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CORRELATIONS BETWEEN LIMNOLOGICAL VARIABLES OF ESTONIAN LAKES

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Abstract. Correlations between 14 limnological variables were investigated in 102 Estonian lakes over the 14-year period reviewed here (1978–91). The investigation of this material revealed 60 statistically significant correlations. Our results confirm that chlorophyll *a* (Chl), phytoplankton biomass (B), total phosphorus (TP), and water transparency are the main trophic parameters as these variables are strongly correlated with one another. Among the biological variables, Chl and B were significantly correlated with most of the measured limnological variables. In general, Chl correlated a little more significantly with the other variables than B. Of organic matter, the permanganate oxidizability (COD_{Mn}) correlated far more significantly with the other variables than dichromate oxidizability. The strong positive correlation observed between COD_{Mn} and colour was the most highly significant relationship ($r = 0.97$) found in this study. Of the nutrient elements, TP showed the greatest number of highly significant correlations with the other variables. The strongest correlation was observed between TP and Chl ($r = 0.80$). The Chl–total nitrogen (TN) relationship in Estonian lakes is weaker than the corresponding Chl–TP relationship as the investigated lakes were mainly phosphorus limited. No significant correlations were found between nitrate ion and the other variables, except for the correlation with TN. Water temperature had no correlation with the other variables.

Key words: lakes, correlations, limnological variables, Estonia.

INTRODUCTION

Accelerated eutrophication of water bodies due to human activity, which deteriorates water quality and endangers ecosystems, is a serious environmental problem. Most freshwater ecosystems are controlled by phosphorus (Schindler, 1977; OECD, 1982). Consequently, great emphasis has been laid on phosphorus as the sole index of the trophic state (Vollenweider, 1976), or its conjunction with other biochemical variables, such as chlorophyll *a* and dissolved oxygen, and with a physical variable – Secchi disk transparency (Carlson, 1977; Walker, 1979;

Aizaki et al., 1981; Steinhart et al., 1982). A large number of investigations (Dillon & Rigler, 1974; Jones & Bachmann, 1976; Carlson, 1977; Schindler, 1978; Canfield, 1983; Shortreed & Stockner, 1986) deal with the relationship between such parameter pairs largely on the basis of regression analysis.

In the early 1970s a strong anthropogenic effect was revealed in Estonian lakes and several lakes became markedly eutrophied in a comparatively short time. Many limnological investigations have been performed on Estonian lakes; however, among them there are relatively few correlation studies of limnological variables (Mäemets, 1980; Mäemets & Lokk, 1982; Ott, 1982; Milius et al., 1987; Ojaveer et al., 1993). The main limnological variables of Estonian small lakes have been regularly investigated by the hydrochemistry team of the Institute of Zoology and Botany since the end of the 1970s; the results have been stored in the data bank of the Institute. The long-term research of 102 small lakes during 1978–91 provides an excellent opportunity for studying correlations between various variables. Our objective was to investigate correlations and to quantify regressions between 14 selected variables representing physical, chemical, and biological features that describe the surface water of lakes.

INVESTIGATED LAKES

The lakes studied are mostly located in South-East Estonia, only a few lakes are situated in the eastern part of the country. In order to illustrate the size distribution of the lakes under study, they were grouped with respect to the surface area and maximum and mean depths (Table 1). Lake surface areas varied

Table 1. Distribution of lakes by surface area and maximum and mean depths

Parameter	Number of lakes[*]
Lake surface, ha	
< 5	29
5–100	62
> 100	11
Max depth, m	
< 5	11
5–10	31
10–20	45
> 20	11
Mean depth, m	
< 3	19
3–5	42
5–10	35
> 10	2

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[*] For some lakes neither maximum nor mean depth was determined.

considerably: from 0.6 to 707.6 ha, in most cases from 5 to 100 ha. Mean depths ranged from 2 to 14 m and maximum depths from 3.5 to 33 m.

All lakes appear to attain thermal stratification during summer, usually from May to September. As regards the trophic type, the lakes include a wide range of limnological conditions from mesotrophic to hypertrophic. Our earlier study (Milius et al., 1991) showed that practically no oligotrophic lakes occur in the southeastern part of Estonia.

MATERIAL AND METHODS

The data used in this paper were collected during 1978–91. The number of lakes studied each year ranged between 18 and 44. Eighteen lakes were studied during 6–9 years, sixty-one lakes during 2–5 years, and twenty-three lakes in only one year. The lakes were sampled on an average five times (range 3–8) after the melting of ice (April or early May) until late August or early September. Water was collected from the surface layer (0.2–0.5 m) in the daytime.

