12. SUMMARY AND CONCLUSIONS

(Anna Hillbricht-Ilkowska)

The chemical composition of water and bottom sediments, productivity and decomposition rates as well the biodiversity and food web functioning (edible algae, organic suspension, bacterio-detrivores, herbivores, grazers, predators) in plankton, benthos and fish were analysed in humic, weakly acid mid-forest lake (Lake Flosek, Masurian Lakeland, Poland) before and after application of powdered lime (Phot. 1 and Fig. 1)

The results of the studies performed 20–23 years (1990–1993) after liming were compared with the studies (partly published in Hillbricht-Ilkowska *et al.* 1977) in the control period (1963, 1966), directly (1–4 years) after liming (1971–1974) and in the treatment year (1970).

Calcium concentration in water (10–16 mg l^{-1}) was maintained at several times higher level than noted prior to liming, though it was slightly lower when compare with the period following liming (14–19 mg l^{-1}) (Figs 2, 3). Annual calcium losses from the lake water were assessed to be 1–2%. Because of the lack of outflow for the lake waters and no calcium input from the catchment area (raised peatbog, coniferous forest), this might result from biological decalcification by algal production, calcium deposition in the lake sediments, as well as ionic exchange processes occurring between the lake waters and *Sphagnum* peatbog surrounding the lake. Liming–induced changes in calcium content of the bottom sediments were manifested by a few-fold increase in the content on dry weight basis (from 0.2–0.3% to 0.4–1.6%) and even a bit higher (0.9–1.7%) 20 years afterwards (Table 10). The values of pH were maintained after liming at a constant level of 7–8 (initially about 6 with temporary falls to 5.5 above the bottom) (Figs 2, 3).

Low trophic state of the lake remained unchanged. This was manifested by low concentrations of phosphate (≤ 10 μg l^{-1}), total phosphorus (≤ 50 μg l^{-1}), mineral nitrogen (~0.2 mg l^{-1}) and organic nitrogen (~1.0 mg l^{-1}) characteristic of oligo- to mesotrophic lakes (Figs 4, 5). However, phosphate concentrations appeared to be highly variable in the whole study period reaching ~25 μg l^{-1} in the control and treatment year, and only ≤ 5 μg l^{-1} 1–3 and 20 years after liming. A tendency of phosphate to increase re-occurred in 1992 and 1993 (i.e. 22 and 23 years after the treatment) (Fig. 4). Likewise, concentrations of organic forms of nitrogen and total phosphorus were significantly higher in 1992–1993 than 1990–1991. A hypothesis has been put forward that the increased fertility of the lake in recent years may indicate eutrophication "new production" or more efficient mechanisms of nutrient recycling and remineralisation. Concentrations of mineral N are generally low and highly variable (Fig. 5).

Lake Flosek has continuously exhibited features characteristic of lakes having specific thermo-mictic regime (bradymictic). Summer stratification of the water with a sharp thermocline (8–10°C per 1 m) at a depth of about 4 m is maintained over 2–3 months (May–July), while freezing period – over or about 4 months (December–April). During remaining periods, the lake is mixed to the bottom. Oxygen deficits at the bottom occur frequently, these however are not long-lasting nor widespread. Hydrogen sulphide is absent (Figs 7, 8).

In summer, gross primary production of plankton measured in the 0–4 m layer 20 years after the treatment (1991–1992) was maintained at a level equal to/lower than 42 kJ m^2 day^{-1} (Table 3). This value approximates those noted in the control period and 1–4 year after liming, and is by ten times lower than in a typical eutrophic lake. This provide additional evidence of the lake to be nutrient-poor and low-productive. Chlorophyll concentration (of a few μg l^{-1} in summer), high water transparency (of 4 m) and low annual mean biomass of phytoplankton (of 1–5 mg l^{-1}) indicate low, and even very low trophic state of the lake and I purity class of its waters (Figs 9, 10 and 11). The above indices were practically similar in the control period and 1–4 and 20–23 years after liming. A clear-cut increase in mean phytoplankton biomass however occurred in the years 1992–1993 (22–23 years after liming) when compare with 1990–1991 (20 and 21 years after the treatment) (Fig. 11). This was well synchronised with the increases in nutrient concentrations (Figs 4, 5).

