduced into Lake Smolak.

Dosage of fertilizers to the volume of lakes Smolak, Piecek and Czarna Kuta were in accordance with suggestions by A b r o s o v (1967). The amount of biogenic substances after dissolving in the water of the lakes, calculated as pure components was to be around 1 mg N/l, 0.1 mg P/l, 4 mg K/l and 40 mg Ca/l. Concentration dosages of calcium and potassium correspond to the average values observed in the eutrophic lakes of the Masurian and Suwałki regions (S t a n g e n b e r g 1936, P a t a l a s 1960c, S z c z e p a ń s k i 1968, K o r y c k a 1969), while those of nitrogen and potassium correspond to the recommendations by A b r o s o v (1967). The concentration of added doses of biogenic substances in Lake Dgał Mały was one half less. Lower fertilizer dosage was applied because of technical reasons. Table II presents the amounts of fertilizers applied in each of the lakes.

Measurements of primary production were carried out in 1970 once each month from May to November. Observations in 1971 were conducted according to the following plan: one measurement in April within ten days after disappearance of ice; in May, June and July one day before each fertilization, and 1, 3, 5, 7, 14, and 21 days after each fertilization; in September, October and November one measurement in each of the last mentioned months. In 1973–1974 the number of observations for the months of fertilization were limited to three.

One position of measurement was selected near the kettle assuming that samples from this position are characteristic for the pelagial as a whole of the lakes under study. This was confirmed by production measurements carried out at six points selected at random on Lake Dgał Mały (June 29th, 1973). Primary production at these positions ranges from 4.75 to 5.25 g O_2/m^2 per day, constituting a difference of the order of ± 5%.

2.3. Method of phytoplankton production measurement

Phytoplankton production was determined by means of the oxygen method of dark and light botles (Winberg 1960). Samples were taken by means of a Ruttner sampler at depths from the surface to five meters, at every meter, and exposed in bottles of around 120 ml capacity at the same depths for twenty-four hours. In view of their small depth, the whole layer of water was taken into consideration in the investigations concerning lakes Smolak and Czarna Kuta. Production measurements up to a depth of five meters in the remaining lakes included the whole trophogenic layer.

Oxygen was determined by means of the non-modified Winkler method with an accuracy of up to 0.05 mg/l. Daily gross production and respiration were expressed in mg of O_2/l for specific depths, and in g of O_2/m^2 of lake surface as the sum of production from the surface to 5 m, or calculated in calories by applying the equation 1 mg O_2 = 3.51 cal (Winberg 1960). The share of respiration in gross production was likewise calculated. This coefficient was calculated for the trophogenic layer and expressed in percentages, and was treated as additional information relating to "net" production and decomposition of organic matter.

2.4. Methods for investigations on the environment

Temperature of the water was measured at each position with an accuracy of up to 0.1°C, as also oxygen content in a vertical profile and water transparency by means of Secchi's disc. Light transmission in the water was measured by means of a selenium photoelement with a maximal sensitivity ranging within a light spectrum of 400–700 nm. Results were given in percentages in relation to values noted for the surface layer. Chemical analyses of water were carried out on the basis of the method described by Just and Hermanowicz (1955).

3. WATER CHEMISM

Description of the water chemism of the lakes under study, as influenced by fertilization, was based on partially published data by Anna Korycka, M.Sc., and Dr. Jerzy Zachwieja (Bnińska et al. – in press, Zdanowski et al. – in press).

Lake Czarna Kuta was found to be the richest in mineral components and Lake Smolak the poorest. Lake Piecak in 1970 was fairly untypical with respect to water chemism, having a very low content of a number of elements at a similar potassium content (3- 8 mg/l) in comparison with the eutrophic lakes (Patalas 1960c, Korycka 1969).

Chemism of the water in the lakes under study changed under the influence of fertilization, this being true especially of the dystrophic ones. Changes in these lakes refer to constant growth of calcium and potassium content (Fig. 1). After four years of fertilization average annual concentration of calcium in Lake Smolak increased 30 times (from 1.0 to 29.0 mg/l) in the surface layers, and 20 times (from 1.5 to 33.0 mg/l) in the bottom layer. The increase in calcium content in Lake Piecek was lower – 9 times in the surface layer (from 3.0 to 27.0 mg/l)

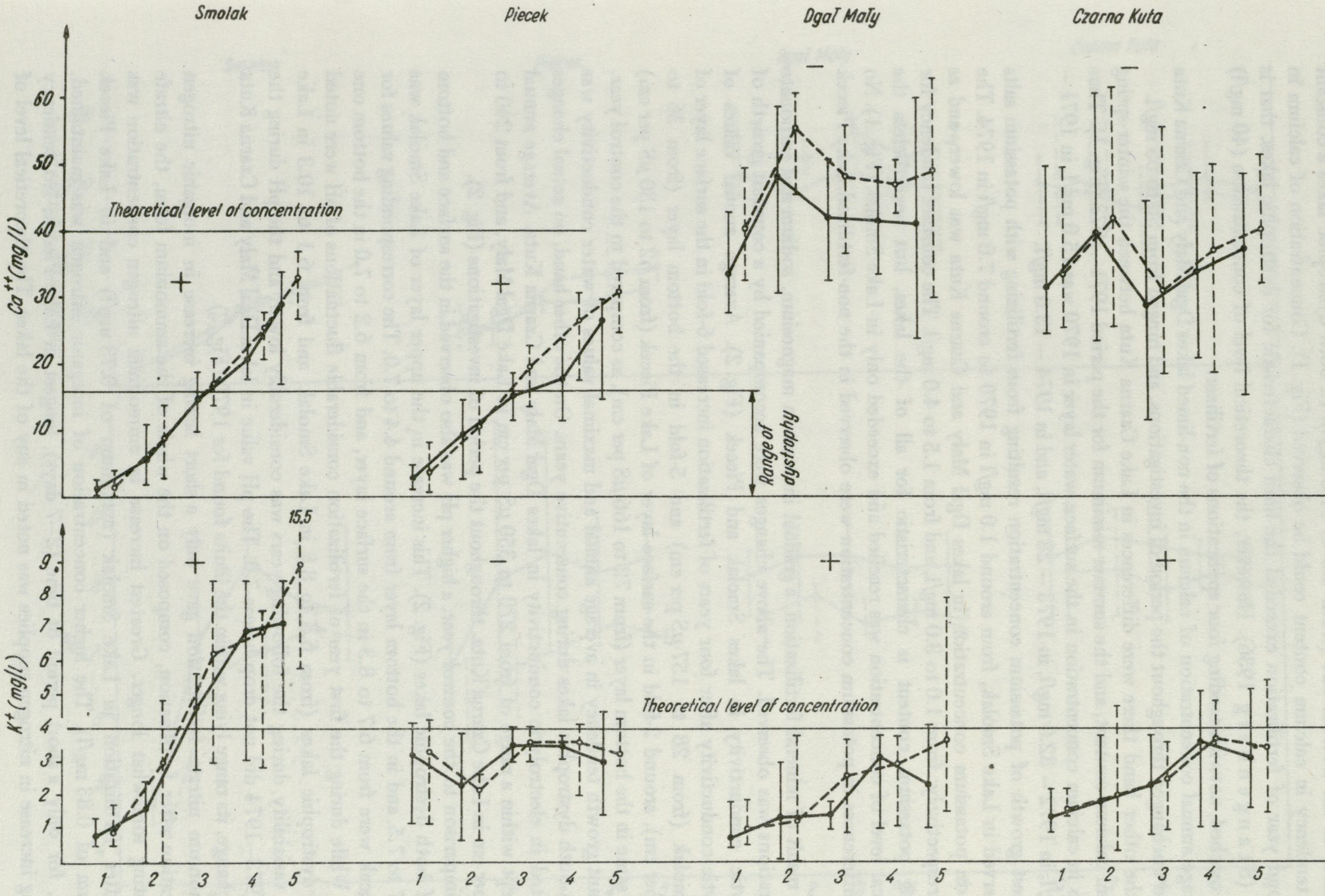

Fig. 1. Range of variability and average annual content of calcium and potassium in surface (continuous line) and bottom (broken line) layers of water of the lakes under study in 1970–1974

1–5 – consecutive years of investigation, + – fertilized lakes, – – non-fertilized lakes and 8 times in the bottom one (from 4.0 to 31.0 mg/l). In both dystrophic lakes a constant growth tendency in calcium content could be observed (Fig. 1). Concentration of calcium in the second year of fertilization exceeded the limit characteristic for dystrophic lakes, that is 16 mg/l (Stangenberg 1936). However, the theoretical level of concentration (40 mg/l) was not reached, notwithstanding four applications of fertilizer.

Average annual concentration of calcium in the non-limed lakes Dgał Mały and Czarna Kuta remained unchanged throughout the period of investigations, and ranged from 30 to 55 mg/l.

On the other hand there were differences in Lake Czarna Kuta between the winter-spring maximum calcium content, and the summer minimum for the period 1971–1973 (Fig. 1). Thus the drop in calcium concentration in the surface water layer in 1970 was 15.0 mg/l, in 1971 – 27.0 mg/l, in 1972 – 32.0 mg/l, in 1973 – 28 mg/l, and in 1974 – 13.0 mg/l.

Highest growth of potassium concentration resulting from fertilizing with potassium salts was observed in Lake Smolak, from around 1.0 mg/l in 1970 to around 7.0 mg/l in 1974. The increase in potassium concentration in lakes Dgał Mały and Czarna Kuta was lower, and as follows respectively: from 1.0 to 3.0 mg/l, and from 1.5 to 4.0 mg/l. The constant tendency for increasing potassium content is characteristic for all of the lakes, but nevertheless the theoretical level of concentration was reached and exceeded only in Lake Smolak (Fig 1). No actual differences in potassium concentration were observed in the non-fertilized Lake Piecek (Fig. 1).

As a result of mineral fertilization, a gradual increase in magnesium, sodium and carbonate concentrations was observed. The above changes were accompanied by a constant growth of electrolytic conductivity in lakes Smolak and Piecek (Fig. 2). Average annual values of electrolytic conductivity after four years of fertilization increased 6-fold in the surface layer of Lake Smolak (from 28 to 157 μS per cm) and 5-fold in the bottom layer (from 36 to 174 μS per cm), around 2-fold in the surface layer of Lake Piecek (from 62 to 130 μS per cm) and the same in the bottom layer (from 72 to 166 μS per cm), as compared to the control year. A constant growth tendency in average annual and maximal values of water conductivity was noted in both dystrophic lakes during consecutive years. On the other hand, no actual changes were noted in electrolytic conductivity in lakes Dgał Mały and Czarna Kuta. Average annual values kept within a range of from 270 to 350 μS per cm in Lake Dgał Mały, and from 240 to 280 μS per cm in Lake Czarna Kuta, throughout the period of investigations (Fig 2).

In comparison to the control year, a higher pH was also observed in the surface and bottom layers of both dystrophic lakes (Fig. 2). This increase in the upper layer of Lake Smolak was from 4.7 to 7.5, and in the bottom layer from around 4.4 to 7.0. The corresponding values for Lake Piecek were from 6.7 to 8.3 in the surface layer, and from 6.2 to 7.0 in the bottom one (Fig. 2). While during the first year of fertilization considerable fluctuations of pH were noted in both dystrophic lakes (from 6.3 to 8.8 in Lake Smolak, and from 6.1 to 10.3 in Lake Piecek), variability during the following years was considerably lower, and the pH during the period 1973–1974 did not drop below 7.0. The pH value in lakes Dgał Mały and Czarna Kuta did not change, its range lying within the limits found for 1970 (Fig. 2).