The water temperature (henceforth t°) and dissolved oxygen (O_2) concentration were found with a thermooximeter. The pH of water was determined by colorimetrical scale. A 30 cm diameter Secchi disk was used for measuring water transparency (SD). Water colour (Col) measurements were made on the $CoSO_4$–$K_2Cr_2O_7$ standard solution scale (Alekin, 1959). Total phosphorus (TP) was determined after persulphate oxidation. The blue phosphomolybdic complex was measured with a spectrophotometer (Reports..., 1977). Phosphate ion (PO_4-P) was determined directly spectrophotometrically by the molybdene blue method (Reports..., 1977). Total nitrogen (TN) was determined spectrophotometrically after the oxidation of the water sample; NO_3^- was reduced to NO_2^- using the Cd–Cu column. Sulphanilamide and *n*-(1-naphthyl)-ethylenediamine dihydrochloride were used for the determination of NO_2^- (Koroleff, 1982). Nitrate ion (NO_3-N) was determined colorimetrically with salicylic acid during 1978–83. Since 1984 NO_3^- was analysed as NO_2^- using the Cd–Cu column (Grasshoff, 1982). Dichromate oxidizability (COD_{Cr}) was determined titrimetrically using $K_2Cr_2O_7$ (Alekin, 1959), permanganate oxidizability (COD_{Mn}) was determined titrimetrically by using $KMnO_4$ (Unifitsirovannye..., 1977). Chlorophyll *a* (Chl) was measured spectrophotometrically on methanol extracted samples after Talling (1969). Phytoplankton was concentrated and counted by means of a Goryaev chamber.

To estimate correlations and empirical relationships we used linear regression analysis on the basis of arithmetical mean data for each lake annually from May to September. These data were transformed into $\log_{10}$.

RESULTS

General characteristics of variables

The summary of 102 lakes investigated for physical, chemical, and biological variables is given in Table 2. The scale of these data can be illustrated by the range of the maximum and minimum mean values of different variables and average data of all lakes.

Table 2. Summary of the mean, minimum and maximum values of limnological variables in the surface waters of Estonian lakes

Variable	Units	Number of mean samples	Mean ± SD*	Min**	Max**
Water temperature	°C	314	15.0 ± 2.2	8.3	19.5
Dissolved oxygen	mg L^{-1}	303	10.9 ± 1.7	7.8	17.2
Water saturation with oxygen	%	292	107.8 ± 15.9	77	177
pH		327	7.97 ± 0.65	4.7	9.1
Secchi disk	m	326	2.45 ± 1.26	0.4	7.1
Colour	°	157	55.6 ± 53.5	11	383
Total phosphorus	mg P m^{-3}	309	48.7 ± 51.2	8.0	466
Phosphate ion	mg P m^{-3}	251	7.7 ± 12.5	< 0.4	135
Total nitrogen	mg N m^{-3}	155	815 ± 401	191	2521
Nitrate ion	mg N m^{-3}	183	147 ± 211	< 1	1552
Dichromate oxidizability	mg O L^{-1}	165	30.0 ± 17.6	8.1	124
Permanganate oxidizability	mg O L^{-1}	79	16.3 ± 15.4	6.1	81
Chlorophyll *a*	mg m^{-3}	327	14.5 ± 17.2	1.6	118
Biomass of phytoplankton	g m^{-3}	279	4.04 ± 5.61	0.11	32.0

* For all lakes studied.

** Average minimum and maximum values for one lake.

All data showed considerable variation in concentrations. The average surface water t° from May to August varied from 8.3 to 19.5 °C. The lowest average O_2 content (7.8 mg L^{-1}) was observed in the highly brown-coloured L. Kadastiku and the highest (17.2 mg L^{-1}) in the hypertrophic L. Pappjärv. The average oxygen saturation (O_2%) of surface water varied from 77% in the brown-coloured L. Piigandi Mustjärv to 177% in L. Pappjärv; oxygen saturation in excess of 100% occurred in several eutrophic and in all hypertrophic lakes. In the majority of the lakes studied the surface water was slightly alkaline. The highest mean pH (9.1) was revealed in the hypertrophic L. Pappjärv while low pH (4.7) naturally associated with highly coloured dystrophic water in L. Partsi Saarjärv. The lakes under study are mostly light-coloured, with yellowish green or greenish yellow water Col up to 50°. The present study includes a large number of highly-coloured lakes whose colour varied from 116° to 383°. The water of these lakes is rich in humic material. The mean SD depth ranged from 0.4 to 7.1 m and averaged 2.45 m for all lakes. The lowest water clarity was found in the dystrophic and productive L. Viroste, the most transparent water in the mesotrophic L. Nohipalu Valgjärv.

