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STRATIFICATION OF ESTONIAN LAKES STUDIED DURING HYDROOPTICAL EXPEDITIONS IN 1995–97

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Abstract. During May–September 1995–97, thermal stratification and vertical profiles of dissolved oxygen, chlorophyll *a*, and primary production were studied in eight Estonian lakes of different morphometry and trophic types. Lake Uljaste, Võrtsjärv, and Kurtna Nõmmejärv were nonstratified. The biggest temperature gradients exceeded 10 °C m^{-1} in lakes Verevi and Nohipalu Mustjärv, both rich in heat absorbing optically active substances. In more transparent lakes the maximum temperature gradient ranged from 6.6 to 7.2 °C m^{-1}. The mixing depth varied from 1–2 m in Äntu Sinijärv and Nohipalu Mustjärv to 8 m in Koorküla Valgjärv. Thermal stratification clearly affected the biological stratification in cyanophyte dominated lakes (L. Verevi, Koorküla Valgjärv) while the thermocline obviously did not represent a barrier for motile flagellated algae, which could migrate throughout the water column (Nohipalu Mustjärv and Nohipalu Valgjärv).

Key words: stratification, temperature, oxygen, chlorophyll *a*, primary production.

INTRODUCTION

During calm days with substantial solar energy input, the surface layer of lakes is heated more rapidly than the heat can be distributed by mixing. The resistance of the floating warm water to vertical mixing results in a thermal–density stratification where epilimnion, the uniformly warm and turbulent upper layer, overlies the cold and stagnated hypolimnion. The metalimnion is defined as the layer of steep thermal gradient (Wetzel, 1975). As wind-driven turbulence is the main force able to distribute the heat vertically in the water column, the stability of thermal–density stratification in lakes depends very strongly on the size and morphometry of lakes. Kling (1988) showed that lake depth exerts a stronger influence on the stability of stratification than the lake area does. Most of the stratified lakes in temperate region are dimictic, i.e. the whole water mass is mixed twice a year, during spring and autumn overturn. Besides seasonal stratification, diurnal formation of thermally different strata can be followed in deep lakes (Pierson et al., 1994). In shallow lakes stratification is often disturbed and such lakes are called polymictic.

The onset of stratification affects strongly the lake ecosystem by isolating the well illuminated productive upper layers from nutrient resources in the sediment. Reynolds & Bellinger (1992) showed phytoplankton to be extremely sensitive to the interaction between light income and thermal stability. In a small 30 m deep mere in England severe light limitation restricted phytoplankton development outside the stratified period, though delayed stratification in spring could promote large diatom crops. Depending on the timing of the clear water phase, either *Microcystis* or *Ceratium* gained the leading position. Extremely stable stratification led to *Scenedesmus* dominance while episodes of summer mixing favoured *Oscillatoria.*

Modelling the effects of climate change on lake eutrophication, Frisk et al. (1997) demonstrated that the global warming has resulted in a longer stagnation period and higher bottom temperature in lakes, which has led, over accelerated oxygen consumption in the hypolimnion, to phosphorus release from anoxic sediments and to an increased algal biomass in autumn. Similar conclusions were made by Adrian et al. (1995) basing on investigations of the Heiligensee. In addition, the authors showed that the 1–3 weeks earlier onset of thermal stratification causes an earlier start of epilimnetic silica limitation and the diatoms commonly dominating in spring are outcompeted by cyanophytes.

The most perceptible consequence of thermal stratification is the formation of secondary chemical, biological, and optical stratification in lakes. Due to steep physical and chemical gradients, metalimnion is often the site of matter accumulation, be it the settling material from the overlying layers (Fee, 1976), *in situ* growing algae (Ichimura et al., 1968) and bacteria, or migrating grazers (Porter et al., 1996). On the other hand, the distribution of optically active substances may have a feedback to thermal stratification. Kling (1988) found a strong positive relationship between water transparency and thermocline depth showing that, besides lake morphometry, deeper penetration of solar radiation is important in establishing mixing depth.

The present paper describes the vertical profiles of temperature, oxygen, chlorophyll, and primary production measured in eight Estonian lakes during hydrooptical expeditions, and attempts to explain their formation basing on the morphometric and ecological characteristics of the lakes.

