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Sources, concentrations and characteristics of organic matter in softwater lakes and streams of the Swedish forest region

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Abstract

18 Swedish forest lakes covering a wide range of dystrophy were studied in order to quantify and characterize the organic matter in the water with respect to origin (allochthonous or autochthonous), physical state (particulate or dissolved) and phosphorus content. Samples were collected repeatedly during a two-year period with unusually variable hydrological conditions. Water from three different depths and from tributaries was analysed with standard monitoring methods, including water colour, Secchi disk transparency, total organic carbon (TOC), COD_{Cr}, COD_{Mn}, total phosphorus and molybdate reactive phosphorus. Interrelationships were used to compare different methods and to assess the concentration and composition of organic matter. It is estimated that in remote softwater lakes of the Swedish forest region, autochthonous carbon is typically < 5 g m^{-3}. Most lakes in this region receive significant amounts of humic matter originating from coniferous forest soils or peatland in the catchment area. In most humic lakes with a water colour of ≥ 50 g Pt m^{-3}, more than half of the organic carbon in the surface water is of allochthonous origin, and in polyhumic lakes (> 200 g Pt m^{-3}) the proportion can exceed 90%. Secchi depth readings were related similarly to organic matter from both sources and provided good estimates of TOC with a single optical measurement. Water colour was used to distinguish allochthonous and autochthonous matter. High concentrations of phosphorus were found in humic waters, most of it being molybdate reactive, and probably associated with humic matter rather than as dissolved free inorganic forms. COD_{Mn} yielded only 25–60% of TOC and appears to include mainly truly dissolved substances of low molecular weight.

Introduction

Organic matter in surface waters can be classified according to origin (allochthonous or autochthonous), physical state (particulate or dissolved) and nutrient content (carbon/phosphorus ratio). In lakes of the boreal forest zone (Bruenig, 1987), two main types of organic matter can be distinguished: organic matter from primary or secondary production in the water body, and humic matter originating from coniferous forest soils, peatland or marginal rooted vegetation. However, the origin and composition of organic matter in inland freshwaters is largely unknown. It is presently not possible to identify all organic compounds in lake water, but the description of gross properties may help in differentiating organic matter from different sources (Cole *et al.*, 1984).

Swedish surface waters are typically oligotrophic and stained to a varying degree by humic substances (SNV, 1986). The bulk of humic substances in brownwater lakes and streams is dissolved, and a minor proportion is colloidal or particulate (Pennanen, 1988; Olofsson, 1989).

The dissolved fraction is dominated by fulvic acids of relatively low molecular weight, which are less coloured than heavier humic substances (Pennanen, 1988; Cole *et al.*, 1984). Organic matter from autochthonous planktonic production occurs both in particulate and dissolved forms, with dissolved components prevailing (Birge & Juday, 1934; Wetzel, 1983), but contributes little to water colour (Birge & Juday, 1934; Åberg & Rodhe, 1942; Hutchinson, 1957).

Various methods have been applied to determine the concentration of organic matter. The greatest convenience is provided by optical methods. Water colour gives a simple estimate of humic content (Åberg & Rodhe, 1942; Hutchinson, 1957; Wetzel, 1983) and is widely used in monitoring programs (e.g. SNV, 1986). Organic matter from autochthonous production causes absorption and dispersion of light, which is easily assessed by measuring water transparency with a Secchi disk. Despite subjective disadvantages, Secchi depth provides a visual index of water clarity (Preisendorfer, 1986) and has been used to describe the trophic state of lakes (e.g. Carlson, 1977). However, Secchi depth readings are also influenced by inorganic and detrital particles (e.g. resuspended sediment), by the humic content of the water, and to a minor degree by the attenuation of light by the water itself (e.g. Åberg & Rodhe, 1942; Wetzel, 1983).