The content of NO_3-N varied more than any other measured variable. There occurred quite a large number of lakes where NO_3-N concentrations were below the analytical detection limit of 1 mg N m^{-3} in summer months; however, in spring and late summer the NO_3-N content was detectable and sometimes even relatively high in early spring (up to 200 mg N m^{-3}). Relatively higher NO_3-N concentrations were found in the lakes of Rõuge. The highest mean concentration (1552 mg N m^{-3}) was observed in L. Kaussjärv in Rõuge. This effect is probably due to N-rich ground water springs feeding the lakes. PO_4-P concentration was less variable than that of NO_3-N and averaged 7.7 mg P m^{-3} for all lakes. The PO_4-P ion content was below the analytical detection limit of 0.1 mg P m^{-3} in some lakes in summer (especially in July). The highest mean PO_4-P content (135 mg P m^{-3}) was observed in the hypertrophic L. Otepää Pikajärv, which is the result of inflowing sewage waters from the home of invalids lying on its shores.

TP and TN varied considerably less. The average concentration of TN ranged from low 191 to 2521 mg N m^{-3}. Such a high TN content was observed in the hypertrophic L. Laose Valgjärv: slurry from a pig factory has been spread on the fields of its catchment area. TP concentrations averaged 48.7 mg P m^{-3} for all lakes and were the highest (466 mg P m^{-3}) in the hypertrophic L. Pappjärv and the lowest (8.0 mg P m^{-3}) in the mesotrophic L. Udsu.

Organic matter was determined as COD_{Cr} and its easily oxidizable fraction, COD_{Mn}. In most light-coloured lakes the average COD_{Cr} varied between 8.1 and 40 mg O L^{-1}, in highly-coloured lakes from 45 to 113 mg O L^{-1}. The highest COD_{Cr} value (124 mg O L^{-1}) was observed in the light-coloured hypertrophic L. Pappjärv. The same tendency was revealed for COD_{Mn}. In light-coloured lakes it ranged from 6.1 to 15 mg O L^{-1} and in dark-coloured lakes from 32 to 81 mg O L^{-1}.

Data on phytoplankton biomass (B) were relatively variable. The average B ranged from 0.11 g m^{-3} in the mesotrophic L. Väike-Palkna to 32.0 g m^{-3} in the hypertrophic L. Kokora Mustjärv. Chl was less variable than B and its average range was from 1.6 to 118 mg m^{-3}.

Relationships between variables

A correlation matrix was calculated from the arithmetical mean data for each lake annually as well as from the same data transformed to their logarithms. The correlation coefficients, the number of mean observations, and the levels of significance ($P \leq 0.0001$; 0.0005) for limnological variables are presented in Table 3. The correlation coefficients of the variables of these two matrices were relatively similar. The greatest difference was observed in correlations between

Table 3. Correlation matrix of the mean limnological variables in Estonian lakes. Asterisks indicate significance of regression $*P < 0.0001$; $**P < 0.0005$; ns, not significant. Upper right: arithmetical regressions. Lower left: logarithmical regressions. Above – correlation coefficients; below – number of samples