Ammonium nitrate fertilization gave only a short lasting increase in inorganic nitrogen concentration after fertilization, composed on the whole of the ammonium form, the nitrate form lasting somewhat longer. Greatest increase in ammonium nitrogen concentration was noted after fertilization in Lake Smolak (maximum of 0.73 mg/l) and in Lake Piecek (maximum of 0.83 mg/l). The higher concentration of inorganic nitrogen was maintained, however, for only a short period of time (2–7 days), longest in Lake Piecek. No tendency indicating increase in nitrogen supplies was noted in any of the lakes. The theoretical level of

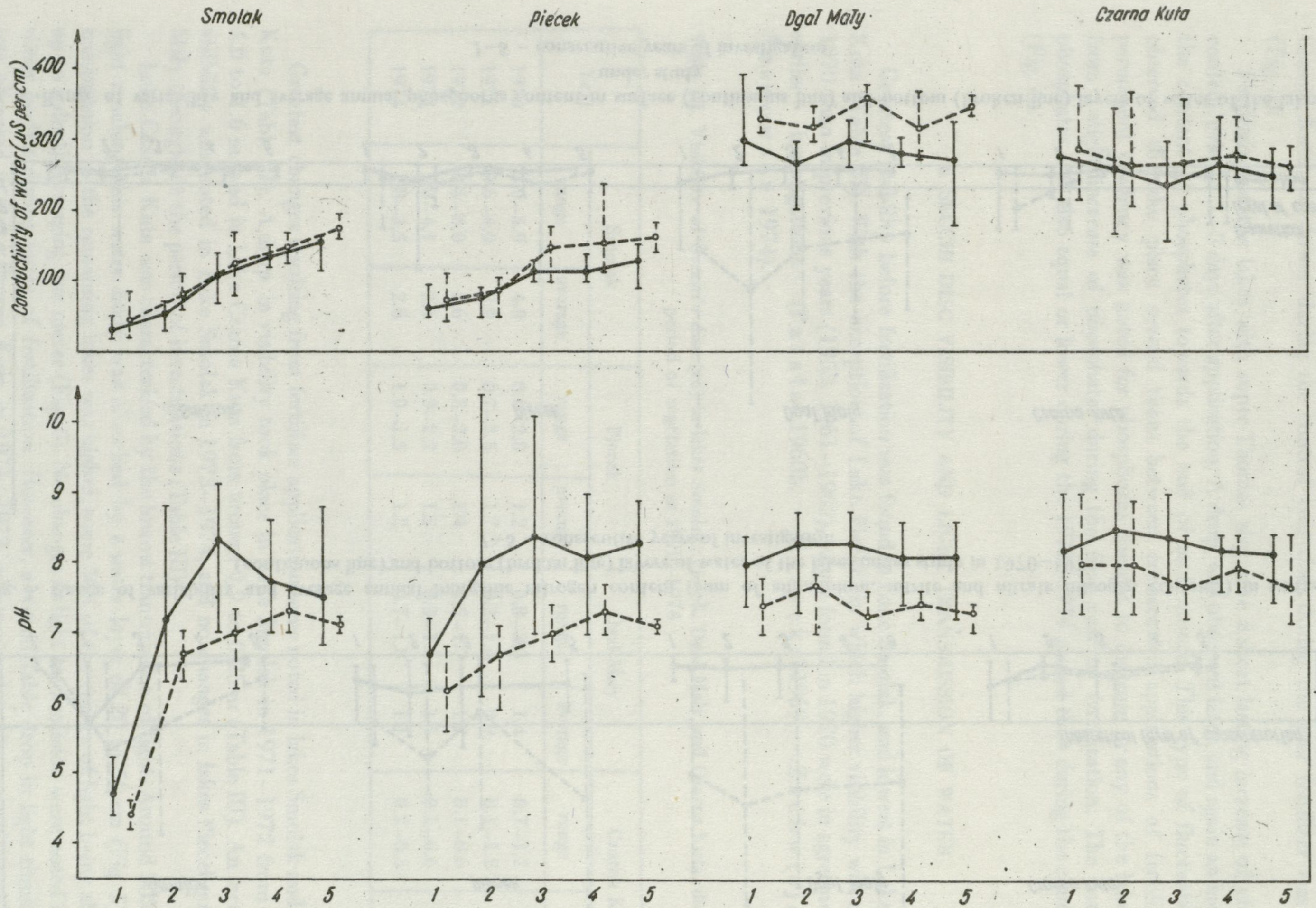

Fig. 2. Range of variability and average annual value of electrolytic conductivity and pH in surface (continuous line) and bottom (broken line) layers of water of the lakes under study in 1970–1974

1–5 – consecutive years of investigation

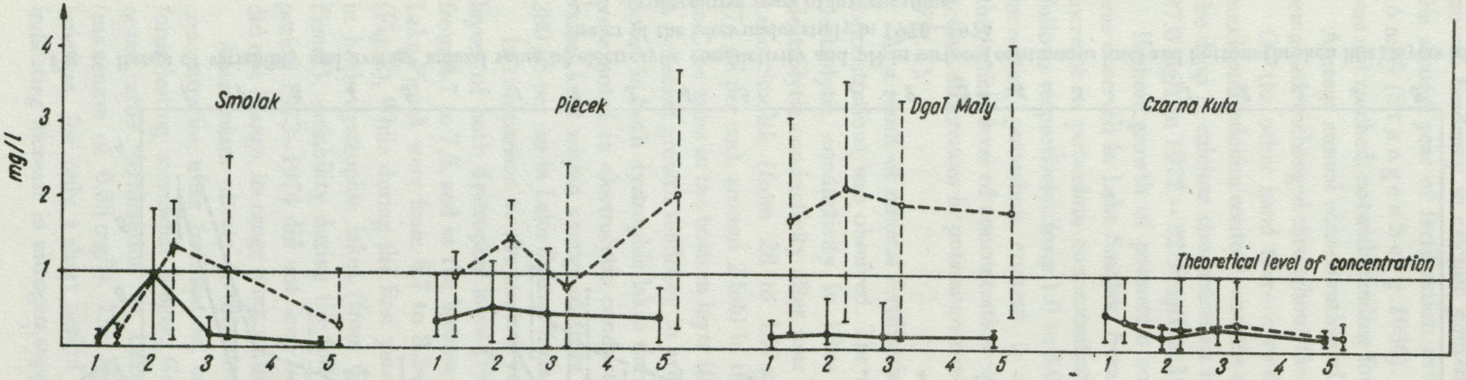

Fig. 3. Range of variability and average annual inorganic nitrogen content (sum of ammonium, nitrite and nitrate nitrogen contents) in surface (continuous line) and bottom (broken line) layers of water of the lakes under study in 1970–1974
1–5 – consecutive years of investigation

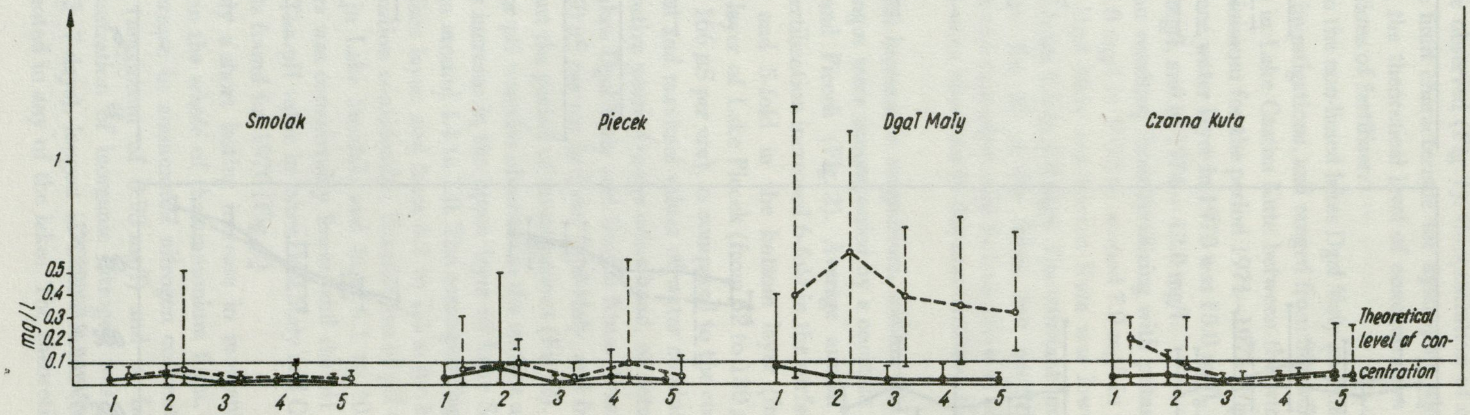

Fig. 4. Range of variability and average annual phosphorus content in surface (continuous line) and bottom (broken line) layers of water of the lakes under study
1–5 – consecutive years of investigation

concentration (maximal values), as compared to the control year, was exceeded after fertilization in lakes Smolak and Piecak only, whereas nitrogen concentration in lakes Dgał Mały and Czarna Kuta was lower during the control year than during the year fertilizer was applied (Fig. 3).

Fertilizing of the lakes with super-Thomas slag gave a short lasting increase of phosphate content evident 1–5 days after application. A drop was observed later, and again an increase in the content of phosphates towards the end of each month. This type of fluctuations was observed to take place several times between consecutive applications of fertilizer. No permanent tendency was noted for phosphorus content to increase in any of the lakes, apart from a slight increase of phosphates during the first year of fertilization. The content of phosphates was also equal or lower during the 1972–1974 period than during the control year (Fig. 4).

4. SECCHI DISC VISIBILITY AND LIGHT TRANSMISSION OF WATER

Greatest visibility before fertilization was found in Lake Smolak, and lowest in Lake Czarna Kuta (Table III). With the exception of Lake Piecek, in which higher visibility was noted in 1970 than in previous years (1953, 1961–1962), values found in 1970 were in agreement with earlier investigations (Patalas 1960b, Korycka 1969, Zachwieja 1972, Sosnowska 1974).

Table III. Visibility of Secchi's disc (m) in lakes Smolak, Piecek, Dgał Mały and Czarna Kuta, during the period of vegetation in 1970–1974

Year	Smolak		Piecek		Dgał Mały		Czarna Kuta	
	range	average	range	average	range	average	range	average
1970	3.0–5.9	4.0	0.6–2.8	1.2	0.8–2.3	1.4	0.7–1.2	0.9
1971	0.6–4.0	2.0	0.7–3.5	1.7	0.2–1.8	0.9	0.1–1.2	0.5
1972	0.6–3.0	1.6	0.8–2.0	1.4	0.5–1.7	1.2	0.1–0.6	0.2
1973	1.8–4.1	2.6	0.9–2.2	1.5	0.8–1.5	1.1	0.1–0.6	0.4
1974	1.8–3.5	2.8	1.0–1.5	1.2	0.7–1.8	1.1	0.2–0.5	0.3

Greatest changes resulting from fertilizer application were noted in lakes Smolak and Czarna Kuta (Table III). A drop in visibility took place in Lake Smolak in 1971–1972 from around 4.0 to 1.6 m, and in Lake Czarna Kuta from around 0.9 to 0.25 m (Table III). An increase of visibility was noted in Lake Smolak in 1973–1974, and no changes in lakes Piecek and Dgał Mały throughout the period of investigations (Table III).

Lake Czarna Kuta was characterized by the lowest transmission of light. Around 50% of the light reaching this water body was absorbed by a water layer of 20 to 50 cm (Fig 5). Light transmission in the remaining lakes was higher, some 50% of the energy of light being absorbed up to a depth averaging one meter (Fig. 5). No changes in light transmission were noted in these water bodies during years of fertilization. However, a considerable drop in light transmission was observed in Lake Czarna Kuta in 1971–1973, as compared to the control year (Fig. 6). Actually the layer of water below one meter was devoid of light.

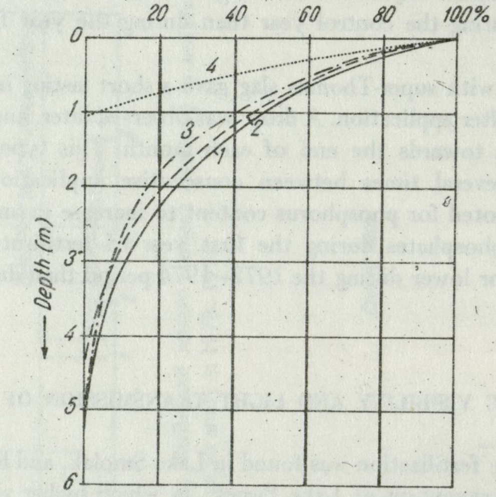

Fig. 5. Characteristic curves of light transmission in the lakes in June 1972
1 – Lake Smolak, *2* – Lake Piecek, *3* – Lake Dgał Mały, *4* – Lake Czarna Kuta

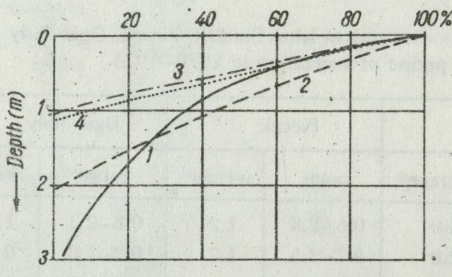

Fig. 6. Characteristic curves for light transmission in Lake Czarna Kuta in July 1970–1973
1 – 1970, *2* – 1971, *3* – 1972, *4* – 1973

5. GROSS PHYTOPLANKTON PRODUCTION

5.1. General

Measurements of primary production carried out during the control year (1970) showed great differences between lakes with respect to production and respiration. As supplies of mineral matter were artificially increased in the lakes, actual changes in production were found, expressed by an increase in the upper layers of water (0–1 m). In view of the fact that the observed changes, after application of fertilizers was begun, differed in each of the water bodies and had different practical consequences, each lake is discussed separately, consecutively from that of low to high production, assuming 1970 as the starting point.