Chemical methods usually include an oxidation or combustion step, where either the consumption of an oxidant or the emerging carbon dioxide is quantified. Consumption measurements (chemical oxygen demand, COD) have traditionally been common in monitoring programs, as high sensitivity combustion techniques are more expensive and have become available only in recent decades. In this study, two chemical oxidation methods were used, one based on dichromate (COD_{Cr}) and one on permanganate (COD_{Mn}). In both methods, the chemical oxygen demand can be converted into concentrations of organic carbon, assuming constant stoichiometric relationships for organic matter and little disturbance by other oxidizable compounds (Wilander, 1988). In this paper, converted COD_{Cr} values are referred to as CrOC, and converted COD_{Mn} values as MnOC. In natural waters, the dichromate method provides a good estimate of total organic carbon, whereas the permanganate method is less efficient in decomposing organic matter and usually yields lower values (*op. cit.*, Hutchinson, 1957).

Primary production in freshwaters is usually limited by the access to nutrients, mainly phosphorus. Concentrations of total phosphorus are therefore frequently used to estimate autochthonous biomass. As a result of an efficient retrieval by organisms, most phosphorus in lakes is usually found in the particulate form (Wetzel, 1983). However, humic substances can efficiently bind dissolved inorganic phosphate in the presence of iron (Jones *et al.*, 1988). In brown waters, a considerable proportion of phosphorus may thus occur in the dissolved or colloidal phase.

The aims of this study are (1) to quantify and characterize the types of organic matter in different natural waters of the boreal forest zone, with special attention to the impact of humic matter and the distribution of different phosphorus forms; (2) to compare and evaluate different methods commonly used to measure the concentration of organic matter; and (3) to provide estimates of organic carbon based on simple analytical procedures, partly for use in low-budget monitoring programs, and partly for conversion and comparison of available data obtained with different methods.

Methods

The study was conducted in 18 Swedish forest lakes in two areas, 8 in central Sweden (Delsbo, Hudiksvall, 61.6–7 °N 16.6–8 °E), and 10 about 500 km further south in southern Sweden (Aneboda, Växjö, 57.2–2 °N 14.4–7 °E). The lakes were selected to represent the typical range of softwater lakes in the Swedish forest region: water colour 20–200 g Pt m^{-3}, total phosphorus 5–25 mg m^{-3}, pH 5–7 (SNV, 1986; Meili *et al.*, 1991; Meili, 1991a). The morphometrical, hydrological and chemical characteristics of the study lakes are given in Table 1.

Table 1. Morphological, hydrological and chemical characteristics of the 18 Swedish forest lakes included in this study.
Location: C = central Sweden (62° N 17° E), S = southern Sweden (57° N 15° E)
Dynamic ratio = $\sqrt{\overline{Lakearea}}$/Mean depth.
Res. time = theoretical hydrological residence time
Cultiv. = cultivated (deforested) land.