Variable	t°	O_2	O_2%	pH	Col	SD	TP	PO_4-P	TN	NO_3-N	COD_{Cr}	COD_{Mn}	Chl	B
t°	1.00 314	–0.25 303	ns 292	ns 314	ns 151	ns 314	ns 296	ns 251	ns 142	ns 183	ns 165	ns 79	ns 314	ns 266
O_2	–0.26* 303	1.00 303	0.95* 292	0.45* 303	–0.33* 148	–0.38* 303	0.42* 285	0.23** 251	0.37* 131	ns 183	ns 165	–0.50* 79	0.55* 303	0.50* 255
O_2%	ns 292	0.95* 292	1.00 292	0.46* 292	–0.35* 137	–0.38* 292	0.41* 274	ns 251	0.39* 120	ns 183	ns 165	–0.53* 79	0.56* 292	0.55* 244
pH	ns 314	0.48* 303	0.49* 292	1.00 327	0.64* 157	–0.22* 326	0.23* 309	ns 251	ns 155	ns 183	–0.32* 165	–0.83* 79	0.24* 327	0.38* 279
Col	ns 151	–0.28** 148	–0.29** 137	–0.43* 157	1.00 157	–0.47* 157	ns 157	ns 137	0.38* 99	ns 69	0.72* 136	0.99* 79	ns 157	ns 137
SD	ns 314	–0.37* 303	–0.38* 292	ns 326	–0.71* 157	1.00 326	–0.50* 308	–0.33* 251	–0.51* 154	ns 183	–0.59* 165	–0.58* 79	–0.59* 326	–0.53* 278
TP	ns 296	0.44* 285	0.41* 274	0.20** 309	0.31* 157	–0.76* 308	1.00 309	0.57* 233	0.64* 155	ns 165	0.54* 165	0.47* 79	0.81* 309	0.71* 262
PO_4-P	–0.26* 251	0.36* 251	0.29* 251	ns 251	0.49* 137	–0.62* 251	0.75* 233	1.00 251	0.42* 79	ns 183	0.48* 165	0.42* 79	0.50* 251	0.51* 204
TN	ns 142	0.37* 131	0.36* 120	ns 155	0.40* 99	–0.60* 154	0.60* 155	0.51* 79	1.00 155	0.64* 39	0.45* 79	0.42* 79	0.54* 155	0.59* 135
NO_3-N	ns 183	ns 183	ns 183	ns 183	ns 69	ns 183	ns 165	ns 183	ns 39	1.00 183	ns 97	ns 39	ns 183	ns 136
COD_{Cr}	ns 165	ns 165	ns 165	ns 165	0.68* 136	–0.82* 165	0.67* 165	0.62* 165	0.47* 79	ns 97	1.00 165	0.82* 79	0.59* 165	0.55* 121
COD_{Mn}	ns 79	–0.52* 79	–0.55* 79	–0.76* 79	0.97* 79	–0.80* 79	0.55* 79	0.56* 79	0.48* 79	ns 39	0.85* 79	1.00 79	0.37* 79	ns 60
Chl	ns 314	0.50* 303	0.50* 292	0.26* 327	0.47* 157	–0.87* 326	0.80* 309	0.63* 251	0.61* 155	ns 183	0.67* 165	0.45* 79	1.00 327	0.74* 279
B	ns 266	0.55* 255	0.58* 244	0.48* 279	ns 137	–0.77* 278	0.71* 262	0.56* 204	0.59* 135	ns 136	0.56* 121	ns 60	0.83* 279	1.00 279

SD and the other variables: in the case of logarithmic data the correlations were higher. Therefore, we selected regressions from log–log transformed values. Significant regressions ($P \leq 0.0001$) between the variables are presented in Table 4.

Our results indicated that Chl, B, TP, and SD are closely interrelated ($r > 0.7$, Table 3). The strongest correlation ($r = -0.87$) was observed between SD and Chl. The correlation of SD with B was weaker ($r = -0.77$) than with Chl. Likewise, inverse high correlations were found between SD and COD_{Cr} ($r = -0.82$) and COD_{Mn} ($r = -0.80$). SD correlated strongly also with TP ($r = -0.76$) and Col ($r = -0.71$). Fairly high correlations were found between SD and PO_4-P ($r = -0.62$) and TN ($r = -0.60$).

Among the biological variables, Chl and B were significantly correlated with most of the measured limnological variables. The correlation of Chl with B showed their strong interrelationship ($r = 0.83$). In general, Chl correlated a little more significantly with other variables than B. A strong positive correlation ($r > 0.70$) was observed between the controlling nutrient element TP and Chl (B). Similarly, slight positive correlations were evident between Chl (B) and COD_{Cr} ($r > 0.56$) and nutrient elements such as PO_4-P and TN ($r = 0.56$–0.63). Conversely, the correlation of O_2 content with B was a little stronger than with Chl.

Table 4. Relationships between limnological variables in Estonian lakes. All regressions are significant at $P < 0.0001$