GENERAL DESCRIPTION OF THE LAKES

The studied lakes (Fig. 1) were of different morphometry and types (Table 1). As to their optical properties (see Secchi depth in Table 1) the lakes covered most of the range characteristic of Estonian lakes from the most transparent

Fig. 1. Location of the studied lakes. 1, Äntu Sinijärv; 2, Uljaste; 3, Kurtna Nõmmejärv; 4, Verevi; 5, Koorküla Valgjärv; 6, Nohipalu Valgjärv and Nohipalu Mustjärv; 7, Võrtsjärv.

Table 1

General features of the studied lakes

Lake	Area*, ha	Mean depth*, m	Maximum depth*, m	Secchi depth**, m	Type***
Koorküla Valgjärv	44.1	8.5	26.8	2.9–4.7	stratified eutrophied oligotrophic
Kurtna Nõmmejärv	15.6	3.1	7.5	2.4–4.5	nonstratified mixotrophic hard-water
Nohipalu Mustjärv	21.9	3.9	8.9	0.5–0.6	anoxic stratified dystrophic
Nohipalu Valgjärv	6.3	6.2	12.5	4.3–5.0	stratified oligotrophic
Uljaste	62.9	2.2	6.4	1.5–3.6	nonstratified eutrophied semidystrophic
Verevi	12.6	3.6	11.0	2.0–3.5	stratified eutrophic hard-water
Võrtsjärv	27 000	2.8	6.0	0.2–0.9	nonstratified eutrophic hard-water
Äntu Sinijärv	2.4	–	8.0	> 6.5	alkalitrophic

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* after Kask, 1964;
** our measurements in 1995–97;
*** after Mäemets, 1977.

Äntu Sinijärv to the extremely dark Nohipalu Mustjärv and to the very turbid Võrtsjärv. By stratification the lakes ranged from nonstratified or polymictic (Võrtsjärv, Kurtna Nõmmejärv, Uljaste) to sharply stratified ones (Verevi, Nohipalu Mustjärv). By trophic scale the chosen set of lakes included the most oligotrophic Nohipalu Valgjärv and nowadays already hypertrophic Lake Verevi.

MATERIAL AND METHODS

The lakes were investigated in May, June, and August 1995; in June, August, and September 1996; and in August 1997. Äntu Sinijärv was studied only in 1995. Instead of it Koorküla Valgjärv was included in the following years.

Profiles of temperature (t°), oxygen (O_2), and oxygen saturation level (O_2%) were measured vertically with one metre intervals using the thermo-oxymeter "Marvet Junior" (Elke-Sensor, Tallinn). Values for 0.5 m, 1.5 m, 2.5 m etc. were calculated using linear extrapolation. As dihydrogen sulphide can spoil the membrane of the oxymeter, measurements were stopped at a depth where O_2 approached zero. For this reason, the t° and O_2 profiles did not reach the bottom in several cases in lakes Verevi, Nohipalu Mustjärv, and Koorküla Valgjärv. A vertical temperature gradient of $\geq 1.5\,°C\ m^{-1}$ was taken as the criterion for metalimnion.

Phytoplankton primary production (PP) was measured using the $^{14}CO_2$ assimilation technique. Water from six layers within the euphotic zone (the sampling depths were chosen separately for every lake depending on the depth and water transparency) was poured into 36 ml glass vials. Sterile $NaH^{14}CO_3$ solution was added to reach the final activity of $0.06\ \mu Ci\ ml^{-1}$. The vials were incubated in the lake for 2 hours around midday at the depths from which the water was sampled. Non-photosynthetic carbon fixation was measured in dark vials. After incubation, water from every vial was filtered through 0.45 µm pore size membranes (Millipore HA). Filters were treated with HCl vapours to remove the excess of the inorganic ^{14}C. Radioactivity of the filters was measured using the LSC RackBeta (LKB-Wallac). The PP values were calculated according to the standard formula (Nielsen & Bresta, 1984).

For chlorophyll measurements, 50–200 ml of water was filtered through Whatman GF/C filters. The filters were put into 5 ml of ethanol and transported in an ice box to the laboratory. Pigments were analysed spectrophotometrically after 24-hour extraction at +4 °C. The formula by Lorenzen (1967) was used to calculate the chlorophyll *a* concentration (Chl *a*).

Phytoplankton samples for microscopic analyses were taken from all lakes, except Äntu Sinijärv, in June, August, and September 1996. The samples were preserved with Lugol solution and examined after settling for species composition under an inverted microscope.