Lake name	Code	Location	Morphology				Hydrology			Catchment area				Surface water chemistry 1985–87		
			Lake area (km^2)	Max. depth (m)	Mean depth (m)	Dyn. ratio	Lake volume (10^6 m^3)	Res. time (yr)	Drain area (km^2)	Lakes (%)	Forest (%)	Mire (%)	Cultiv. (%)	pH	Water colour (gPt m^{-3})	Total P (mg m^{-3})
Blacksåstjärn	BL	C	0.12	6.8	2.4	140	0.3	0.5	2.2	<1	76	15	9	6.0–7.1	75–130	11–14
Bottentjärn	BO	C	0.15	4.9	2.9	140	0.4	0.4	4.2	<1	83	17	<1	5.2–6.4	70–130	8–12
Loppesjön	LO	C	0.28	14.0	5.4	100	1.5	1.2	4.4	2	73	<1	25	6.5–7.6	15–80	15–24
Stensjön	ST	C	0.59	8.5	4.3	180	2.6	2.5	3.6	1	74	25	<1	5.8–6.6	40–80	7–13
Löjesjön	LÖ	S	0.31	2.5	1.5	380	0.5	0.8	2.1	<1	74	19	7	6.2–6.6	80–120	18–23
Skärhultsjön	SK	S	0.36	14.0	3.8	160	1.1	0.8	6.0	1	76	8	16	5.2–6.1	80–140	10–21
Gårdsjön	GÅ	S	0.15	8.5	3.2	120	0.5	1.9	0.9	<1	71	3	21	6.3–7.3	20–45	9–20
Holmeshultasjön	HO	S	0.69	16.0	4.5	180	3.1	1.8	6.0	7	70	3	20	6.4–7.3	20–40	9–15
Sörsjön	SÖ	C	0.25	7.2	3.2	150	0.8	0.2	17.9					5.5	160	12
Vålåssjön	VÅ	C	0.38	11.0	4.8	130	1.8	1.3	4.8					7.1	40	12
Håknorrbosjön	HÅ	C	0.50	17.0	4.5	160	2.2	0.9	8.5					6.7	55	10
Lillbosjön	LI	C	0.65	18.0	5.8	140	3.8	4.1	3.2					7.0	25	9
Fräjen	FR	S	0.21	1.2	0.8	600	0.2	0.1	5.7					5.6	280	26
Vrången	VR	S	0.55	6.4	1.2	600	0.7	0.2	15.8					5.2	165	28
Hacksjön	HA	S	0.28	7.0	1.4	380	0.4	0.8	1.7					6.5	35	11
Lundasjön	LU	S	0.10	8.3	4.0	80	0.4	2.8	0.5					6.5	10	10
Burken	BU	S	0.21	7.0	3.1	150	0.7	2.0	1.2					5.5	65	12
Klintsjön	KL	S	0.11	17.0	4.4	70	0.5	3.6	0.5					5.8	5	7

Water samples were collected between August, 1985 and May, 1987. In late summer 1985, all 18 lakes were sampled once (23–28 August in central Sweden, 18–25 September in southern Sweden). In 1986, samples were taken in eight lakes during four periods: a few days after ice break-up (5–6 May in southern Sweden, 16–21 May in central Sweden), in early summer (16–30 June), in late summer (29 July–11 August), and in autumn during or (in deep lakes) shortly before overturn (2–6 September in central Sweden, 13–17 September in southern Sweden). Complementary surface samples were taken in four lakes in spring 1987 (6–7 May). Both hydrology and water chemistry were unusually variable during the study period, especially in central Sweden, where the theoretical water residence time repeatedly dropped from several months to a few days in many lakes (cf. Meili *et al.*, 1991).

Lake water samples were collected with a Ruttner sampler at three depths at the deepest point of each lake. After recording the temperature profile, epilimnion samples were taken at 0.5 m depth to represent the most productive layer of the water body, metalimnion samples were taken in the lower part of the thermocline where effects of mixing, production, decomposition and accumulation of organic matter presumably are least pronounced, and hypolimnion samples were taken 0.5 m above the sediment surface to obtain water with decomposed organic matter. Stream water was collected where possible once in late summer 1985 from a major inflow close to the lakes. Samples were kept cool, and subsamples were frozen within 2–12 hours of sampling for storage until analysis. In 1985, a portion of the samples was filtered before freezing with Whatman GF/C glassfibre filters (apparent pore size $\approx 1.2\ \mu$m).