$\log O_2 = -0.906 + 0.956 \log O_2\%$

$\log O_2 = 1.013 + 0.069 \log B$

$\log O_2 = 1.146 - 0.116 \log COD_{Mn}$

$\log O_2 = 0.959 + 0.078 \log Chl$

$\log O_2 = 0.681 + 0.044\ pH$

$\log O_2 = 0.903 + 0.085 \log TP$

$\log O_2 = 1.066 - 0.098 \log SD$

$\log O_2 = 0.693 + 0.119 \log TN$

$\log O_2 = 0.989 + 0.058 \log PO_4\text{-}P$

$\log O_2 = 1.320 - 0.244 \log t°$

$\log O_2\% = 1.056 + 0.942 \log O_2$

$\log O_2\% = 2.006 + 0.069 \log B$

$\log O_2\% = 2.146 - 0.117 \log COD_{Mn}$

$\log O_2\% = 1.957 + 0.075 \log Chl$

$\log O_2\% = 1.678 + 0.044\ pH$

$\log O_2\% = 1.911 + 0.076 \log TP$

$\log O_2\% = 2.060 - 0.097 \log SD$

$\log O_2\% = 1.733 + 0.104 \log TN$

$\log O_2\% = 1.992 + 0.046 \log PO_4\text{-}P$

$pH = 10.638 - 2.561 \log COD_{Mn}$

$pH = 2.938 + 5.373 \log O_2\%$

$pH = 2.636 + 5.147 \log O_2$

$pH = 7.846 + 0.533 \log B$

$pH = 9.949 - 1.248 \log Col$

$pH = 7.549 + 0.433 \log Chl$

$\log PO_4\text{-}P = -0.668 + 0.880 \log TP$

$\log PO_4\text{-}P = 0.123 + 0.599 \log Chl$

$\log PO_4\text{-}P = -0.861 + 1.082 \log COD_{Cr}$

$\log PO_4\text{-}P = 1.021 - 1.001 \log SD$

$\log PO_4\text{-}P = 0.547 + 0.434 \log B$

$\log PO_4\text{-}P = -0.132 + 0.686 \log COD_{Mn}$

$\log PO_4\text{-}P = -0.754 + 0.661 \log TN$

$\log PO_4\text{-}P = -0.365 + 0.625 \log Col$

$\log PO_4\text{-}P = -1.618 + 2.246 \log O_2$

$\log PO_4\text{-}P = -3.085 + 1.868 \log O_2\%$

$\log PO_4\text{-}P = 2.583 - 1.610 \log t°$

Table 4 continued

$\log \mathrm{SD} = 0.823 - 0.508 \log \mathrm{Chl}$
$\log \mathrm{SD} = 1.728 - 0.994 \log \mathrm{COD_{Cr}}$
$\log \mathrm{SD} = 1.073 - 0.721 \log \mathrm{COD_{Mn}}$
$\log \mathrm{SD} = 0.450 - 0.349 \log \mathrm{B}$
$\log \mathrm{SD} = 1.187 - 0.552 \log \mathrm{TP}$
$\log \mathrm{SD} = 1.370 - 0.649 \log \mathrm{Col}$
$\log \mathrm{SD} = 0.592 - 0.383 \log \mathrm{PO_4\text{-}P}$
$\log \mathrm{SD} = 2.363 - 0.718 \log \mathrm{TN}$
$\log \mathrm{SD} = 3.315 - 1.472 \log \mathrm{O_2\%}$
$\log \mathrm{SD} = 1.751 - 1.377 \log \mathrm{O_2}$

$\log \mathrm{TP} = 0.928 + 0.646 \log \mathrm{Chl}$
$\log \mathrm{TP} = 1.904 - 1.059 \log \mathrm{SD}$
$\log \mathrm{TP} = 1.122 + 0.639 \log \mathrm{PO_4\text{-}P}$
$\log \mathrm{TP} = 1.375 + 0.499 \log \mathrm{B}$
$\log \mathrm{TP} = 0.003 + 1.083 \log \mathrm{COD_{Cr}}$
$\log \mathrm{TP} = -1.313 + 0.966 \log \mathrm{TN}$
$\log \mathrm{TP} = 0.751 + 0.615 \log \mathrm{COD_{Mn}}$
$\log \mathrm{TP} = -0.756 + 2.245 \log \mathrm{O_2}$
$\log \mathrm{TP} = -2.898 + 2.200 \log \mathrm{O_2\%}$
$\log \mathrm{TP} = 0.903 + 0.371 \log \mathrm{Col}$

$\log \mathrm{TN} = 2.561 + 0.304 \log \mathrm{Chl}$
$\log \mathrm{TN} = 2.315 + 0.378 \log \mathrm{TP}$
$\log \mathrm{TN} = 3.015 - 0.494 \log \mathrm{SD}$
$\log \mathrm{TN} = 2.761 + 0.260 \log \mathrm{B}$
$\log \mathrm{TN} = 2.634 + 0.306 \log \mathrm{PO_4\text{-}P}$
$\log \mathrm{TN} = 2.439 + 0.348 \log \mathrm{COD_{Mn}}$
$\log \mathrm{TN} = 2.242 + 0.411 \log \mathrm{COD_{Cr}}$
$\log \mathrm{TN} = 2.355 + 0.279 \log \mathrm{Col}$
$\log \mathrm{TN} = 1.645 + 1.169 \log \mathrm{O_2}$
$\log \mathrm{TN} = 0.373 + 1.219 \log \mathrm{O_2\%}$