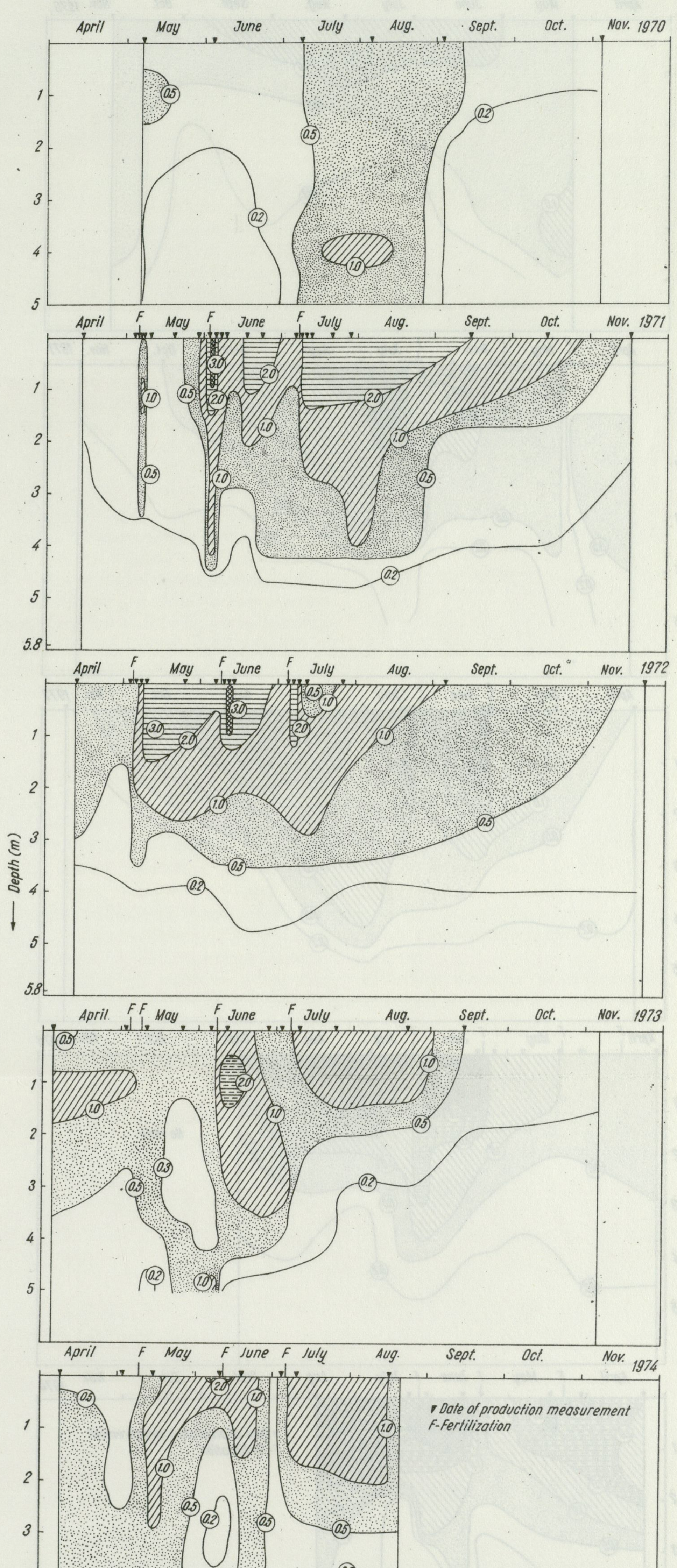

Fig. 7. Isopleths for gross primary production (mg 0_2/l per day) representing variations in time and depth in Lake Smolak in 1970–1974

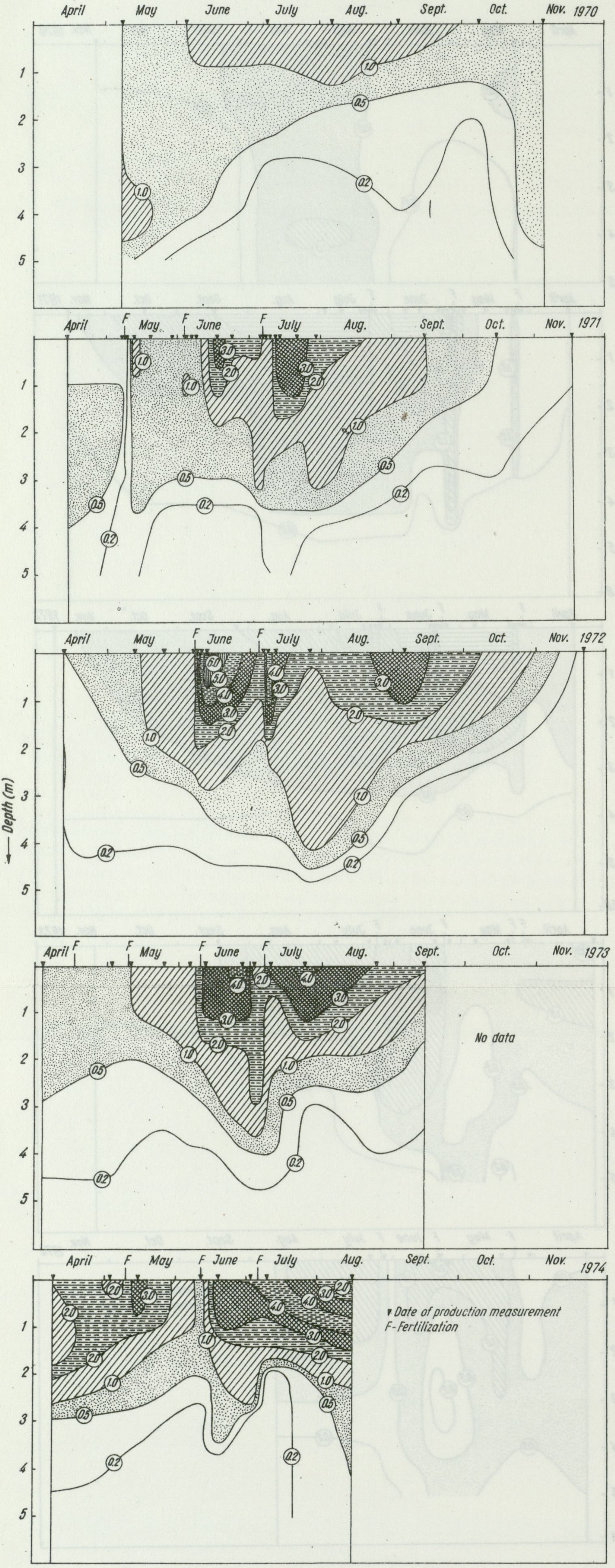

Fig. 9. Isopleths for gross primary production (mg 0_2/l per day) representing variations in time and depth in Lake Piecek in 1970–1974

5.2. Lake Smolak

Dystrophic Lake Smolak was found to be of lowest production in 1970. Gross phytoplankton production under 1 m^2 of surface area was low and ranged from 0.5 to 3.1 g O_2/m^2 per day, with a maximum in the summer. "Net" production (gross production minus respiration of the whole complex) was zero during the mentioned year, or showed minus values.

During the spring and autumn seasons maximal production of Lake Smolak was noted in the surface layers (0–1 m), while during the period of summer stagnation at a depth of 4 m (Fig. 7). Intensity of production at the various depths was low and ranged from 0.2 to 1.2 mg O_2/l per day (Fig. 7).

A considerable growth in gross production was noted in the surface layer under the influence of fertilization, this having resulted in a change of the character of the production curve in a vertical profile (Fig. 8). After first application of mineral fertilizers, gross production rose from 0.8 to 2.1 g O_2 per m^2 per day, with the maximal value at 1 m of depth (Fig. 7). Production fell to that noted before fertilization after several days. Production in a vertical profile continued to be typical for dystrophic lakes. A basic change took place after second fertilization in June of the same year. A considerable growth in gross production was noted, from 2.0 to 6.5 g O_2 per m^2 per day, remaining at this high level throughout the period of investigations in 1971–1972.

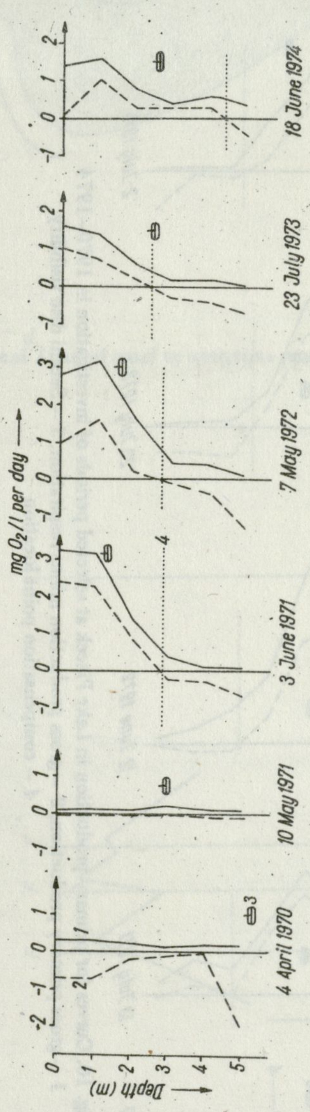

Fig. 8. Curves for primary production in Lake Smolak at selected periods of investigation in 1970–1974
1 – gross primary production, 2 – gross production minus respiration, 3 – Secchi disc visibility, 4 – compensation point location

Maximal production in Lake Smolak was noted beginning with June 1971 in the surface layers (0–1 m), the compensation level lying at an average depth of around 2.5 m (Fig. 8). As compared to 1971, reach of the trophogenic layer in 1972 was around 1 m less, this being conditioned by the higher production of the surface layer of water and its lower transparency in 1972 (Figs. 7, 8). Maximal production (P_{max}) in the trophogenic layer increased gradually from 0.7 mg O_2 per l per day in 1970 to 3.1 mg O_2 per l per day in the years of fertilization. Net production, impossible to determine in 1970, increased during the period 1971–1972 to around 2.0 mg O_2 per l per day.

A considerably lower reaction to each application of fertilizer was noted during the period 1973–1974 (Fig. 7). Production growth after fertilizing was not as great as in previous years. Maximal production (P_{max}) was 2.6 mg O_2/l per day in 1973, and 2.1 mg O_2/l per day in 1974 (Fig. 7).

5.3. L a k e P i e c e k

Lake Piecek was the second lake which reacted strongly to fertilization. Seasonal variability of gross production in 1970 and the production curve in a vertical profile differed considerably from typical characteristics for dystrophic lakes, as proved by high maximal production (P_{max}) in the surface water layer (1.5 mg 0_2/l per day; Fig. 9). Maximal production in the spring season of 1970 was noted at a depth of 4 m, and in the summer in the surface layer up to a depth of 1 m (Fig. 9). Location of the compensation level was as a rule observed at a depth of 2–3 m (Fig 10). As compared to the remaining lakes, this one was characterized by the lowest variability of seasonal production (from 1.2 to 4.5 g $0_2/m^2$ per day).