RESULTS AND DISCUSSION

Thermal regime

The spring-fed lake Äntu Sinijärv was the coldest among the lakes studied with a summer maximum temperature reaching only 16.4 °C (Table 2). In the dark water Nohipalu Mustjärv the temperature reached 28.2 °C, which exceeded by three degrees the temperature in the neighbouring colourless Nohipalu Valgjärv.

According to summer temperature profiles, lakes Võrtsjärv, Uljaste, and Kurtna Nõmmejärv could be considered nonstratified or polymictic. In the last one we found in most cases a 1–5 °C temperature difference between the surface and the bottom layer, which could be partially caused by numerous springs opening to the lake bottom (Mäemets, 1977). Measurements made during hydrooptical expeditions did not reveal any stratification in Võrtsjärv. Still the

Table 2

Thermal characteristics of studied lakes measured during expeditions in 1995–97

Lake	Maximum surface t, °C	Vertical t difference, °C	Maximum t gradient, °C m^{-1}	Mixing depth, m
Koorküla Valgjärv	25.7	5.6–17.2	6.8	3.5–8
Kurtna Nõmmejärv	24.1	0.1– 5.9	2.3	2–bottom
Nohipalu Mustjärv	28.2	0.7–13.5	10.3	1–2
Nohipalu Valgjärv	25.2	2.4–14.8	6.6	2–6
Uljaste	24.5	0.1– 5.5	4.2	2–bottom
Verevi	24.7	1.8–17.7	10.2	2.5–4
Võrtsjärv	25.3	0 – 1.9	1.4	bottom
Äntu Sinijärv	16.4	2.7–10.5	7.3	1–2

lake may stratify for short periods. In 1995 thermally stable conditions lasted for 1–2 weeks in June and July (Fig. 2) when the temperature difference between surface and bottom layers reached 4 °C (the maximum difference of 8.8 °C was measured in the extremely warm July of 1994). Both the summer stratification and the inverse stratification in winter affected strongly the oxygen content above the sediment.

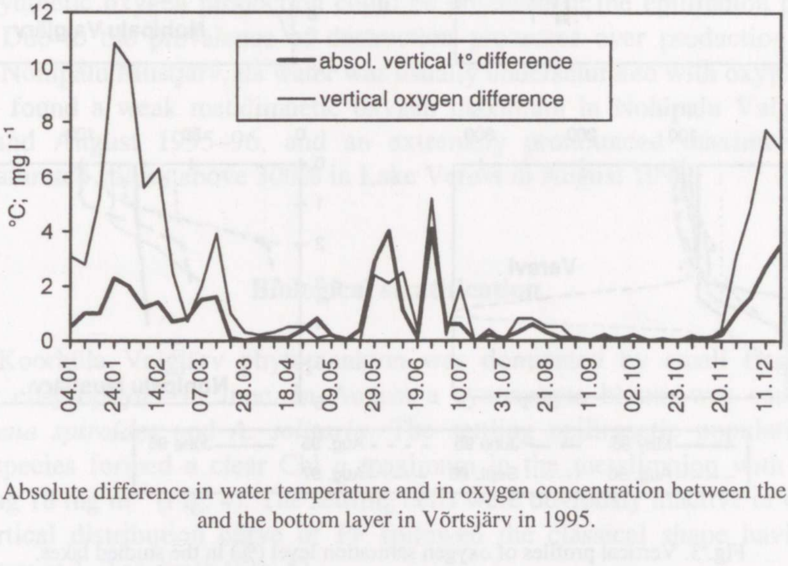

Fig. 2. Absolute difference in water temperature and in oxygen concentration between the surface and the bottom layer in Võrtsjärv in 1995.