$\log \mathrm{COD_{Cr}} = 0.643 + 0.702 \log \mathrm{COD_{Mn}}$
$\log \mathrm{COD_{Cr}} = 1.636 - 0.673 \log \mathrm{SD}$
$\log \mathrm{COD_{Cr}} = 0.585 + 0.519 \log \mathrm{Col}$
$\log \mathrm{COD_{Cr}} = 0.781 + 0.417 \log \mathrm{TP}$
$\log \mathrm{COD_{Cr}} = 1.108 + 0.333 \log \mathrm{Chl}$
$\log \mathrm{COD_{Cr}} = 1.185 + 0.356 \log \mathrm{PO_4\text{-}P}$
$\log \mathrm{COD_{Cr}} = 1.354 + 0.209 \log \mathrm{B}$
$\log \mathrm{COD_{Cr}} = -0.079 + 0.533 \log \mathrm{TN}$

$\log \mathrm{COD_{Mn}} = -0.545 + 0.950 \log \mathrm{Col}$
$\log \mathrm{COD_{Mn}} = -0.350 + 1.027 \log \mathrm{COD_{Cr}}$
$\log \mathrm{COD_{Mn}} = 1.354 - 0.887 \log \mathrm{SD}$
$\log \mathrm{COD_{Mn}} = 2.884 - 0.227 \mathrm{pH}$
$\log \mathrm{COD_{Mn}} = 0.404 + 0.494 \log \mathrm{TP}$
$\log \mathrm{COD_{Mn}} = 0.822 - 0.463 \log \mathrm{PO_4\text{-}P}$
$\log \mathrm{COD_{Mn}} = 6.386 - 2.614 \log \mathrm{O_2\%}$
$\log \mathrm{COD_{Mn}} = 3.535 - 2.380 \log \mathrm{O_2}$
$\log \mathrm{COD_{Mn}} = -0.754 + 0.661 \log \mathrm{TN}$
$\log \mathrm{COD_{Mn}} = 0.801 + 0.318 \log \mathrm{Chl}$

$\log \mathrm{Chl} = 1.466 - 1.505 \log \mathrm{SD}$
$\log \mathrm{Chl} = 0.747 + 0.689 \log \mathrm{B}$
$\log \mathrm{Chl} = -0.582 + 1.000 \log \mathrm{TP}$
$\log \mathrm{Chl} = -0.986 + 1.364 \log \mathrm{COD_{Cr}}$
$\log \mathrm{Chl} = 0.493 + 0.664 \log \mathrm{PO_4\text{-}P}$
$\log \mathrm{Chl} = -2.466 + 1.209 \log \mathrm{TN}$
$\log \mathrm{Chl} = -2.407 + 3.264 \log \mathrm{O_2}$
$\log \mathrm{Chl} = -5.823 + 3.344 \log \mathrm{O_2\%}$
$\log \mathrm{Chl} = -0.191 + 0.710 \log \mathrm{Col}$
$\log \mathrm{Chl} = 0.273 + 0.643 \log \mathrm{COD_{Mn}}$
$\log \mathrm{Chl} = -0.315 + 0.161 \mathrm{pH}$

$\log \mathrm{B} = -0.637 + 0.992 \log \mathrm{Chl}$
$\log \mathrm{B} = 0.902 - 1.710 \log \mathrm{SD}$
$\log \mathrm{B} = -1.227 + 1.015 \log \mathrm{TP}$
$\log \mathrm{B} = -3.438 + 1.322 \log \mathrm{TN}$
$\log \mathrm{B} = -9.570 + 4.878 \log \mathrm{O_2\%}$
$\log \mathrm{B} = -1.833 + 1.520 \log \mathrm{COD_{Cr}}$
$\log \mathrm{B} = -0.193 + 0.728 \log \mathrm{PO_4\text{-}P}$
$\log \mathrm{B} = -4.153 + 4.329 \log \mathrm{O_2}$
$\log \mathrm{B} = -3.082 + 0.425 \mathrm{pH}$

$\log \mathrm{Col} = 0.639 + 0.994 \log \mathrm{COD_{Mn}}$
$\log \mathrm{Col} = 1.883 - 0.776 \log \mathrm{SD}$
$\log \mathrm{Col} = 0.364 + 0.887 \log \mathrm{COD_{Cr}}$
$\log \mathrm{Col} = 1.382 + 0.386 \log \mathrm{PO_4\text{-}P}$
$\log \mathrm{Col} = 1.347 + 0.309 \log \mathrm{Chl}$
$\log \mathrm{Col} = 2.798 - 0.145 \mathrm{pH}$
$\log \mathrm{Col} = 0.122 + 0.572 \log \mathrm{TN}$
$\log \mathrm{Col} = 1.265 + 0.254 \log \mathrm{TP}$