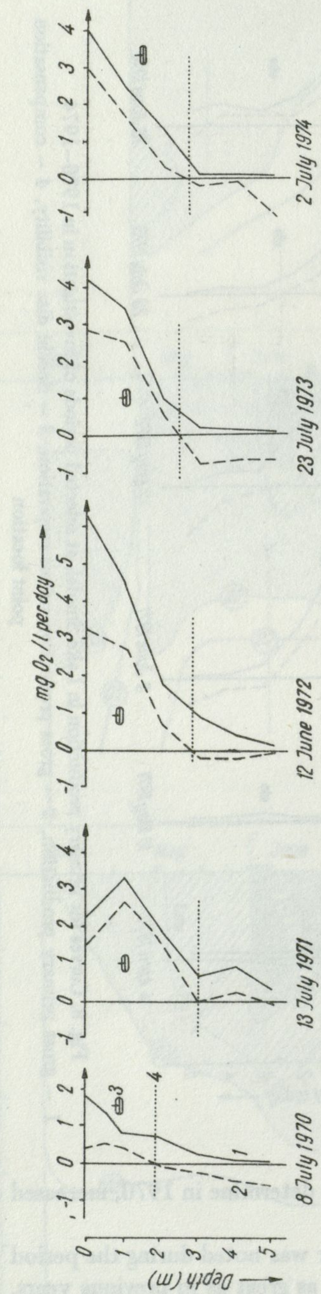

Fig. 10. Curves for primary production in Lake Piecek at selected periods of investigation in 1970–1974
1 – gross primary production, 2 – gross production minus respiration, 3 – Secchi disc visibility,
4 – compensation point location

It was noted that fertilization gave a stronger growth of production in the surface water layer than in Lake Smolak. The greatest effect of fertilization was observed in June and July of 1972, and a somewhat smaller influence during the first year of studies (Fig 9). Maximal production (P_{max}) was 6.3 mg 0_2/l per day, noted during the first two years of fertilizer application. The effect of fertilization was smaller in 1973–1974 than in 1972, but nevertheless maximal production was high – 4.8 mg 0_2/l per day (Fig 9).

During the first two years of fertilization production growth in Lake Piecek took place in a water layer of up to 3 m in depth, and in the third and fourth years of fertilization – up to 4 m (Fig. 9). In this connection production under 1 m^2 of lake surface gradually increased, reaching a maximum in June of 1972 (10.5 g $0_2/m^2$ per day).

The character of the production curve in Lake Piecek differed considerably from that in the control year. During the years fertilizer was applied production was sharp and was expressed as a decisive maximum in the surface layers, and its drop in the deeper layers of water (Fig 10). The compensation layer was found during years of fertilizing in the same layer of water as in the control year (Fig. 10).

5.4. L a k e D g a ł M a ł y

Lake Dgał Mały was characterized by the greatest seasonal variation of gross production in

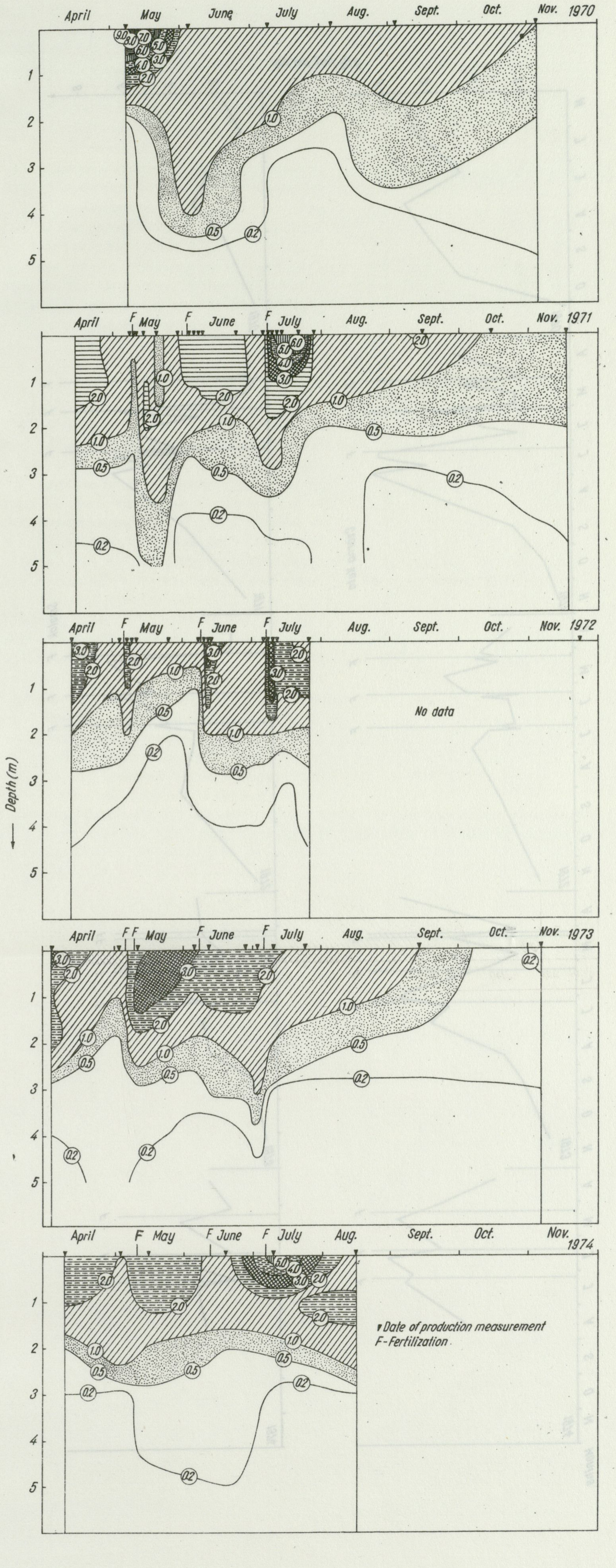

Fig. 11. Isopleths for gross primary production (mg O_2/l per day) representing variations in time and depth in Lake Dgał Mały in 1970–1974

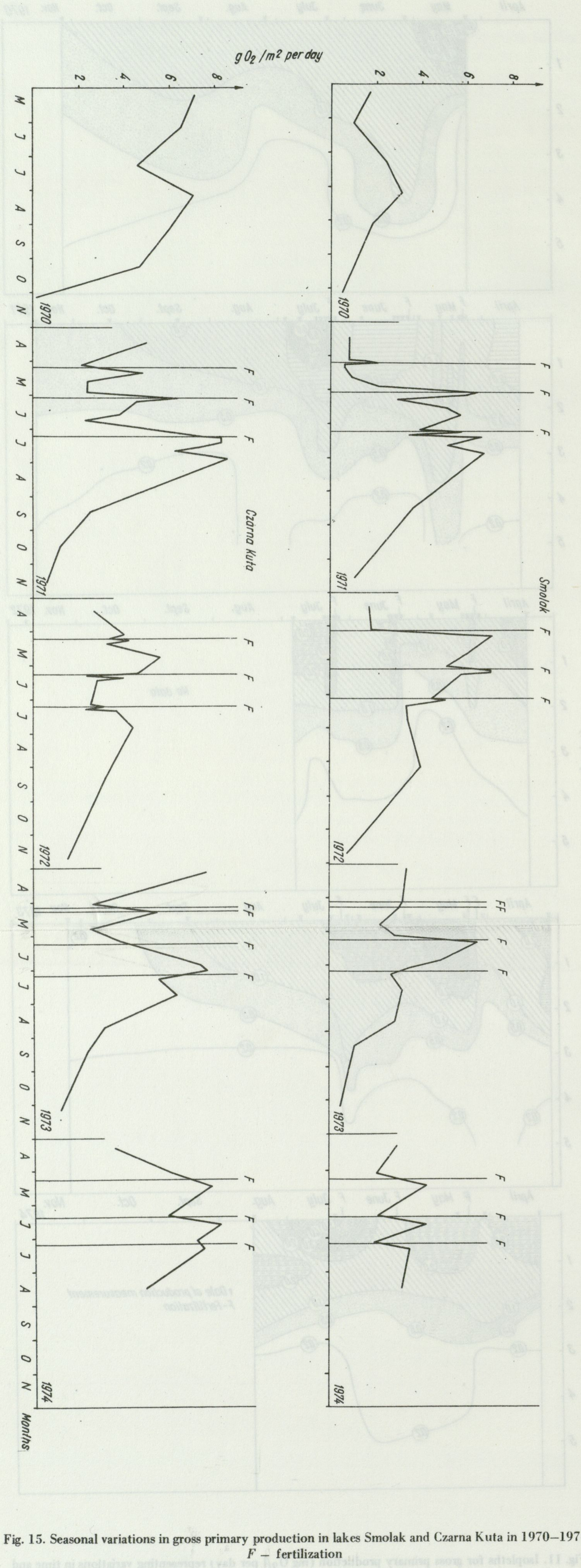

Fig. 15. Seasonal variations in gross primary production in lakes Smolak and Czarna Kuta in 1970–1974
F – fertilization

1970 (1.6–8.9 g O_2/m^2 per day). The maximum was noted in May, the minimum in summer. Most of the production in this water body took place in the upper two meter layer of water, and the compensation level was as a rule at a depth of 2–3 m (Figs. 11, 12).

Introduction of mineral matter into Lake Dgał Mały in one half lower applications did not give an expected effect as great as that for dystrophic lakes (Fig. 11). A slight and short lasting growth in production was noted only in July 1971, and after three consecutive fertilizer applications in 1972. During the remaining periods, no changes in gross production were noted. In comparison to the control year, the character of the production curve did not change in the following years, and likewise no change was noted in placement of the compensation level (Fig. 12). A change in the production maximum from the spring season to summer can be acknowledged as the only effect of fertilization (Fig. 11).

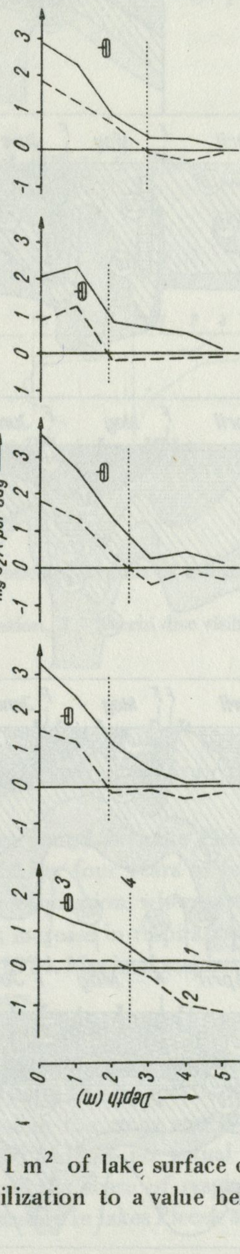

Fig. 12. Curves for primary production in Lake Dgał Mały at selected periods of investigation in 1970–1974
1 – gross primary production, 2 – gross production minus respiration, 3 – Secchi disc visibility, 4 – compensation point location

5.5. Lake Czarna Kuta

Lake Czarna Kuta represented a totally different character of gross production in 1970. This water body showed the highest gross production under 1 m^2 of surface (4.6–7.2 g O_2 per m^2 per day), the maximum of which was noted toward the end of summer. A considerable part of the production in Lake Czarna Kuta took place in the surface water layers, and its level was highly limited below a depth of 2 m (Figs. 13, 14). The compensation level was at a depth of around 1.5 m (Fig. 14).

Changes resulting from fertilizing the lake were expressed as a considerable growth in production in the surface layers (P_{max} – 8.0 mg O_2/l per day), and as an increased drop in production below a depth of 1 m during the period of fertilizer application (Fig. 13). Maximal production moved from a late summer period to the period of fertilization (July). The high level of production in the surface water layer resulted in a limitation of water transparency and in decreasing the thickness of the trophogenic layer to around 0.5 m (Fig. 14). Gross production under 1 m^2 of lake surface consequently began to drop during the two consecutive years of fertilization to a value below that for dystrophic lakes.