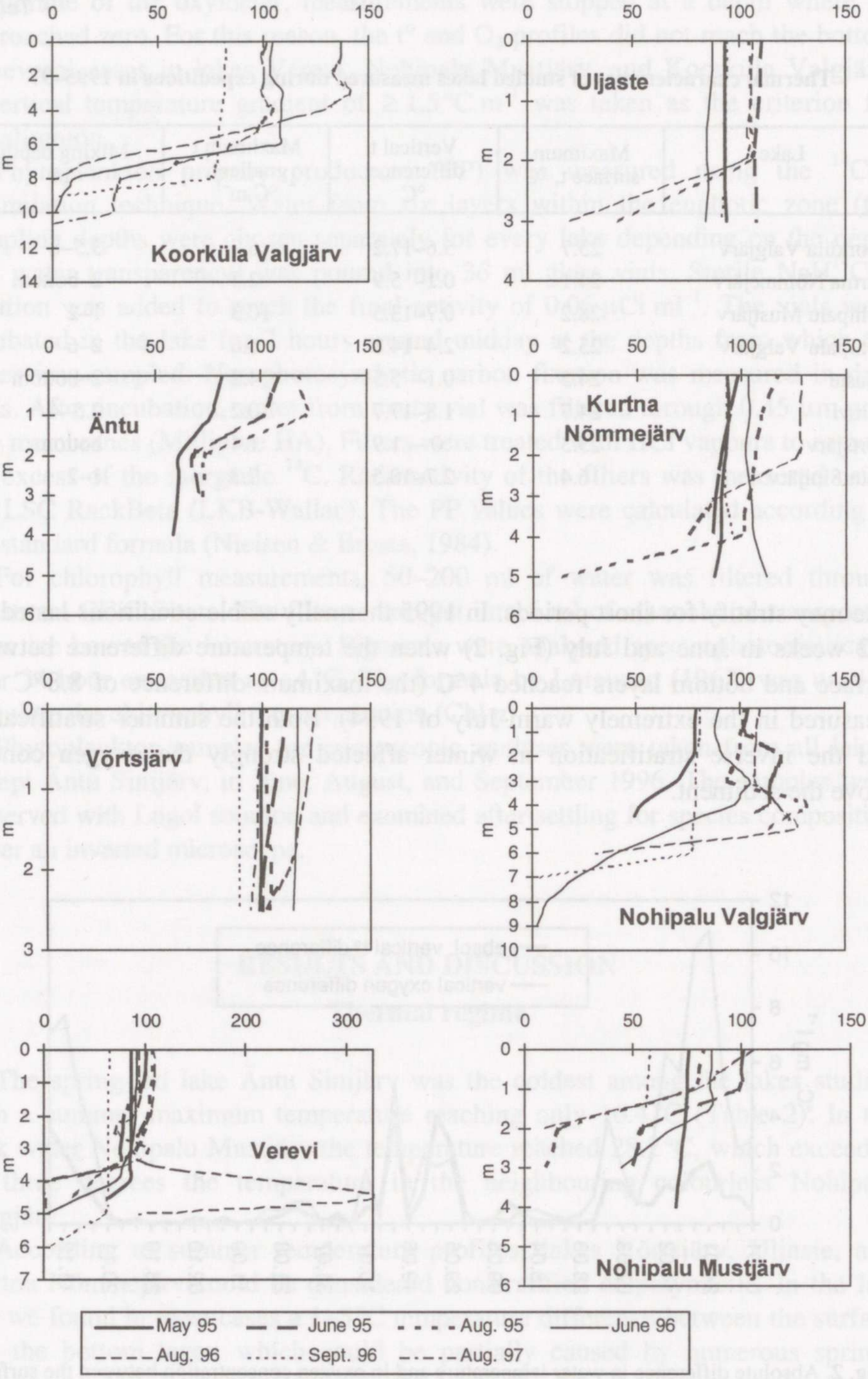

Fig. 3. Vertical profiles of oxygen saturation level (%) in the studied lakes.

There was a more or less stable thermal stratification in the rest of the lakes with established epi-, meta-, and hypolimnion. The biggest temperature gradients exceeded 10 °C m^{-1} in lakes Verevi and Nohipalu Mustjärv, both of which have high concentrations of optically active substances. In more transparent lakes the maximum temperature gradient ranged from 6.6 to 7.3 °C. The mixing depth or the thickness of epilimnion was the smallest (1–2 m) in diametrically different Äntu Sinijärv and Nohipalu Mustjärv. The former is a small and well sheltered forest lake while the thermal stability of the latter is based on high buoyancy resistance to mixing of the dark heat absorbing surface layer. In some cases, diurnal heating caused temperature gradients over 1.5 °C starting just from the surface in both lakes. The mixing extended down to 8 m in Koorküla Valgjärv, which is the largest, deepest, and the most wind-exposed among the stratified lakes.