Of organic matter COD_{Mn} correlated far more significantly with the other selected variables than COD_{Cr}. The strong positive correlation observed between COD_{Mn} and Col was the most highly significant relationship ($r = 0.97$) found in this study. Naturally, a strong correlation occurred between COD_{Cr} and COD_{Mn} ($r = 0.85$); COD_{Cr} and its easily oxidizable fraction appeared to have a strong negative relationship with SD ($r \geq -0.8$). A rather strong negative correlation was revealed between COD_{Mn} and pH ($r = -0.76$), while no significant correlation was found between COD_{Cr} and pH. Fairly high correlations were observed between COD_{Cr} and COD_{Mn} and some chemical variables such as TP and PO_4-P ($r = 0.55$–0.67).

Of the nutrient elements, TP showed the greatest number of highly significant correlations with the other variables (Table 4). The strongest correlation was observed between TP and Chl ($r = 0.80$), while the correlation with B ($r = 0.71$) was somewhat weaker. A relatively strong negative correlation occurred between TP and SD ($r = -0.76$) and a positive correlation between TP and PO_4-P ($r = 0.75$). Correlations between TP and COD_{Cr} ($r = 0.67$) and TN ($r = 0.60$) were fairly strong. A positive but a little weaker correlation occurred between TP and COD_{Mn} ($r = 0.55$). The dissolved inorganic form PO_4-P correlated considerably more weakly with the selected variables than the total form of phosphorus. No strong relationship was observed between PO_4-P and the other variables (except for the correlation with TP, $r = 0.75$). PO_4-P appeared to have a slight correlation with Chl ($r = 0.63$), B ($r = 0.56$), and organic matter (COD_{Cr}, $r = 0.62$ and COD_{Mn}, $r = 0.56$).

Another essential nutrient element TN correlated far more weakly with the other variables than TP. There existed fairly strong positive correlations with Chl ($r = 0.61$), B ($r = 0.59$), TP ($r = 0.60$), and PO_4-P ($r = 0.51$), and a slight negative correlation with SD ($r = -0.60$). Surprisingly, no significant correlations were found between NO_3-N and the other variables, except for the correlation with TN.

Relatively slight correlations were found between O_2 (also $O_2\%$) and B ($r > 0.55$), Chl ($r > 0.5$), and COD_{Mn} ($r > 0.52$). A strong relationship existed between O_2 and $O_2\%$ ($r = 0.95$). No correlation was found between t° and the other variables (Table 3).

DISCUSSION

The excessive enrichment of lakes with plant nutrients (mainly P and N) from the catchment area leads to the undesirable growth of algae, which, in its turn, causes a reduction in water clarity. Our present results confirm that Chl, B, TP, and SD are the main trophic parameters as they are strongly correlated with one another. Relationships between Chl–B, Chl–TP, and Chl–SD have been well documented for many lakes all over the world. Highly significant positive correlations between B and Chl were also found in our earlier study (Milius &

Kõvask, 1987), which analyses both the material pertaining to every single lake and the mean data on all the lakes studied. The strong positive relationship between TP and Chl indicated that TP is the main factor limiting phytoplankton production in the lakes. The Chl–TP relationship determined for 102 Estonian small lakes ($\log \mathrm{Chl} = 1.000 \log \mathrm{TP} - 0.582$; $n = 309$; $r = 0.80$) was similar to a number of other published relationships established for northern temperate lakes (Vollenweider & Kerekes, 1980; Riley & Prepas, 1985; Marshall & Peters, 1989).

The Chl–TN relationship in Estonian lakes is weaker than the corresponding Chl–TP relationship ($r = 0.61$ and 0.80, respectively), which is in accordance with the studies of Forsberg & Ryding (1980) on Swedish lakes and Niemi (1985) on Finnish lakes. However, in the subtropical lakes of Florida the Chl–TN relationship is stronger than the Chl–TP relationship, which supports the hypothesis that TN is the limiting element in these lakes (Canfield, 1983). Canfield's data show clearly that if the TP concentration is over 100 mg P m^{-3} the N : P ratio will be lower than 10 : 1 in nearly all lakes, and if the TP concentration is between 1 and 100 mg P m^{-3} the N : P ratio will be higher than 17 : 1 in most lakes. This suggests that while TP is the primary limiting nutrient below the TP concentration of 100 mg P m^{-3}, TN becomes the limiting factor above this value. For example, in the sampled lakes the ratio N : P is mostly higher than 17 : 1 and the TP concentration is below 100 mg P m^{-3}; hence, P is the element controlling algal biomass. Nitrogen is the limiting nutrient only in a few (hypertrophic) lakes where the N : P ratio is lower than 10 : 1 and the TP concentration above 100 mg P m^{-3}.