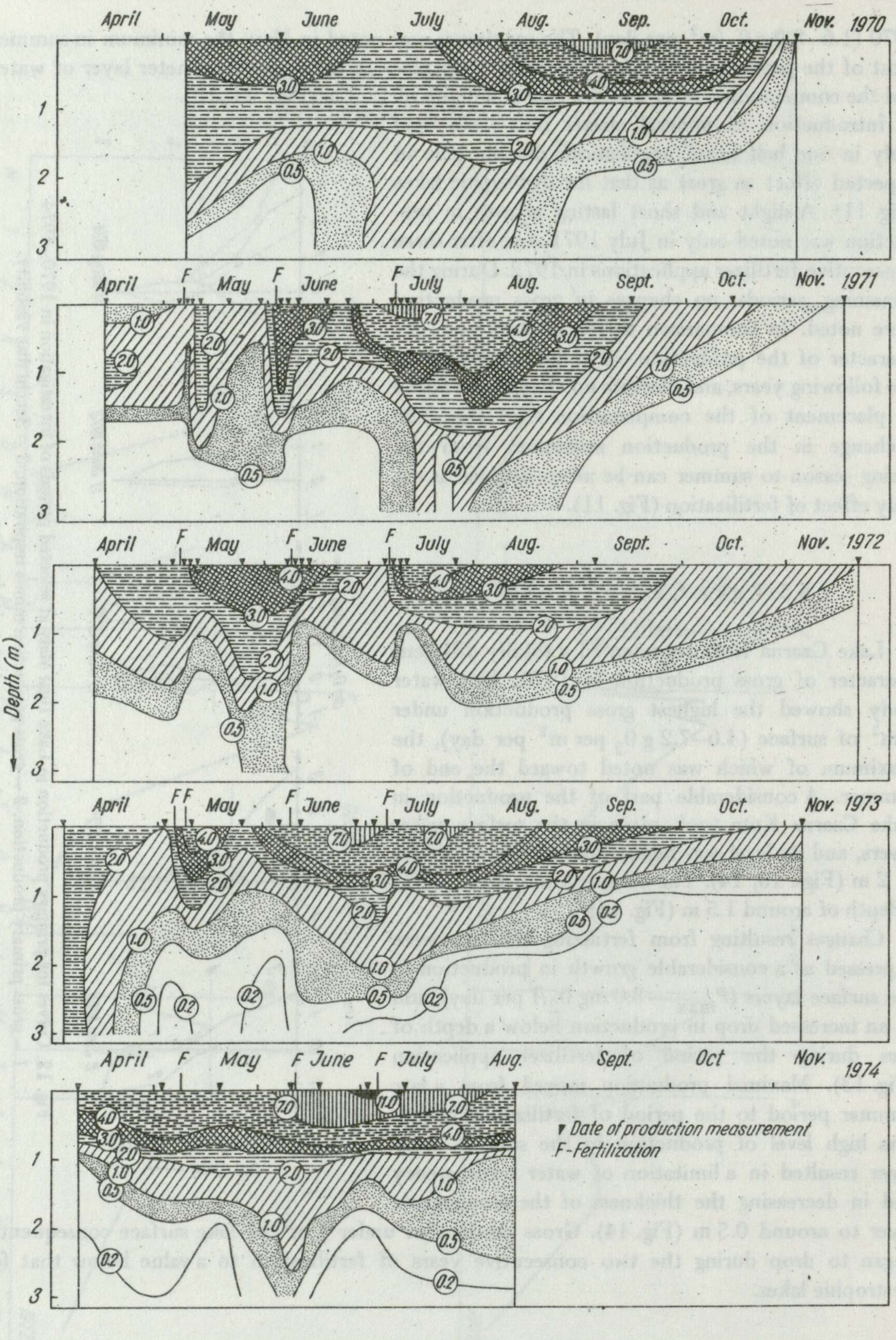

Fig. 13. Isopleths for gross primary production (mg 0_2/l per day) representing variations in time and depth in Lake Czarna Kuta in 1970–1974

Production growth in 1973–1974 after introducing mineral matter into the lake was not as intensive as during previous years. A slight increase in water transparency was noted, deepening of the trophogenic layer, and transfer of maximum production to the late summer period, that is similarly as in 1970 (Figs. 13, 14). Maximal production (P_{max}) was 8.4 mg/l per day in 1973 and 11.9 mg/l per day in 1974).

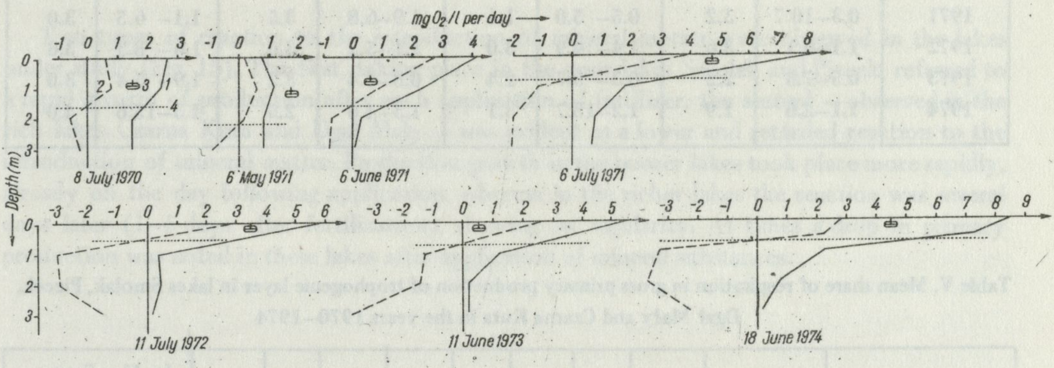

Fig. 14. Curves for primary production in Lake Czarna Kuta at selected periods of investigation in 1970–1974

1 – gross primary production, *2* – gross production minus respiration, *3* – Secchi disc visibility, *4* – compensation point location

6. RESPIRATION AND ITS PERCENTUAL SHARE IN GROSS PRODUCTION

Lowest maximal and average respiration in 1970 was found in Lake Piecek, while the remaining water bodies showed similar values (Table IV). After four years of fertilization, no changes were noted in lakes Dgał Mały and Czarna Kuta in respiration, whereas a slight drop in respiration took place in Lake Smolak in 1973–1974. An increase in respiration was noted in Lake Piecek in 1972, remaining at a similar level in 1973–1974. Maximal respiration was noted in all of the lakes in July, minimal in May of each of the years.

The greatest share of respiration in gross production was noted in Lake Smolak in 1970, the lowest in Lake Czarna Kuta (Table V). The share of respiration in gross production in Lake Smolak exceeded 100% throughout the vegetation season (with the exception of May). During the first year of fertilizer application, a decline was noted in the range and average seasonal value of this index in this water body (Table V). In 1972–1974 no actual changes were observed as compared to 1971. Average seasonal values of the share of respiration in gross production did not change throughout the period of the studies in lakes Piecek and Dgał Mały,

Table IV. Respiration (g $0_2/m^2$ per day) in lakes Smolak, Piecek, Dgał Mały and Czarna Kuta, during the period of vegetation in 1970–1974

Year	Smolak		Piecek		Dgał Mały		Czarna Kuta	
	range	average	range	average	range	average	range	average
1970	0.8–7.2	3.1	1.4– 2.4	1.6	1.0–5.7	2.9	1.1– 5.3	2.7
1971	0.3–10.7	3.2	0.5– 5.0	1.6	1.9–6.8	3.5	1.1– 6.5	3.0
1972	1.1–6.1	3.6	1.4– 4.9	3.0	1.1–5.2	3.0	1.6– 8.3	3.8
1973	0.5–7.8	2.2	0.3– 5.7	2.4	0.8–5.4	3.2	1.9– 5.4	3.0
1974	1.1–2.6	1.9	1.2–13.7	3.1	1.3–4.0	2.5	1.5–15.6	4.0

Table V. Mean share of respiration in gross primary production of trophogenic layer in lakes Smolak, Piecek, Dgał Mały and Czarna Kuta in the years 1970–1974

Lake	Year	April	May	June	July	Aug.	Sept.	Oct.	Nov.	In May-Sept.	
										range	mean
Smolak	1970	–	34	370	110	220	150	–	350	34–370	220
	1971	61	96	53	122	–	44	51	40	21–330	79
	1972	74	68	72	90	–	44	–	25	44–210	68
	1973	47	64	70	142	53	53	–	200	46–300	70
	1974	92	55	77	54	105	–	–	–	50–105	71
Piecek	1970	–	61	48	62	73	65	50	80	48– 73	62
	1971	46	86	50	38	–	35	35	66	6–160	52
	1972	53	63	48	83	–	39	—	140	22–140	58
	1973	67	38	42	55	47	86	–	–	20 – 86	53
	1974	85	55	73	29	155	–	–	–	15–155	69
Dgał Mały	1970	–	51	33	82	157	70	–	48	33–157	79
	1971	46	86	83	51	–	53	50	25	48–170	68
	1972	54	130	88	70	–	–	–	230	22–200	93
	1973	46	95	60	63	–	17	–	60	10–180	72
	1974	57	54	84	43	103	–	–	–	33–103	66
Czarna Kuta	1970	–	17	16	79	40	58	35	500	16– 79	42
	1971	42	89	51	53	–	51	44	125	31–144	61
	1972	84	75	78	94	–	63	–	40	46–200	77
	1973	75	58	39	70	49	51	–	13	26– 85	53
	1974	37	52	60	45	136	–	–	–	33–136	61

notwithstanding an increase in the variability range in Lake Piecek in 1971–1972 (Table V). An increase in range and average seasonal values of the share of respiration in gross production was, however, noted in Lake Czarna Kuta during the first two years of fertilization (Table V).

7. DIRECTIONAL CHANGES IN THE LAKES

Two types of reaction to the introduction of mineral matter were observed in the lakes under study (Fig. 15). The first, taking place in the poor lakes Smolak and Piecek, referred to a rapid growth of production after each application of fertilizer, the second – observed in the rich lakes Czarna Kuta and Dgał Mały – was evident as a lower and retarded reaction to the introduction of mineral matter. Production growth in the poorer lakes took place more rapidly, already on the day following application, whereas in the richer lakes the reaction was several days later (1–5 days after fertilization), showing no regularity. At times a drop in primary production was noted in these lakes after application of mineral substances.

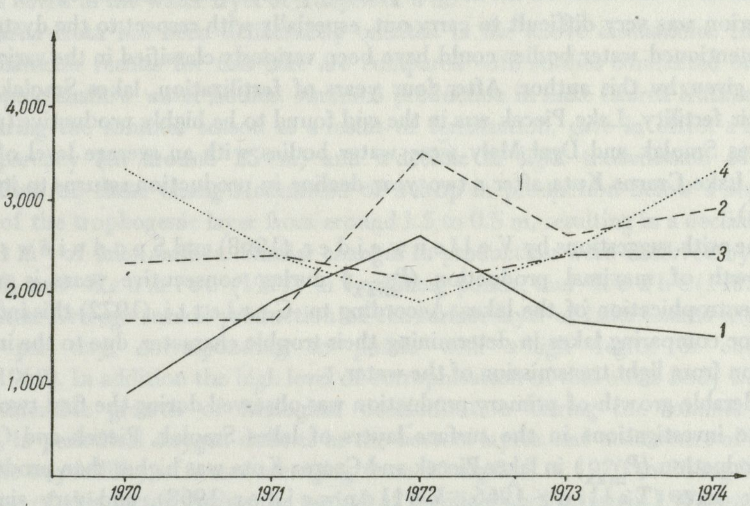

Fig. 16. Changes in gross primary production calculated for the period of vegetation (May-September) in fertilized lakes in 1970–1974
1 – Lake Smolak, *2* – Lake Piecek, *3* – Lake Dgał Mały, *4* – Lake Czarna Kuta

Multi-year tendencies appearing in the lakes under study after changing their fertility are illustrated in Figure 16, the value of production being given calculated for the vegetation period from May to September (150 days). A gradual growth of primary production was observed in Lake Smolak during the first two years of fertilization, which was higher than in the eutrophic lakes Czarna Kuta and Dgał Mały. A drop in production of this lake was noted in 1973–1974. Reaction of Lake Piecek to fertilization took place with a retardation of one year, however, the level of production in the following year (1972) was higher than in any of the lakes. A drop in production was noted in this lake in 1973, followed again by an increase in 1974. No changes in production were noted in Lake Dgał Mały throughout the period of investigations, whereas a decline in production took place in Lake Czarna Kuta during the first two years of fertilization, and an increase again in 1973–1974.

8. DISCUSSION OF RESULTS

8.1. General

The data obtained confirmed the observations of many authors (references given below), that as mineral matter content of the lakes is increased, changes take place in primary production expressed as: (1) growth of the intensity of production, especially growth of maximal production (P_{max}); (2) change in the character of the production curve in a vertical profile; (3) change in the share of respiration in gross production, as a consequence of production growth when respiration values do not change.

Classification of the lakes on the basis of primary production according to the W i n b e r g (1960) criterion was very difficult to carry out, especially with respect to the dystrophic lakes. These last mentioned water bodies could have been variously classified in the various ranges of production given by this author. After four years of fertilization, lakes Smolak and Piecek changed their fertility. Lake Piecek was in the end found to be highly productive (polytrophy), whereas lakes Smolak and Dgał Mały were water bodies with an average level of production (eutrophy). Lake Czarna Kuta after a two year decline in production returns to its initial state (polytrophy).

1. In line with suggestions by V o l l e n w e i d e r (1968) and S p o d n i e w s k a (1974), gradual growth of maximal production (P_{max}) during consecutive years is proof of the progressive eutrophication of the lakes. According to G e r l e t t i (1972) this index is a good parameter for comparing lakes in determining their trophic character, due to the independence of production from light transmission of the water.