Liming enhanced organic matter decomposition measured by O_2 uptake and the ratio of decomposition to primary production. The ratio was constantly about 200%, while in the control year – about 60% (Table 4). This indicates that heterotrophic decomposition of matter resources POM and DOM accumulated in the lake waters and sediments predominates over *in situ* production. Abundance of bacterioplankton also increased (data for the liming period and 1–4 years afterwards in Hillbricht-Ilkowska *et al.* 1977). Enhanced decomposition and production of bacterial flora owing to acidity neutralisation has often been observed in limed lakes.

Significant many-year changes have been found in species composition (Table 5) and size distribution (Figs 11, 12) of phytoplankton. Liming has caused dinoflagellates (*Peridinium*, *Ceratium*) to diminish in favour of chrysophytes (principally a few *Dinobryon* species) (Table 5). The latter group is believed to feed heterotrophically and prefer calcium-rich waters. However 20 years after Lake Flosek liming, some additional changes took place in phytoplankton structure. Dinoflagellates (e.g. *Gymnodinium*), a group characteristic of humic lakes and dominant before liming but clearly declining after the treatment, increased again. In 1991, chloromonads (a group characteristic of humic lakes and dominant in the years 1992 and 1993) appeared with *Vacuolaria viridis* dominating (Table 5). Participation of edible algae or nanoplankton (of cell size up to 20 m) found 20 years after liming was by a few times lower than before and directly after the treatment (Fig. 12). This may point out over-grazing of this phytoplankton component by zooplankton (*Asplanchna* sp. div., *Diaptomidae*). Moreover, green algae and diatoms as well as flagellates occurred more abundantly 1–4 and/or 20–23 years after liming (Fig. 11 and Table 5).

Certain chemical elements contained in water (e.g. phosphate, calcium, ammonium nitrogen) as well as oxygen and gross primary production and matter decomposition (diurnal oxygen uptake *in situ*) sometimes increased sharply at a depth of about 3–4 m or over the bottom in different seasons of a year like in winter under ice cover, during summer stratification and autumn overturn (Figs 5, 6, 8 and 10).

Composition of littoral vegetation is typical of humic lakes and raised peatbogs predominated by peatmoss (*Sphagnetum*) patches having strongly acidic water. Since 1974 no evident peatmoss mat spreading over the water table has been observed neither has the mat diminished as it could have been expected beyond pH and calcium thresholds for *Sphagnum*. Periphytonic algae attached to branches lying on the bottom of the lake (nitrogen fixing *Tolypothrix tenuis* Kütz) and filamentous algae floating freely (metaphyton) in water mass (*Mougeoia*) occurred numerously (Figs 13, 14). The algae attained periodically very high biomass and modified chemical composition of waters. Shifts in pH values corresponding with periods of their growth and decomposition have been revealed (Fig. 3). These algal communities are characteristic of nutrient-poor oligotrophic and mesotrophic lakes of high water transparency. They are tolerant of pH shifts between 5 and 6. No submerged macrophytes (an effect of semi-liquid consistency of sediments) nor *Utricularia* genus typical of weakly acidic humic lakes was reported to occur.

Highly significant changes were found in planktonic communities of rotifers and crustaceans (Figs 15–18, Tables 6, 7). After liming, their diversity and number of co-occurring species increased nearly two times and permanently for rotifers (Fig. 15). Slightly lower and variable value was reported for crustaceans (Fig. 17). Certain species preferring low pH diminished, while others increased their numbers. Large cladocerans of the genus *Daphnia* replaced smaller ones (e.g. *Ceriodaphnia, Bosmina*) (Fig. 18). Succession of species of the genus *Cyclops* took place (Table 7). Macrofilter feeders, i.e. *Diaptomidae*, and particularly small rotifers (suspension feeders and raptors), increased their abundance reaching overall numbers comparable to those in eutrophic lakes (Figs 15, 17). Twenty-twenty three years after the treatment, heavy predator pressure was observed comprising *Chaoborus, Cyclops* and *Asplanchna priodonta* as well as fish (roach, bleak) (Tables 1, 6 and 7). This was manifested by a drop in crustacean abundance, striking changes in mean size of adult individuals (Fig. 17), a sharp spatial separation of predator from its prey and diurnal migrations mitigating predatory pressure, as well as predomination of rotifer species having a gelatinous sheath and thus resistant to predation (Ejsmont-Karabin 1996, Węgleńska *et al.* 1996).