Water transparency measured routinely with the Secchi disk has proved to be the index of visual water clarity in studies on lakes. In the case of many lakes studied all over the world, hyperbolic curves have been obtained when SD depth is plotted against parameters related to algal biomass such as Chl. Our SD–Chl regression ($\log \mathrm{SD} = 0.823–0.508 \log \mathrm{Chl}$; $n = 326$, $r = -0.87$) is not significantly different from several regressions reported in literature for lakes in various countries (Bul'on, 1977; Jones & Bachmann, 1978; Forsberg & Ryding, 1980; Zdanowski, 1982). The advantage of using SD as a trophic parameter is that it correlates strongly with several trophic parameters such as Chl, TP, and B.

Analogously to the findings of Carlson (1977) and Lambou et al. (1982), we found a significant inverse relationship between SD and TP ($r = -0.76$) for Estonian lakes. Our results show that the SD–Chl relationship is stronger ($r = -0.87$) than the relationship between SD and TP. However, unlike Carlson (1977) and the authors of this study, Lambou et al. (1982) showed that SD may be a better indicator or parameter for prognosticating TP than Chl. TP is likely to correlate best with SD when it is the primary factor controlling the level of algae in a lake.

In addition to the above relationships, there occur strong negative relationships between SD and organic matter, and Col. Several authors (Brezonik, 1978; Rintanen, 1982; Canfield & Hodgson, 1983) have also found a strong hyperbolic relationship between SD and Col. It is well known that colour affects greatly phytoplankton productivity in highly coloured lakes because humic substances restrain the penetration of light into the water column. Therefore, in polyhumic lakes, the photosynthetically active water layer is relatively thin, which also limits productivity in such lakes. However, our data show that there is no inverse relationship between Col and Chl. In fact, we found a weak but significant positive relationship ($r = 0.47$, $P \leq 0.0001$; Table 3) when we used log–log transformed data. This is also similar to the findings of Canfield & Hodgson (1983).

Some authors (Lorenzen, 1980; Megard et al., 1980) have stated that SD might be expected to yield erroneous values for lakes with high nonalgal turbidity, for highly coloured and unproductive lakes, as well as for high-clarity lakes. Our study on Estonian lakes suggests that SD is an important trophic parameter for lakes where P is the primary limiting factor, and for highly coloured lakes where algal productivity is high.

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EESTI JÄRVEDE LIMNOLOOGILISTE NÄITAJATE VAHELINE KORRELATSIOON

Anu MILIUS ja Henno STARAST

On uuritud 102 Eesti järve neljateistkümne limnoloogilise näitaja vahelist korrelatsiooni aastail 1978–91. Kogu materjalist selgus 60 statistiliselt olulist korrelatsiooni. Meie andmed kinnitavad, et klorofüll *a* (Chl), fütoplanktoni biomass (B), üldfosfor (TP) ja vee läbipaistvus on põhilised troofsusparameetrid nendevahelise tugeva korrelatsiooni tõttu. Bioloogilistest näitajatest korreleerusid Chl ja B oluliselt enamiku teiste limnoloogiliste näitajatega, sealjuures oli Chl seos alati veidi tugevam kui B-l. Orgaanilise aine puhul selgus, et permanganaatne oksüdeeritavus ($\mathrm{COD_{Mn}}$) korreleerus teiste näitajatega rohkem kui dikromaatne oksüdeeritavus. Kõige tugevam positiivne seos ($r = 0{,}97$) oli $\mathrm{COD_{Mn}}$ ja vee värvuse vahel. Toitainetest täheldati TP-l kõige rohkem tugevaid seoseid teiste näitajatega, sealjuures tugevamaiks osutus TP ja Chl vaheline seos ($r = 0{,}80$). Korrelatsioon Chl ja üldlämmastiku (TN) vahel oli Eesti järvedes tunduvalt nõrgem kui Chl ja TP seos, sest uuritud järvedes esines enamasti fosfori limiteerimine. Nitraatiooni ja teiste näitajate vahel ei täheldatud olulist seost, välja arvatud TN-ga. Samuti puudus statistiliselt oluline korrelatsioon vee temperatuuri ja ülejäänud näitajate vahel.