A considerable growth of primary production was observed during the first two consecutive years of the investigations in the surface layers of lakes Smolak, Piecek and Czarna Kuta. Maximal production (P_{max}) in lakes Piecek and Czarna Kuta was higher than production noted in eutrophic lakes (T a l l i n g 1966, V o l l e n w e i d e r 1968), and very similar to that noted by many authors in the eutrophic lakes of the Masurian Lakes' Region (C z e c z u g a 1959, M u c h a 1974, S p o d n i e w s k a 1974). Maximal production growth in Lake Smolak was not as intensive as in lakes Piecek and Czarna Kuta, but nevertheless can be acknowledged as proof of progressive eutrophication of the first mentioned. The very low maximal production in Lake Smolak after first fertilizer application was in all probability due to low pH stability, which increased considerably after second application of fertilizers. As stated by B i n d l o s s et al. (1972), the various values of maximal production, apart from the seasonal variability of the phytoplankton, depends upon the pH range, which has a limiting influence on nitrogen and phosphorus availability at very low and very high values. Experimental studies by B u r n e t and W a l l a c e (1973) confirmed the above statement, and showed that a pH range of from 6.5 to 8.5 is the best for the most intensive production.

2. Change in the character of the production curve is another factor indicating eutrophication of lakes. This index is closely connected with maximal production (P_{max}), and is an

indication of the general environmental conditions of a lake, which change depending upon the fertility and light transmission of the water (F i n d e n e g g 1964, R o d h e 1965, G e r - l e t t i 1972).

The character of the production curve showed a change during years of fertilization, changing from a dystrophic type to a curve similar to that observed in eutrophic lakes (R o d h e 1958, F i n d e n e g g 1964, S z c z e p a ń s k i 1966, V o l l e n w e i d e r 1968, Z d a n o w s k i – in press). Maximal production was noted in these lakes in the upper water layers (0–1 m), where around 50% of the light reaching the water bodies penetrated. Production decline was in line with a decline in light transmission, the curves for which correspond to those described by R o d h e (1965) for eutrophic lakes. As concerns Lake Dgał Mały curves for light transmission are in agreement with those described earlier for this lake (M y k i t a and T a r a s i e w i c z 1967).

In comparing light transmission by the water and primary production at various depths, it was found that around 1% of the total light in the surface layer of water penetrates most frequently to a depth of 4–5 m. According to some authors (Y o s h i m u r a 1935, S a k a m o t o 1966, T a l l i n g 1966) this depth is the limit for light transmission at which photosynthesis can take place. Lowest production, determined by means of the oxygen method, was noted in the water layer at a depth of 5 m.

Lake Czarna Kuta has been deliberately omitted in the above discussions. In view of its pond like character results for this lake are compared with studies conducted on ponds and highly eutrophic shallow water bodies. Maximal production in Lake Czarna Kuta, considerably increased during the summer season as a result of fertilization, gave in effect a high drop in water transparency (to around 25 cm) and a decline in light transmission of the water. A further effect of these changes consisted of a drop in production below a depth of 1 m, a reduction of the trophogenic layer from around 1.5 to 0.5 m, resulting in a decline of production under 1 m^2 of lake surface. Similar changes in production were observed by W r ó b e l (1962, 1966) and S z u m i e c (1971) in fertilizing ponds, and R o d h e (1965) in highly eutrophic lakes. Average annual production of the surface layer of Lake Czarna Kuta exceeded 3.0 mg O_2/l per day, corresponding to ponds with a high degree of eutrophication (W r ó b e l 1962). In addition the high level of eutrophication of this water body was expressed in the considerable growth of biological decalcification during the summer periods of 1971–1973, in periodical oxygen deficits in the bottom layers, and occurrence of H_2S, as also growth of the oxydability of water averaging from 15 mg O_2/l in 1970 to 20 mg O_2/l in 1972. Maximal value of this factor during the period of fertilizer application in 1972 was 37 mg O_2/l (A. Korycka and J. Zachwieja – unpublished data). The consequences and a description of the changes presented above are given by W r ó b e l (1966) with respect to ponds, and will be discussed later.

3. Change in the share of respiration in gross production in dystrophic lakes and in Lake Czarna Kuta was a consequence of changes in primary production. As gross production grew in Lake Smolak, a decline in the share of respiration in gross production was observed from values higher than 100%, that is values typical for dystrophic lakes (C z e c z u g a 1959, 1966), to values noted for eutrophic lakes (C z e c z u g a 1959, 1966, J a v o r n i c k y 1966, H i l l b r i c h t-I l k o w s k a and S p o d n i e w s k a 1969, S p o d n i e w s k a 1974, Z d a n o w s k i – in press). The high share of respiration in the very low producing Lake Smolak in 1970 was condition by the utilization of oxygen for the partial mineralization of allochthonous organic matter. Production growth during years of fertilizer application led to a change in this proportion, notwithstanding that absolute values of respiration during the

1971–1972 period did not change. Accumulation of organic matter in the littoral could have taken place in 1973–1974, at which time this part of the lake was limed (formation of sorptive complexes of calcium salts and organic particles inflowing from the forest basin), and hence the drop in respiration in 1973–1974. Respiration growth at an unchanged level of its share in production took place in Lake Piecek in 1972, when the whole complex reacted to fertilization, and that not only phytoplankton, but also zooplankton and bacterio-plankton (B n i ń s k a et al. – in press, S. Niewolak – unpublished data). Growth of the activity of phytoplankton consumers thus led to utilization of oxygen for respiration processes and mineralization of organic matter in the water body, whereas high production growth, notwithstanding increased respiration, maintained the latter share at a similar level throughout the period of investigations.

The high seasonal variability in production in Lake Czarna Kuta during the period 1971–1972 took place simultaneously with a high variability of the share of respiration in gross production. Average values of respiration, however, did not show any basic change. Lake Czarna Kuta is a polymictic water body. During windless weather thermo-oxygen stratification took place with high oxygen deficits at the bottom. Furthermore the summer period of 1971–1972 was characterized by average water temperatures around 2°C higher. Conditions were thus formed rarely met with in this type of lakes. High production variability, and that of the share of respiration, in the 1971–1972 period could thus result from the high variability of phytoplankton activity and its biomass, the moreso that during this time a two-fold drop in zooplankton numbers was noted, one of the basic consumers of oxygen in the lake. In view of the lack at present of data on phytoplankton, explanation of this phenomenon is very difficult.

8.2. Phytoplankton production as an indicator of the effects of fertilization

Effects of fertilization were based on changes in primary production on the background of changes in the concentration of biogenic substances. The character and direction of changes in the lakes varied and depended upon the degree of fertility and morphometry. Greatest changes were noted in the dystrophic lakes. This is in line with the statement that due to the enrichening of this type of water bodies with mineral matter, highest productivity growth is reached (N e l s o n and E d m o n d s o n 1955, W e a t h e r l e y and N i c h o l s 1955, B e r g e 1969, S m i t h 1969, P a r s o n s, S t e p h e n s and T a k a h a s h i 1972).

Introduction of mineral matter did not change the concentration of nitrogen and phosphorus in the water of any of the lakes, and remained more or less at the same levels in 1971–1974 as in the control year. This lack of changes in the concentration of biogenic substances was probably connected with their rapid withdrawal by bottom sediments, algae and macrophytes (C o f f i n et al. 1949, H a y e s and C o f f i n 1951), this being proved by the short lasting and slight increase in the concentration of nitrogen and phosphorus after fertilizer application.

Growth of production after mineral fertilization is understandable and known for some time from studies on fertilization of lakes (B e r g e 1969, P a r s o n s, S t e p h e n s and T a k a h a s h i 1972, S c h i n d l e r and F e e 1974), especially from studies on fertilization of ponds (W r ó b e l 1962, D e b e l j a k 1968, H e r z o g and H e t e š a 1968, L e w k o w i c z and W r ó b e l 1971, B o y d 1973). The more rapid and stronger reaction of dystrophic lakes was due to their low fertility, in contrast to eutrophic lakes in which the accepted applications of fertilizers only slightly changed their trophism. Hence production growth in these water bodies was as a rule retarded and took place irregularly within 1–5 days. At times a drop in production was noted after fertilizing. A similar irregularity in production growth was observed by Berge (1969). This retarded reaction is explained by this author as being due to the toxic effect of the salts introduced, and the formation of colloid substances less available to phytoplankton.

Application of potassium salts resulted in a growth of potassium concentration in all of the fertilized lakes, but especially in Lake Smolak, in which the concentration of this element exceeded the theoretical concentration level in the second year of fertilization, and twice as high in the last year as in any of the remaining lakes. The constant increase in potassium concentration during successive years indicates non-utilization of this element by phytoplankton, and especially by macrophytes. The biomass of macrophytes in Lake Smolak in 1970–1973 was very low in comparison to other lakes (J. Radziej – unpublished data). Investigations by M. Bnińska (unpublished data, Bnińska et al. – in press, Zdanowski et al. in press) showed that notwithstanding that macrophytes in Lake Smolak utilized potassium more intensively per g of dry matter than in other lakes, nevertheless partially slower growth of potassium concentration in the surface water layers was noted not earlier than in 1973 (strong development of water thyme), but especially in 1974 when the macrophyte biomass increased considerably with a simultaneous change in species composition and appearance of species characteristic for eutrophism. It can thus be assumed that potassium introduced into Lake Smolak was not a factor conditioning phytoplankton production, but could stimulate the development of macrophytes, especially of submerged ones.

The continuous increase in calcium concentration in the water of these lakes was the most important factor responsible for the change in production in dystrophic lakes, and their transition from low production to high productive water bodies. At the same time this factor led to higher electrolytic conductivity of the water, a higher content of acid carbohydrates, and stabilization of the pH at a level noted in eutrophic lakes. Higher electrolytic conductivity of the water as a consequence of calcium content growth is in accordance with the investigations of many authors (Rodhe 1949, Szczepański 1968, Korycka 1969). Distribution of points for lakes Smolak and Piecek correspond to values taken from the curve of correlation between electrolytic conductivity of water and calcium content as given by Korycka (1969).

Calcium concentration in the second year of fertilization exceeded the limit characteristic for dystrophic lakes in both lakes, that is 16 mg/l (Stangenberg 1936). Notwithstanding further liming in 1973–1974, calcium concentration in the eutrophic lakes was lower (Stangenberg 1936, Patalás 1960c, Szczepański 1968, Korycka 1969). A change in the method of liming dystrophic lakes from pelagic to liming the littoral belt in 1973–1974 resulted in the cumulation of calcium in this latter part of the lake. The rate of calcium increase in waters of the pelagial was retarded especially in the stable Lake Piecek, where also the rate of electrolytic conductivity was slower, and the pH dropped. These changes could lead to slowering the rate of liberating biogenic substances from sorptive complexes, thereby lowering availability of biogenic substances for the phytoplankton, and resulting in a decline of production. Hence increased calcium content in the waters of dystrophic lakes results in changes in the environment leading toward eutrophism, and creating conditions for production during years of fertilizer application to be at a higher level than in the control year. This takes place through a stimulating influence on the rate of liberating mineral matter from bottom sediments, and on increasing the pH of the water. Furthermore, calcium carbonate was a carrier of carbon, an indispensible element in the process of photosynthesis. Nitrogen and phosphorus salts did in reality lead to short lasting growth of production after each application of fertilizer, but were not responsible for its general character, as proved by the continuation of a high level of production in dystrophic lakes in autumn in contrast to eutrophic lakes, where a drop in production was noted.

8.3. Directional changes in the lakes

Changes in production calculated for the period of vegetation (Fig. 16) were the starting point in determining directional changes of lake productivity. The gradual growth of production in Lake Smolak constituted a reflection of the dominant role played by phytoplankton in eliminating the mineral salts added during the first two years of fertilizer application. Phytoplankton development in the following years was considerably limited by the intensive uptake of introduced mineral salts by abundantly developing macrophytes (Bnińska et al. – in press, Zdanowski et al. – in press). During 1973–1974 *Elodea canadensis* Rich. introduced in July 1972 was dominant among macrophytes (M. Bnińska – personal communication). The above observations are in accordance with investigations conducted by many authors (Hutchinson and Bowen 1947, Coffin et al 1949, Hayes and Coffin 1951, Weatherley and Nichols 1955), who emphasized the great role of macrophytes as competitors for food with phytoplankton.

Mass occurrence of filamentous algae is another expression of eutrophication of Lake Smolak, this being in accordance with studies by other authors (Ball 1950, Hooper and Ball 1964, Hayes and Coffin 1951). Filamentous algae appeared in Lake Smolak for the first time in the second half of May, 1973, and their maximal abundance was noted in June 1973 and 1974, this being characteristic for their seasonal occurrence (Pieczyńska and Szczepańska 1966, Pieczyńska 1970). *Spirogyra* sp. was dominant in these algae (J. Sosnowska – personal communication), frequently found in highly fertilized ponds (Stangenberg-Oporowska and Marek 1974).