Oxygen profiles

The vertical distribution of dissolved oxygen followed the clinograde (with a decrease in the hypolimnion) or a positive heterograde (with a metalimnetic maximum) curves (Fig. 3) according to the classification by Åberg & Rodhe (1942). We could not find the orthograde profile (with maximum concentrations in the hypolimnion due to a 100% saturation throughout the water column) described by the above-mentioned authors for oligotrophic lakes. It means that even the most oligotrophic among the studied lakes, Nohipalu Valgjärv and Koorküla Valgjärv, are remarkably eutrophic. As all the measurements were made around noon, a slight supersaturation from 105 to 135% caused by photosynthetic oxygen production could be observed in the epilimnion of most lakes. Due to the prevalence of destruction processes over production in the humic Nohipalu Mustjärv, its water was usually undersaturated with oxygen.

We found a weak metalimnetic oxygen maximum in Nohipalu Valgjärv in June and August 1995–96, and an extremely pronounced maximum with supersaturated values above 300% in Lake Verevi in August 1996.

Biological stratification

In Koorküla Valgjärv phytoplankton was dominated by small flagellates, mainly chrysophytes in June. In August a cyanophyte bloom was caused by *Anabaena spiroides* and *A. solitaria*. The settling epilimnetic populations of these species formed a clear Chl *a* maximum in the metalimnion with values reaching 18 mg m^{-3} (Fig. 4). The settling cells were obviously inactive or dead as the vertical distribution curve of PP followed the classical shape having the maximum at 1–2 m depth (Fig. 5).

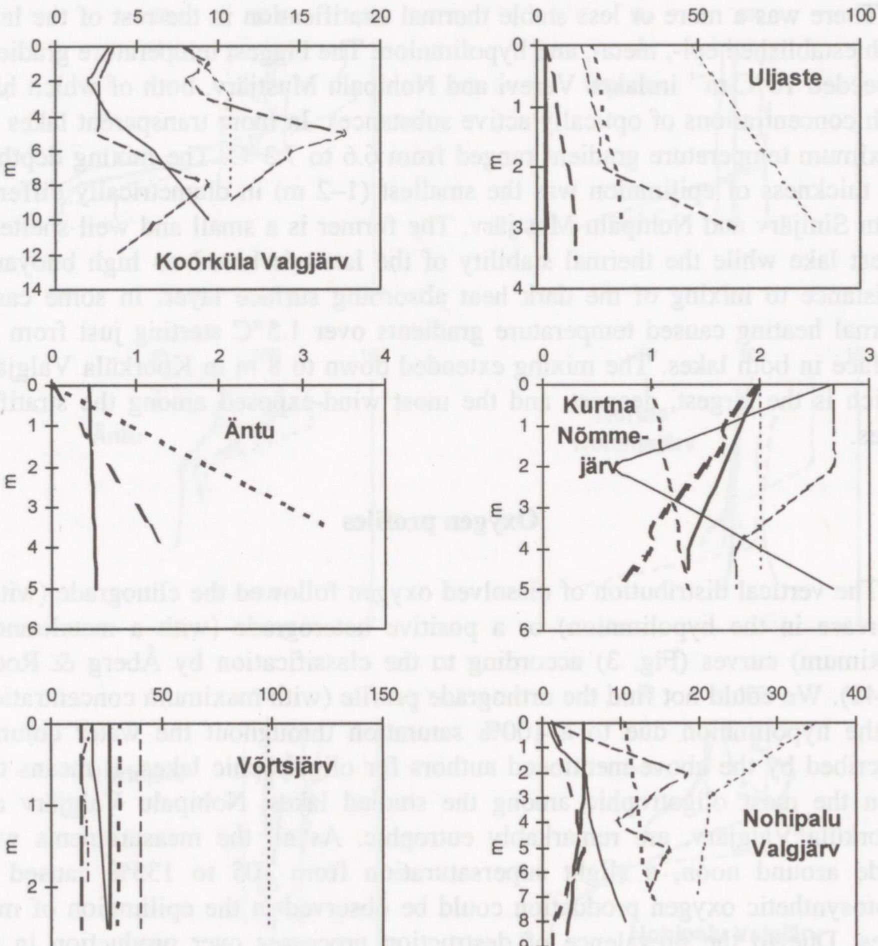

Fig. 4. Vertical profiles of chlorophyll *a* concentration (mg m^{-3}) in the studied lakes.