Water transparency (Secchi depth) was recorded with a Secchi disk of 0.25 m diameter in the shadow of a boat to minimize disturbances caused by light reflections from the water surface. Water colour was measured within 24 h in untreated water using a Hellige colour comparator and expressed as g Pt m^{-3} (= Pt units). Particle concentrations were usually low, and no significant colour difference was observed between unfiltered and filtered water. Total organic carbon (TOC) was measured after combustion in a Shimadzu TOC500 carbon analyser. Chemical oxygen demand (COD$_{Cr}$ and COD$_{Mn}$) was analysed from frozen samples according to standard methods (Ahlgren & Ahlgren, 1978; cf. Wilander, 1988). For the determination of COD$_{Cr}$, samples were autoclaved for 1 hour (120 °C) in 4 mN $K_2Cr_2O_7$, 0.08 N $AgNO_3$ and 50% H_2SO_4. For COD$_{Mn}$, samples were treated with 1.6 mN $KMnO_4$ in 1% H_2SO_4 in a 100 °C water bath for exactly 20 min. Care was taken to keep digestion time and temperature constant, and to avoid effects of oxidant exhaustion by diluting samples when required. The samples were then titrated with Fe(II)ammoniumsulphate (phenanthroline as indicator) and thiosulphate (iodide/starch as indicator), respectively. COD values were converted into concentrations of organic carbon (CrOC and MnOC) assuming constant stoichiometry for organic matter ($O_2/C = 32/12$, cf. Wilander, 1988). Phosphorus concentrations were determined according to Murphy & Riley (1962). Molybdate-reactive phosphorus (MRP) was determined in filtered samples, whereas total phosphorus (TP) was obtained by analysis of MRP after oxidation of unfiltered samples in 1% peroxodisulphate ($K_2S_2O_8$) in an autoclave (120 °C) for 1 hour (Menzel & Corwin, 1965).

Mathematical relationships were generated partly by means of least square regression, partly by graphically or mathematically fitting the parameters of conceptually or mathematically suitable functions with a microcomputer. Parameters were rounded to the lowest feasible number of significant digits in order to generate simple, appealing and useful conversion formulas with a high predictive power.

Results and discussion

In surficial lake water, total organic carbon (TOC) ranged from 3 to 28 g m^{-3}, water colour from 5 to 280 g Pt m^{-3}, total phosphorus from 7 to 24 mg m^{-3}, and Secchi depth from 0.4 to 5.5 m

Table 2. Ranges of chemical and optical water characteristics at different sites in 18 Swedish forest lakes 1985–1986.

	Inflow	Epilimnion	Metalimnion	Hypolimnion
pH	4.1–6.6	5.2–7.6	5.1–7.0	5.0–6.9
Alkalinity [meq m^{-3}]	0–220	0–200	0–280	0–850
Conductivity [mS m^{-1}]	1.8–17.6	1.9–8.5	1.9–9.0	2.3–11.8
Oxygen saturation [%]	–	72–134	2–120	0–114
Water colour [g Pt m^{-3}]	130–660	5–280	10–190	25–500
Secchi depth [m]	–	0.4–5.5	–	–
Total organic carbon [g m^{-3}]	13–55	3–28	3–19	3–35
Labile organic carbon (MnOC) [g m^{-3}]	6–30	1–12	1–9	1–16
Total phosphorus [mg m^{-3}]	9–35	7–34	7–42	7–107
Molybdate-reactive P [mg m^{-3}]	3–32	0.4–11	0.4–11	0.7–26

(Tables 1 and 2). Metalimnetic water was usually quite similar to surface water. In contrast, samples from the deepest strata of the water column often differed markedly from the other samples. Due to incomplete mixing, this water layer was temporarily anoxic in some lakes, and during the whole study period in two deep lakes with a sheltered deep hole (mesotrophic Loppesjön and polyhumic Skärhultsjön). In most inflow samples, all measures of organic carbon (13 to 55 g m^{-3}) and phosphorus (9 to 35 mg m^{-3}) yielded higher values than in the surface water of the respective lake. This indicates that a significant proportion of the organic matter in the lake is produced in the drainage area and transported to the lakes with surface runoff.

Chemical measures of organic carbon

Results from combustion (TOC) and chemical oxidation methods (COD_{Cr} and COD_{Mn}) were very well correlated but differed in yield. When applying strong oxidants, most estimates of organic carbon from wet oxidation (CrOC) were within 80 and 90% of TOC, which shows the high reproducibility of both methods. In undiluted samples with high concentrations of organic matter, the chemical method was less efficient due to the depletion of oxidant, but TOC can be estimated with good reliability from CrOC with a correction formula accounting for the proportion of oxidant remaining after analysis (Ox = 0...1):

$$\text{TOC} = \text{CrOC}/(0.9 \cdot \text{Ox}^{0.27}) \qquad (1)$$

This relationship was also valid in anoxic waters, which indicates that the interference from inorganic reduced compounds such as Fe-hydroxides on CrOC is of minor importance. 65% of corrected CrOC values were within ± 5% of TOC, and 80% within ± 10%, which shows that both methods produce equivalent results, provided appropriate dilution is applied.