These observations explain the considerably weaker reaction of Lake Smolak to fertilization in 1973–1974, its lower maximal production (P_{max}), and the decline in production under 1 m^2 of lake surface. Primary production of Lake Smolak changed from the domination of phytoplankton to the domination of filamentous algae and macrophytes.

The weak reaction to fertilization and the lack of changes in the productivity of Lake Piecek in 1971 were connected with the considerable fluctuation of the pH in the surface water layers. Abundant growth of production in 1972 was due to stabilization of the pH level resulting from an increase in the concentration of calcium during the autumn of 1971 and the winter-spring period of 1972. Calcium concentration in the waters of this lake exceeded the value characteristic for dystrophic lakes (Stangenberg 1936). The decline in production in 1973 might have been connected with the change in the method of liming (from pelagic to littoral). Lake Piecek is a water body with a higher level of static than Lake Smolak (Patalas 1960a), and for this reason exchange between the pelagial and littoral, and bottom sediments, is limited by morphometric factors. Data for 1972–1974 indicate a high level of stability of this water body, notwithstanding a drop in production in 1973, and the continuous growth of its trophic character.

Productivity of Lake Dgał Mały did not change throughout the period of investigations. The lack of reaction to fertilization of this lake was due to the application of fertilizer amounts one half of those given in the remaining lakes. In addition this lake was characterized by a lower rate of mineral salt exchange due to the influence of morphometric factors (stable thermal and oxygen conditions, IV degree of statics according to the P a t a l a s (1960a) criterion). This is in agreement with assumptions by P a t a l a s (1960d) that the effect of fertilization in this type of water bodies should be the lowest. Change of production maxima from the spring season to the period of fertilizing the lake is the only effect of fertilization in the case of this water body. The negative effect of eutrophication at a high level of thermal stratification should be apparent in the hypolimnion through a growth of oxygen deficits, in accordance with suggestions by O h l e (1953), and as proved by studies by B a l l (1950) and P a r s o n s, S t e p h e n s and T a k a h a s h i (1972). Changes of this type were not noted in Lake Dgał Mały due to high fertility and considerable oxygen losses in the hypolimnion observed over a period of several years (Z a c h w i e j a 1972).

The direction of changes and practical consequences of fertilizing the highly eutrophic Lake Czarna Kuta differed from those noted in the remaining lakes. Changes during the first two years of fertilization reflected over-fertilization of this lake, and degradation from the point of view of water quality and fish production. According to W r ó b e l (1962, 1966) positive inter-relation between eutrophicattion and fish production in ponds is maintained only in certain limits, the transgression of which results in a decline of fish production output as a result of the deterioration for fish of environmental conditions. During periods of windless weather in the first years of fertilizer application, high oxygen deficits occurred at the bottom (2–3 m) of Lake Czarna Kuta, rendering considerable parts of the bottom inaccessible for the feeding of fish (maximal depth 3.6 m). It was noted that growth conditions of such fish species as roach and bream worsened, and annual growth increments of carp were lower. Only in the case of perch-pike was there an accelerated growth observed during two years of fertilization (M a r c i a k – in press). At the same time a two-fold drop in numbers of crustaceans and a several-fold decline in the biomass of meio- and macrobenthos was noted (B n i ń s k a et al., in press, K. Prejs and L. Leszczyński – unpublished data). The considerable fluctuations in primary production in Lake Czarna Kuta taking place over a multi-year period, at its very low stability (polymyxy and polytrophy), can be acknowledged as typical for this water body. Notwithstanding the drop in primary production and degradation of Lake Czarna Kuta in 1971–1972 from the point of view of water quality, there is a growth of primary production and an improvement in environmental conditions in 1973–1974 in spite of the continuous introduction of mineral salts. Maximal production growth per unit of water volume and under 1 m^2 of surface in Lake Czarna Kuta in 1974 was in all probability due to a change in the phytoplankton species composition directed toward the domination of species having greater photosynthetic ability. However, the lack of studies on phytoplankton data renders final explanation of these changes difficult. In view of the high fish production output of Lake Czarna Kuta (recreational advantages have been for some time of little importance) efforts should be made to maintain production of this lake at a maximal level by intensive fishery exploitation or by regulating phytoplankton production by introducing plant consuming fish species.

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9. SUMMARY

The study was aimed at determining changes in phytoplankton production under the influence of mineral fertilization. Observations were conducted over the period 1970–1974 on four lakes differing trophically and morphometrically (from dystrophic to eutrophic; Table I). Control investigations were carried out in 1970. Nitrogen-phosphorus fertilization was applied on all of the lakes (three times each year), and potassium on three of them (once each year); liming of the dystrophic lakes was carried out each year in winter (Table II). The amount of fertilizer applied was adapted to the volume of the lake on the assumption that upon dissolving in the lake water, the theoretical concentration of salts will be as follows: 0.1 mg P/l, 1 mg N/l, 4 mg K/l and 40 mg Ca/l. Primary production and respiration of the whole complex were determined by means of the oxygen method of dark and light bottles. The investigations were supplemented by measurements of water chemism, temperature, water transparency and light transmission in the water.

It was found that application of mineral fertilizers changed the water chemism of the lakes under study, especially of the dystrophic lakes Smolak and Piecek. Changes in these lakes refer to a constant increase in calcium and potassium content (Fig. 1) and to a higher pH value and higher electrolytic conductivity (Fig. 2). No change in the content of nitrogen and mineral salts was on the other hand noted (Figs. 3, 4).

Highest production growth was noted in the dystrophic lakes. Gross production in Lake Smolak showed a maximum increase of from around 0.5 do 3.1 mg $0/_2$/l per day (Fig. 7). At the same time a drop was noted in water transparency and in the share of respiration in gross production (Tables III, V). A higher growth of production was noted in Lake Piecek, from around 1.5 to 6.5 mg 0_2/l per day (Fig. 9), at a lack of changes in water transparency and share of respiration in gross production (Tables III, V). No changes were noted in Lake Dgał Mały in production throughout the period of studies (Figs. 11, 12, Tables III, V). A transfer of the period of maximum production from autumn to the summer season (Fig. 13) took place in the shallow eutrophic Lake Czarna Kuta. This was accompanied by a drop in production below 1 m, a drop in water transparency, light conductivity, and a growth in the variability of the share of respiration in gross production (Figs. 6, 14, Tables III, V).

Two tendencies of changes in the lakes were noted, that is, gradual eutrophication of dystrophic lakes in 1971–1972 (growth of production), and excessive fertility of Lake Czarna Kuta (decline in production). No changes were noted in the deep eutrophic Lake Dgał Mały (Fig. 16). Increasing the trophic characteristics of dystrophic lakes did not lead to their gradual eutrophication in the following years, while Lake Czarna Kuta returned to the state noted in the control year notwithstanding fertilization (Fig. 16). Introduction of calcium salts was the factor responsible for productivity changes in the dystrophic lakes.

10. POLISH SUMMARY (STRESZCZENIE)

Celem pracy było określenie zmian produkcji fitoplanktonu pod wpływem mineralnego nawożenia. Obserwacje prowadzono w latach 1970–1974 w czterech jeziorach zróżnicowanych troficznie i morfometrycznie (od dystrofii do eutrofii; tab. I). W 1970 roku przeprowadzono badania kontrolne. We wszystkich jeziorach zastosowano nawożenie azotowo-fosforowe (trzykrotnie każdego roku), potasowe – w trzech jeziorach (raz w roku) oraz wapnowanie jezior dystroficznych (każdego roku zimą; tab. II). Dawki nawozów dostosowano do objętości jezior przyjmując, że po rozpuszczeniu się w wodzie jeziornej teoretyczne stężenie soli będzie wynosiło: 0.1 mg P/l, 1 mg N/l, 4 mg K/l i 40 mg Ca/l. Produkcję pierwotną i respirację całego zespołu określano z pomocą tlenowej metody ciemnych i jasnych butelek. Badania uzupełniono pomiarami chemizmu wody, temperatury, przezroczystości wody i transmisji światła w wodzie.

Pod wpływem mineralnego nawożenia stwierdzono zmianę chemizmu wody badanych jezior, zwłaszcza dystroficznych jezior Smolak i Piecek. Zmiany w tych jeziorach odnoszą się do stałego wzrostu zawartości wapnia i potasu (fig. 1) oraz wzrostu wartości pH i przewodnictwa elektrolitycznego (fig. 2). Nie zanotowano natomiast zmian w zasobności jezior w sole azotu i fosforu (fig. 3, 4).

Najsilniejszy wzrost produkcji notowano w dystroficznych jeziorach. W jeziorze Smolak produkcja brutto wzrosła maksymalnie z około 0,5 do 3,1 mg 0_2/l na dzień (fig. 7). Jednocześnie stwierdzono spadek przezroczystości wody i spadek udziału respiracji w produkcji brutto (tab. III, V). W jeziorze Piecek notowano silniejszy wzrost produkcji z około 1,5 do 6,5 mg 0_2/l na dzień (fig. 9), przy braku zmian w przezroczystości wody i udziale respiracji w produkcji brutto (tab. III, V). W jeziorze Dgał Mały nie stwierdzono zmian w produkcji przez cały okres badań (fig. 11, 12, tab. III, V). W płytkim eutroficznym jeziorze Czarna Kuta nastąpiło przesunięcie maksimum produkcji z okresu jesiennego na okres letni (fig. 13). Towarzyszył temu

spadek produkcji poniżej 1 m, spadek przezroczystości wody i przepuszczalności światła oraz wzrost zmienności udziału respiracji w produkcji brutto (fig. 6, 14, tab. III, V).

Stwierdzono dwie tendencje zmian w jeziorach, tj. stopniową eutrofizację dystroficznych jezior w latach 1971–1972 (wzrost produkcji) oraz przeżyźnianie jeziora Czarna Kuta (spadek produkcji). W głębokim eutroficznym jeziorze Dgał Mały nie zanotowano zmian (fig. 16). Zwiększenie trofii dystroficznych jezior w latach następnych nie prowadziło do stopniowej ich eutrofizacji, natomiast jezioro Czarna Kuta – mimo nawożenia – powróciło do stanu notowanego w roku kontrolnym (fig. 16). Czynnikiem odpowiedzialnym za zmiany w produktywności jezior dystroficznych było wprowadzenie soli wapnia.