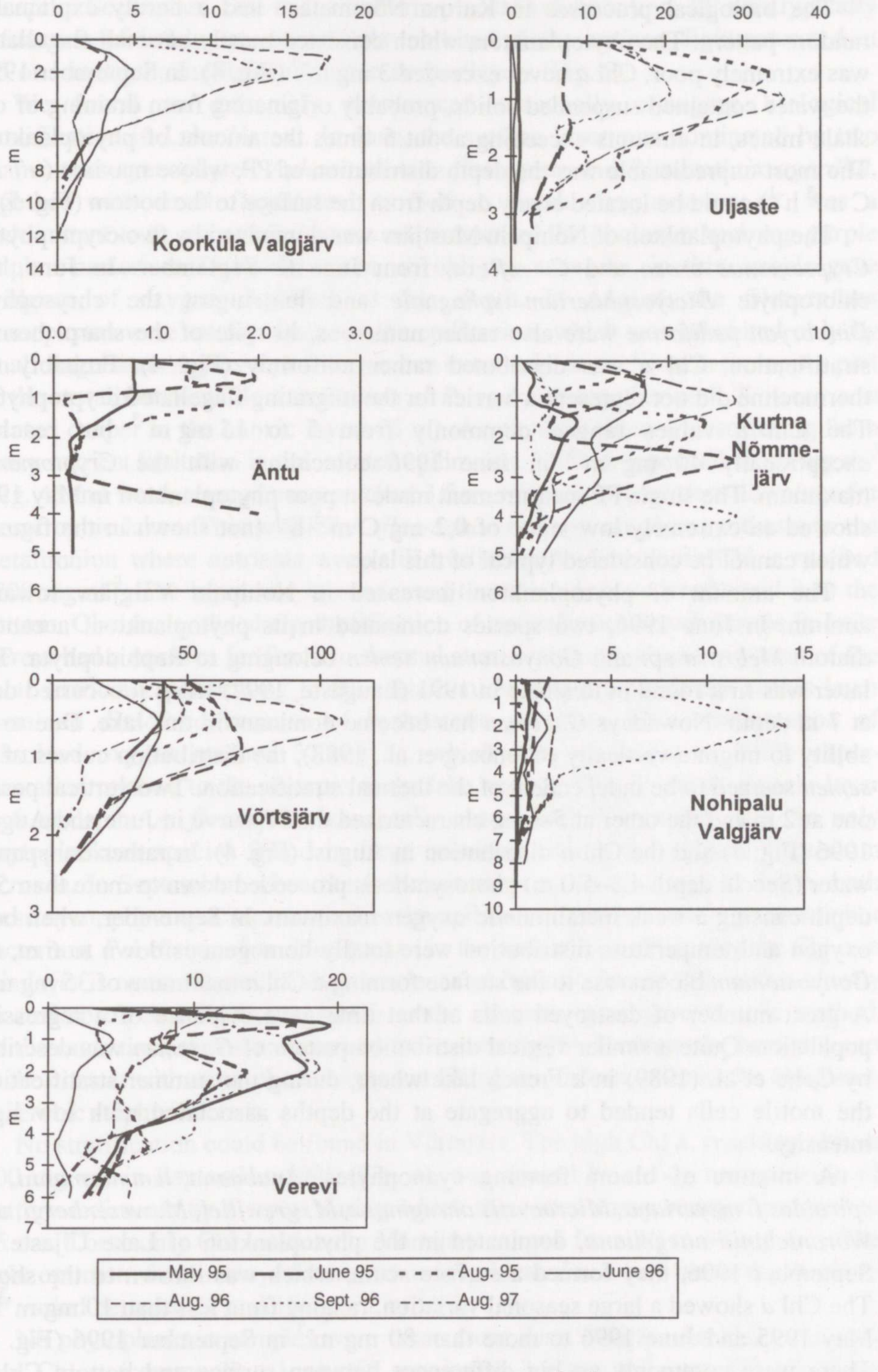

Fig. 5. Vertical profiles of primary production (mg C m^{-3} h^{-1}) in the studied lakes.

The biological processes in Kurtna Nõmmejärv had a hardly explainable random pattern. The phytoplankton, which consisted mostly of small flagellates, was extremely poor. Chl *a* never exceeded 3 mg m^{-3} (Fig. 4). In September 1996, the water contained suspended solids, probably originating from draining of oil-shale mines, in amounts exceeding about 5 times the amount of phytoplankton. The most unpredictable was the depth distribution of PP, whose maxima (~7 mg C m^{-3} h^{-1}) could be located at any depth from the surface to the bottom (Fig. 5).