Estimates of organic carbon from the less efficient permanganate method (MnOC) deviated significantly and systematically both from TOC and CrOC. In the clearest lakes, MnOC yielded only 25–40% of TOC, in brownwater lakes (> 100 g Pt m^{-3}) about 35–50% and in forest streams 40–60% (Fig. 1a, 2b). This shows that the widely used permanganate method provides poor information about the total amount of organic matter present, especially in clearwater lakes, and that the yield of the method strongly depends on water quality (cf. Wilander, 1988). On the other hand, the non-linear correlation of the MnOC/TOC ratio with water colour is fairly consistent for both stream and lake surface water (Fig. 2b). This indicates that the translation of permanganate numbers into MnOC concentrations may provide information about the character of organic matter. The MnOC/TOC ratio in surface waters can be quantitatively described as a function of water colour [g Pt m^{-3}]:

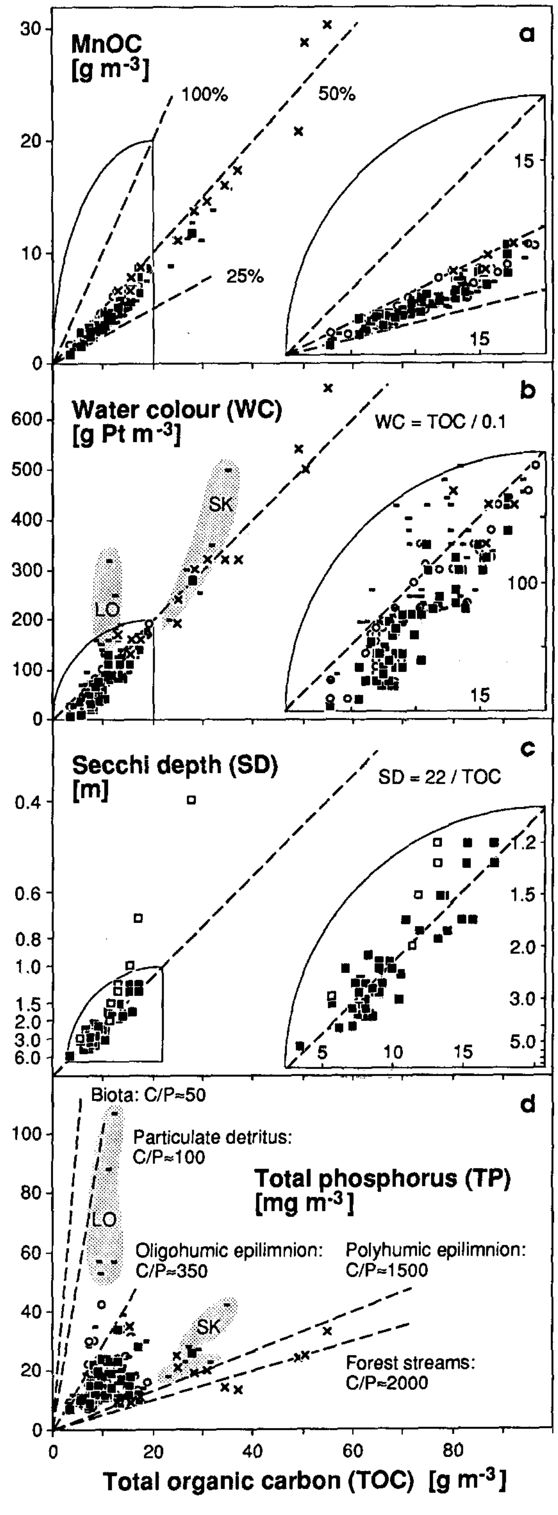

Fig. 1. Correlation of optical and chemical water characteristics with the concentration of total organic carbon (TOC) in 18 Swedish forest lakes and streams 1985–1986. Enlarged insets show the lake data in more detail. Data from epilimnion (squares), metalimnion (circles), hypolimnion (hatches) and inflow (crosses) are shown. Anoxic hypolimnion samples from mesotrophic Loppesjön and polyhumic Skärhultsjön are highlighted. Open squares denote shallow lakes. MnOC = labile organic carbon susceptible to permanganate oxidation.