11. REFERENCES

1. A b r o s o v V. N. 1967 – Problema udobrenija ozer i sviazannye s nej voprosy – Izv. gos. naučno-issled. Inst. ozer. rečn. ryb. Choz. 64: 61–78.
2. B a l l R. C. 1950 – Fertilization of natural lakes in Michigan – Trans. Am. Fish. Soc. 78: 145–155.
3. B e r g e G. 1969 – Predicted effects of fertilizers upon the algae production in Fern Lake – Fisk. Dir. Skr. Ser. HavUnders. 15: 339–355.
4. B e r n a t o w i c z S. 1965 – Wpływ koszenia na występowanie makrofitów w jeziorze Dgał Mały – Acta Hydrobiol. 7: 71–82.
5. B i n d l o s s M. E., H o l d e n A. V., B a i l e y-W a t t s A. E., S m i t h I. R. 1972 – Phytoplankton production, chemical and physical conditions in Loch Leven (In: Productivity problems of freshwaters, Eds. Z. Kajak, A. Hillbricht-Ilkowska) – PWN, Warszawa-Kraków, 709–723.
6. B n i ń s k a M., H i l l b r i c h t-I l k o w s k a A., K a j a k Z., W ę g l e ń s k a T., Z d a n o w s k i B. (in press) – Influence of mineral fertilization on lake ecosystem functioning – Limnologica (Berlin).
7. B o y d G. E. 1973 – Summer algal communities and primary productivity in fish ponds – Hydrobiologia, 41: 357–390.
8. B u r n e t A. M. R., W a l l a c e D. A. 1973 – The relation between primary productivity, nutrients, and the trout environment in some New Zealand Lakes – Fish. Res. Bull. 10: 1–27.
9. C o f f i n C. C., H a y e s F. R., J o d r e y L. H., W h i t e w a y S. G. 1949 – Exchange of materials in a lake as studied by addition of radioactive phosphorus – Can. J. Res. 27: 207–222.
10. C z e c z u g a B. 1959 – Produkcja pierwotna Jezior Rajgrodzkich. Jeziora Rajgrodzkie, Białe i Krzywe – Acta Soc. Bot. Pol. 28: 555–578.
11. C z e c z u g a B. 1966 – Procesy destrukcyjne na tle produkcji pierwotnej w różnych ekosystemach wodnych – Zesz. probl. Kosmosu, 13: 107–116.
12. D e b e l j a k L. 1968 – Utjecaj rezlicitih doza kombiniranih mineralnih gnojiva na primarnu organsku produkciju u pokusnim rybnjacima "Daganič" – Ribarst. Jugosl. 23: 57–60.
13. E i n s e l e W. 1941 – Die Umsetzung von zugefuhrten, anorganischen Phosphat im eutrophen See und ihre Ruckirkungen auf seinen Gesamthaushalt – Z. Fisch. 39: 407–488.
14. F i n d e n e g g I. 1964 – Types of planktic primary production in the lakes of the Eastern Alps as found by the radioactive carbon method – Verh. int. Verein. Limnol. 15: 352–359.
15. G e r l a c z y ń s k a B. 1973 – Distribution and biomass of macrophytes in Lake Dgał Mały – Ekol. pol. 21: 743–752.
16. G e r l e t t i M. 1972 – Comparative trends of primary productivity and some chemical parameters in Lake Maggiore on a pluriannual basis (In: Productivity problems of freshwaters, Eds. Z. Kajak, A. Hillbricht-Ilkowska) – PWN, Warszawa-Kraków, 709–713.
17. H a s l e r A. D., E i n s e l e W. G. 1948 – Fertilization for increasing productivity of natural inland waters – Trans. 13-th N. Am. Wildl. Conf. March 8–10: 527–555.
18. H a y e s F. R., C o f f i n C. C. 1951 – Radioactive phosphorus and exchange of lake nutrients – Endeavour, 10: 78–81.
19. H a y e s F. R., M c C a r t e r J. A., C a m e r o n M. L., L i v i n g s t o n e D. A. 1952 – On the kinetics of phosphorus exchange in lakes – J. Ecol. 40: 202–216.
20. H o r z o g R., H e t e š a J. 1968 – Primárni produkce plankton jako ukazatel uéinnosti hnojeni rybniků – Výzkumný Ústav Rybářský a Hydrobiologický, Vodňany ČSSR, 8: 7–25.
21. H i l l b r i c h t-I l k o w s k a A., S p o d n i e w s k a I. 1969 – Comparison of the primary production of phytoplankton in three lakes of different trophic type – Ekol. pol. A, 17: 241–261.
22. H o o p e r F. F., B a l l R. C. 1964 – Responses of a marl lake to fertilization – Trans. Am. Fish. Soc. 93: 164–173.
23. H u t c h i n s o n G. E., B o w e n V. T. 1947 – A direct demonstration of the phosphorus cycle in a small lake – Proc. natn. Acad. Sci. U.S.A. 33: 148–153.

24. J a v o r n i c k ý P. 1966 – Measurements of production and turnover of phytoplankton in four localities of Poland – Ekol. pol. A, 14: 203–214.

25. J u s t J., H e r m a n o w i c z W. 1955 – Fizyczne i chemiczne badania wody do picia i potrzeb gospodarczych – Warszawa, 320 pp.

26. K o č e v y c h V. P. 1972 – Soderžanie biogenov v vode dlitel'no udobrjaemogo ozera – Rybochoz. Izuč. Vnutr. Vod, 9: 8–10.

27. K o n d r ą c k i J., S z o s t a k M. 1960 – Zarys geomorfologiczny i hydrograficzny jezior okolic Węgorzewa – Roczn. Nauk roln. B, 77: 7–59.

28. K o r y c k a A. 1969 – Seasonal changes in water chemical composition in seven lakes – Pol Arch. Hydrobiol. 16: 1–29.

29. L a c k e y J. B., S a w y e r C. N. 1945 – Plankton productivity of certain south eastern Wisconsin lakes as related to fertilization. I Survey – Sewage Wks J. 17: 573–585.

30. L e s z c z y ń s k i L. 1969 – Studia nad ilościowym i jakościowym zróżnicowaniem fauny dennej w jeziorach różnych typów troficznych – Ph.D. Thesis, Univ. of Nicolas Copernicus, Toruń, 71 pp.

31. L e w k o w i c z S., W r ó b e l S. 1971 – Some chemical factors and primary production of phytoplankton in fingerling ponds – Pol. Arch. Hydrobiol. 18: 189–201.

32. M a r c i a k Z. (in press) – Influence of mineral fertilization of lakes on fish growth – Verh. int. Verein. Limnol.

33. M u c h a A. 1974 – Produkcja pierwotna Jeziora Długiego i Jeziora Miejskiego w Szczytnie – Zesz. nauk. Akad. roln.-techn., Olsztyn, 3: 67–79.

34. M y k i t a E., T a r a s i e w i c z J. 1967 – Pomiary natężenia w widmie światła słonecznego w jeziorach – Acta hydrobiol., Kraków, 9: 193–203.

35. N e l s o n P. R., E d m o n d s o n W. T. 1955 – Limnological effects of fertilizing Barc Lake, Alaska – Fishery Bull. Fish Wildl. Serv. U.S. 102: 414–436.

36. O h l e W. 1953 – Phosphor als initial Faktor der Gewässereutrophierung – Vom Wass. 20: 11–23.

37. O l s z e w s k i P., P a s c h a l s k i J. 1959 – Wstępna charakterystyka limnologiczna niektórych jezior Pojezierza Mazurskiego – Zesz. nauk. wyższ. Szk. roln. Olsztyn, 4: 1–109.

38. P a r s o n s T. R., S t e p h e n s K., T a k a h a s h i M. 1972 – The fertilization of Great Central Lake. I. Effect of primary production – Fish. Bull. 70: 13–23.

39. P a t a l a s K. 1960a – Mieszanie wody jako czynnik określający intensywność krążenia materii w różnych morfologicznie jeziorach okolic Węgorzewa – Roczn. Nauk roln. B, 77: 223–242.

40. P a t a l a s K. 1960b – Stosunki termiczne i tlenowe oraz przezroczystość wody w 44 jeziorach okolic Węgorzewa – Roczn. Nauk roln. B, 77: 105–222.

41. P a t a l a s K. 1960c – Charakterystyka składu chemicznego wody 48 jezior okolic Węgorzewa – Roczn. Nauk roln. B, 77: 243–297.

42. P a t a l a s K. 1960d – Punktowa ocena pierwotnej produktywności jezior okolic Węgorzewa – Roczn. Nauk roln. B, 77: 299–326.

43. P a t a l a s K. 1963 – Sezonowe zmiany w pelagicznym planktonie skorupiakowym sześciu jezior okolic Węgorzewa – Roczn. Nauk roln. B, 82: 209–234.

44. P i e c z y ń s k a E. 1970 – Periphyton in the trophic structure of freshwater ecosystems – Pol. Arch. Hydrobiol. 17: 141–147.

45. P i e c z y ń s k a E. 1972 – Ecology of the eulittoral zone of lakes – Ekol. pol. 20: 637–732.

46. P i e c z y ń s k a E., S z c z ę p a ń s k a W. 1966 – Primary production in littoral of several Masurian lakes – Verh. int. Verein. Limnol. 16: 372–379.

47. R o d h e W. 1949 – The ionic composition of lake water – Verh. int. Verein. Limnol. 10: 377–386.

48. R o d h e W. 1958 – Primärproduktion und Seetypen – Verh. int. Verein. Limnol. 10: 121–141.

49. R o d h e W. 1965 – Standard correlations between pelagic photosynthesis and light – Memorie Ist. ital. Idrobiol. 18: 365–381.

50. S a k a m o t o M. 1966 – Primary production by phytoplankton community in some Japanese lakes and its dependence on lake depth – Arch. Hydrobiol. 62: 1–28.

51. S c h i n d l e r D. W., F e e E. J. 1974 – Experimental lakes area: whole-lake experiments in eutrophication – J. Fish. Res. Bd Can. 31: 937–953.

52. S m i t h M. W. 1948 – Preliminary observations upon the fertilization of Crecy Lake, New Brunswick – Trans. Am. Fish. Soc. 75: 165–174.

53. S m i t h M. W. 1955 – Fertilization and predator control to improve trout angling in natural lakes – J. Fish. Res. Bd Can. 12: 210–237.

54. S m i t h M. W. 1969 – Changes in environmental biota of a natural lake after fertilization – J. Fish. Res. Bd Can. 26: 3101–3132.
55. S o s n o w s k a J. 1974 – Zbiorowiska planktonowe trzech jezior mazurskich i zawartość chlorofilu w ich fitoplanktonie – Monografie bot. 42: 1–128.
56. S p o d n i e w s k a I. 1974 – The structure and production of phytoplankton in Mikołajskie Lake – Ekol. pol. 22: 65–106.
57. S t a n g e n b e r g M. 1936 – Szkic limnologiczny na tle stosunków hydrochemicznych Pojezierza Suwalskiego – Rozpr. Spraw. Inst. badaw. Las. państ. A, 19: 7–54.
58. S t a n g e n b e r g-O p o r o w s k a K., M a r e k J. 1974 – Glony nitkowate przyczyną wiosennych śnieć w stawach karpiowych – Gospod. rybna, 26: 18–19.
59. S t e w a r t K. M., R o h l i c h G, A. 1967 – Eutrophication – a reviev – A report to the State Water Quality Control Board, California, 34: 1–181.
60. S z c z e p a ń s k i A. 1966 – Bemerkungen über die Primärproduktion des Pelagials – Verh. int. Verein. Limnol. 16: 363–371.
61. S z c z e p a ń s k i A. 1968 – Limnology of the Krutynia drainage area – Pol. Arch. Hydrobiol. 15: 191–209.
62. S z u m i e c M. 1971 – Solar radiation, water temperature and primary production in carp ponds – Pol. Arch. Hydrobiol. 18: 175–187.
63. T a l l i n g J. F. 1966 – The annual cycle of stratification and phytoplankton growth in lake Victoria (East Africa) – Int. Rev. ges. Hydrobiol. 51: 545–621.
64. V o l l e n w e i d e r R. A. 1968 – Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication – Organization for Economic Co-operation and Development, Paris, 159 pp.
65. W e a t h e r l y A., N i c h o l s A. G. 1955 – The effects of artificial enrichment of a lake – Aust. J. mar. Freshwat. Res. 6: 443–468.
66. W i n b e r g G. G. 1960 – Pervičnaja produkcija vodoemov – Izdatel'stvo Akad. Nauk BSSR, Minsk, 329 pp.
67. W i n b e r g G. G., L a c h n o w i c z W. P. 1968 – Nawożenie stawów – PWRiL, Warszawa, 334 pp.
68. W i s z n i e w s k i J. 1953 – Uwagi w sprawie typologii jezior polskich – Pol. Arch. Hydrobiol. 1: 11–23.
69. W r ó b e l S. 1962 – Wpływ nawożenia azotowo-fosforowego na skład chemiczny wody, produkcję pierwotną fitoplanktonu i przyrosty ryb w stawach – Acta Hydrobiol. 4: 151–204.
70. W r ó b e l S. 1966 – Produkcja pierwotna fitoplanktonu w stawach – Zesz. probl. Kosmosu, 13: 31–37.
71. Y o s h i m u r a S. 1935 – Relation between depth for maximum amount of excess oxygen during the summer stagnation period and the transparency of freshwater lakes – Proc. imp. Acad. Japan, 11: 356–358.
72. Z a c h w i e j a J. 1972 – Zmienność wieloletnia właściwości fizycznych i chemicznych wody w jeziorach pod wpływem warunków meteorologicznych – Ph.D. Thesis, Agricultural-Technical Academy, Olsztyn, 50 pp.
73. Z a w i s z a J. 1961 – Wzrost ryb w jeziorach okolic Węgorzewa – Roczn. Nauk roln. B, 77: 681–748.
74. Z d a n o w s k i B. (in press) – Wieloletnie zmiany w produkcji pierwotnej pelagialu jezior podgrzanych – Roczn. Nauk roln.
75. Z d a ń o w s k i B., B n i ń s k a M., K o r y c k a A., S o s n o w s k a J. (in press) – The effect of mineral fertilization on ecosystem structure and functioning in lakes of different trophic type. Part I. The effect of lake fertilization on changes in chemical composition of water and macrophytes, chlorophyll content and primary production of pelagic zone – Pol. Arch. Hydrobiol.

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