After liming also increased: diversity of benthic community (new taxa appeared mainly among *Chironomidae*), especially in shallow parts of the lake, abundance of detrivores (*Chironomide*, *Oligochaeta*, *Asellus*) and predatory larvae of *Chaoborus flavicans* (to 13 10^3 indiv. m^{-2}), particularly in the central part of the lake (presumably less penetrated by fish) (Table 8 and Fig. 19). Increased abundance of *Chaoborus* seems to result primarily from development of small zooplankton (rotifers, nauplii of *Diaptomidae*), and secondarily – from occurrence of larger *Daphnia*. Despite elevated calcium concentration in water, molluscs have not been found to occur.

It has been revealed that contents of organic matter, calcium, magnesium and other components of Lake Flosek sediments were maintained in a range characteristic of humic lake, despite the liming-induced changes (Table 10). Phosphorus release from sediments is minimal (by one or two orders of magnitude lower than in non-humic meso-eutrophic lakes) and rather stable regardless of oxygen concentrations above or in bottom sediments (Fig. 21). It has been shown that about 70–80% of phosphorus is bound to humic compounds and aluminium oxide, hence the sediments are possibly not significantly involved in nutrient recycling (Fig. 20).

The main conclusions from long term study of limed, humic Lake Flosek can be formulated as following.

Twenty years after liming of primarily dystrophic, weakly acidic Lake Flosek, its trophic state, production and phytoplankton abundance was maintained at a relatively low level, and water transparency remained high, despite continuous neutrality and elevated calcium content. This enabled some species characteristic of humic lakes to reoccur, and species typical of transparent low productive lakes to appear. Still the elevated calcium concentration did not disturb distribution of peatmoss mat nor littoral vegetation, although it restrained the mat expansion over the water table. Thereby, moderate single-dose lime application to a weakly acidic humic lake does not greatly disturb natural features of this type of lakes. By contrast, liming provides a lake with long-lasting ability to neutralise strongly acid precipitation and thus prevents pH falls below a level (≤ 5.0) eliminating many unique nature resources of this type of lakes. However, the evidenced continuous slow loss of calcium from the lake water implies such conditions to last possibly a few decades.

Despite the fact that oligotrophic conditions and habitat properties associated with *Sphagnum* surroundings and humic nature of Lake Flosek were maintained, liming led to clear-cut and long-lasting (about two decades) changes in food web structure of the lake (Fig. 22A). Transformations of the structure are, in turn, an effect of altered biodiversity and abundance of suspended food and composition of consumers (herbivores and detrivores) as well as their predators (invertebrates and fish). It seems that a food web found in the period directly following liming results from increased abundance of bacterio-detrital suspension (bottom-up type of the control) and development of detrivores in plankton and benthos (Fig. 22A, B). By contrast, the food web found 20 years after the treatment exhibits heavy predator pressure (*Chaoborus* larvae, fish) and top-down control (Fig. 22C). Thus the liming affected first of all the biodiversity (increase of species richness in plankton and benthos). Then it stimulated the mobilisation of food reserves in the lake system which eventually led to the greater and stable complexity of food web. The complex, species rich and top-down controlled food web was installed in the lake without interfering with high quality of lake waters (low-productive, high-transparenty).

Some recent results (1992 and 1993, i.e. 22 and 23 years after the treatment) suggest appearing of symptoms of increased nutrient concentrations and higher algal biomass (including edible algae) (Figs 4, 5, 11 and 12). This seems to be a consequence of more efficient mechanisms of in-lake nutrient recycling (an effect of strong top-down control of food web), as well as possible external nutrient supplies (Fig. 22).

The latter case may result from influx from the catchment area (forest clearance in the lake surrounding) as well as intensive outdoor recreation or fishery practice (e.g. fish feeding). The above sources of possible nitrogen and phosphorus loadings provide the nutrients in forms assimilable to algae. Presence of these forms may signalise first symptoms of eutrophication, the process able to modify the lake completely and make it resemble lakes of the meso-eutrophic type (with possible algal blooms and further consequences). This is a threat of relatively greater importance than input of acid-forming compounds from the atmosphere or the peatbog surrounding. Lake Flosek is a representative of humic lakes, many of which are reserves protected and located in areas of national or landscape parks. The results of the studies indicate that susceptibility of these lakes to acidification may be effectively controlled by moderate single dose lime application (without disturbing the peatmoss surroundings and high lake water quality), whereas threat of eutrophication may evade control.

ACKNOWLEDGEMENTS: The authors thank very much dr. Irena Spodniewska for elaborating the phytoplankton samples collected in 1990–1993 years. We are also grateful to dr. Taida Tarabuła for doing the translation of the paper into English as well as dr. Krassimira Ilieva-Makulec for final editorship of the paper.