The phytoplankton of Nohipalu Mustjärv was dominated by two cryptophytes, *Cryptomonas erosa* and *C. reflexa,* from June to September. In June, the chlorophyte *Dictyosphaerium sphagnale* and in August the chrysophyte *Dinobryon pediforme* were also rather numerous. In spite of the sharp thermal stratification, Chl *a* was distributed rather uniformly (Fig. 4). Probably the thermocline did not represent a barrier for the migrating flagellated cryptophytes. The Chl *a* values ranged commonly from 5 to 15 mg m^{-3} but reached exceptionally 40 mg m^{-3} in June 1996 coinciding with the *Cryptomonas* maximum. The single PP measurement made in poor phytoplankton in May 1995 showed an extremely low value of 0.2 mg C m^{-3} h^{-1} (not shown in the figure), which cannot be considered typical of this lake.

The amount of phytoplankton increased in Nohipalu Valgjärv towards autumn. In June 1996, two species dominated in its phytoplankton: a centric diatom *Melosira* sp. and *Gonyostomum semen* belonging to Raphidophyta. The latter was first found in this lake in 1991 (Laugaste, 1992) when it occurred only at 7 m depth. Nowadays *G. semen* has become dominant in this lake. Due to its ability to migrate vertically (Cronberg et al., 1988), the distribution curves of *G. semen* seemed to be independent of the thermal stratification. Two vertical peaks, one at 2 m and the other at 5–6 m, characterized the PP curve in June and August 1996 (Fig. 5) and the Chl *a* distribution in August (Fig. 4). In rather transparent water (Secchi depth 4.3–5.0 m) photosynthesis proceeded down to more than 5 m depth causing a weak metalimnetic oxygen maximum. In September, when both oxygen and temperature distribution were totally homogenous down to 6 m, the *Gonyostomum* bloom rose to the surface forming a Chl *a* maximum of 35 mg m^{-3}. A great number of destroyed cells at that time gave evidence of a regressing population. Quite a similar vertical distribution pattern of *G. semen* was described by Cohu et al. (1989) in a French lake where, during the summer stratification, the motile cells tended to aggregate at the depths associated with low light intensity.

A mixture of bloom forming cyanophytes, *Anabaena lemmermanni*, *A. spiroides f. meyeriana*, *Microcystis aeruginosa*, *M. grewillei*, *M. wesenbergi*, and *Woronichinia naegeliana*, dominated in the phytoplankton of Lake Uljaste. In September 1996, they formed a surface scum, which was thrown to the shore. The Chl *a* showed a large seasonal variation, ranging from less than 10 mg m^{-3} in May 1995 and June 1996 to more than 80 mg m^{-3} in September 1996 (Fig. 4). There were commonly no big differences between surface and bottom Chl *a*, except in September. Due to the uniform plankton distribution, PP was typically a function of irradiance, being light-inhibited at the surface, light-saturated at 0.5 or 1 m depth, and light-limited in deeper layers (Fig. 5).

We found an extremely pronounced seasonally changing biological stratification in Lake Verevi. In June, the surface layer was dominated by two filamentous cyanophytes, *Aphanizomenon flos-aquae* and *Planktothrix agardhii*, together with small flagellates. At 5–6 m depth *Cryptomonas* sp. was a codominant to *P. agardhii.* A mass occurrence of the photosynthesizing purple sulphur bacterium *Thiopedia rosea,* an obligate anaerobe, in this sample gave evidence of oxygen depletion at this depth. In August, the filamentous cyanophytes were totally absent in the epilimnion, which was inhabited only by small flagellates. *A. flos-aquae* formed an extremely dense layer in the upper part of the metalimnion while a maximum of *P. agardhii* together with *T. rosea* was located deeper in the anoxic layers (6 m). As phytoplankton was suffering from heavy nutrient limitation in the isolated epilimnion, Chl *a* dropped below 10 mg m^{-3} (Fig. 4) and water transparency reached 3.5 m, which are characteristic values for mesotrophic lakes. This enabled *A. flos-aquae* to carry on photosynthesis in the metalimnion where nutrients were still available. At 4 m depth Chl *a* reached 1700 mg m^{-3}. The layer was so condensed that the echosounder showed it as the bottom. Obviously, the sharp stratification of optically active substances in Lake Verevi had a positive feedback to thermal stratification by absorbing most of the solar irradiance penetrating to the metalimnion. Oxygen produced in this layer remained dissolved because of hydrostatic pressure. The concentration of dissolved oxygen reached 31 mg l^{-1}, which was equivalent to 327% supersaturation relative to the pressure at the lake surface (Fig. 3). In the anoxic layer at 6 m depth *A. flos-aquae* was totally absent and *P. agardhii* was the only phytoplankton species found in large numbers among the sulphur bacterium *T. rosea*. In September, when the turbulent mixing extended to 5 m depth, both these cyanophyte species occurred in the epilimnion. At that time a green sulphur bacterium, *Pelodictyon luteolum*, peaked in the anoxic layer. Probably the Chl *a* in this layer is overestimated as the occurrence of bacteriochlorophyll, with a closely located absorption maximum, interferes the common spectrophotometric method. At the same time, the technique used for measuring PP dismisses the bacterial part as the contact with atmospheric oxygen at filling the vials intoxicates the obligatory anaerobic sulphur bacteria.

No stratification could be found in Võrtsjärv. The high Chl *a*, reaching almost 100 mg m^{-3} in September 1996 (Fig. 4), was caused by strong resuspension of bottom sediments by a storm during which the water transparency decreased to 15 cm. Commonly Chl *a* values in Võrtsjärv ranged from 10 to 40 mg m^{-3}. The light optimum for photosynthesis was usually located at a half metre depth where PP varied between 32 and 108 mg C m^{-3} h^{-1}.

No phytoplankton samples were taken from Äntu Sinijärv but the extremely low Chl *a* (commonly <1 mg m^{-3}, maximum 3.3 mg m^{-3}; see Fig. 4) gives evidence of a very poor phytoplankton. Low PP, less than 2 mg C m^{-3} h^{-1}, was usually restricted to 1–1.5 m layer, although the irradiance level in the transparent water could enable photosynthesis in the whole water column.

CONCLUSIONS

1. A permanent summer–early autumn thermal stratification was found in five of the eight Estonian lakes studied during hydrooptical expeditions in 1995–97. Lakes Uljaste, Võrtsjärv, and Kurtna Nõmmejärv could be considered non-stratified or polymictic.

2. Thermal stratification clearly affected the biological stratification when cyanophytes were dominating (L. Verevi, Koorküla Valgjärv) while the thermocline obviously did not represent a barrier for motile flagellated algae, which distributed quite uniformly throughout the water column (Nohipalu Mustjärv and Nohipalu Valgjärv).

3. The amount and distribution of optically active substances had a clear feedback to thermal stratification: in lakes with strongly coloured water (Nohipalu Mustjärv) or with a high plankton density (L. Verevi) the solar irradiance was rapidly absorbed resulting in a steeper temperature gradient.

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HÜDROOPTILISTE EKSPEDITSIOONIDE KÄIGUS AASTATEL 1995–97 UURITUD EESTI JÄRVEDE KIHISTUMINE

Peeter NÕGES ja Tiina NÕGES

Aastatel 1995–97 uuriti termilist kihistumist ning hapniku, klorofüll *a* ja primaarproduktsiooni sügavusjaotust kaheksas erineva morfomeetria ja troofsustüübiga Eesti järves. Uljaste järv, Võrtsjärv ja Kurtna Nõmmejärv olid kihistumata. Kiirgust neelavate optiliselt aktiivsete ainete poolest rikastes Verevi järves ja Nohipalu Mustjärves ületas suurim temperatuuri gradient 10 °C m^{-1}. Läbipaistvama veega järvedes oli see näitaja vahemikus 6,6–7,2 °C m^{-1}. Segunemissügavus ulatus 1–2 meetrist Äntu Sinijärves ja Nohipalu Mustjärves kuni 8 meetrini Koorküla Valgjärves. Termiline kihistumine mõjutas selgesti järve bioloogilist kihistumist, kui fütoplanktonis domineerisid sinivetikad (Verevi järv, Koorküla Valgjärv). Samal ajal ei kujutanud termokliin endast barjääri viburvetikatele, mis võisid migreeruda kogu veesamba ulatuses (Nohipalu Mustjärv ja Nohipalu Valgjärv).