$$\mathrm{MnOC/TOC} = 0.5\cdot(\mathrm{WC} + 25)/(\mathrm{WC} + 50) \tag{2}$$

This formula can be used to estimate TOC [g m^{-3}] in surface waters when both permanganate number (= 10.5·MnOC) [g m^{-3}] and water colour [g Pt m^{-3}] are available:

$$\mathrm{TOC} = \mathrm{Perm.}\cdot 0.19\cdot(\mathrm{WC} + 50)/(\mathrm{WC} + 25) \tag{3}$$

Optical measures of TOC

Water colour was, as expected, correlated with TOC concentrations (Fig. 1b). However, the deviation of the values from proportionality is evident, and the scatter is considerable, especially among the lake samples. Consequently, direct estimates based on proportionality, as are sometimes applied, will be doomed to failure. Only for highly coloured (>200 g Pt m^{-3}) samples of stream and lake waters, can a reasonable estimate of TOC [g m^{-3}] be obtained from water colour [g Pt m^{-3}] by applying

$$\mathrm{TOC} = 0.1\cdot\mathrm{WC} \tag{4}$$

whereas in clear waters, proportionality factors were several times higher (cf. Fig. 1b). A better correlation and proportionality with water colour was observed for MnOC (Fig. 2a). Water colour is well established as a measure for the concentration of humic substances (Birge & Juday, 1934; Åberg & Rodhe, 1942; Hutchinson, 1957; Wetzel, 1983; SNV, 1986), most of which are dissolved or colloidal (Pennanen, 1988). This is a first indication that MnOC in fact is a measure of dissolved organic carbon (DOC) rather than of TOC. Dissolved compounds are likely to be most susceptible to mild chemical oxidation, whereas particulate matter is more resistant.

Some hypolimnion samples deviated from the rest of the samples, being considerably more stained than would be expected from their TOC concentration (Fig. 1b). These samples all represent strongly hypoxic or anoxic waters from oligo-mesohumic lakes, where iron compounds are likely to accumulate. The observed water colour in these cases is caused by inorganic rather than organic matter. The strongest deviations were observed in mesotrophic lake Loppesjön, where the deepest water was anoxic on all sampling occasions due to incomplete mixing even during spring overturn. However, in other samples from hypoxic strata, high colour values corresponded fairly well to values expected from TOC, e.g. in the polyhumic lake Skärhultsjön (Fig. 1b), where anoxia in the bottom water appeared to be permanent, similar to Loppesjön. This suggests that in the polyhumic lake, settling organic matter is dominated by humic colloids, whereas in the mesotrophic lake, autochthonous matter appears to prevail (cf. C/P ratios, Fig. 1d). Colour values may be depressed when iron occurs in reduced forms, and may also be affected by differences in pH or iron content (Åberg & Rodhe, 1942; Gjessing, 1976). However, no correlation was found between the colour/TOC-ratio and pH in humic surface waters.

Another optical measure of water quality was derived from Secchi disk transparency. Inverse values of Secchi depth, which describe the light attenuation by surficial lake water, provided excellent proportionality with TOC, when disregarding very shallow lakes. The scatter was comparatively small and constant over the TOC range of 3–20 $\mathrm{g\,m^{-3}}$, and systematic deviations were insignificant (Fig. 1c). A good prediction of TOC [$\mathrm{g\,m^{-3}}$] is provided with a simple equation for inverse proportionality with Secchi depth [m]:

$$\mathrm{TOC} = 22/\mathrm{SD} \qquad (5)$$

In some lakes, all rich in TOC, the Secchi disk transparency was sometimes lower than expected

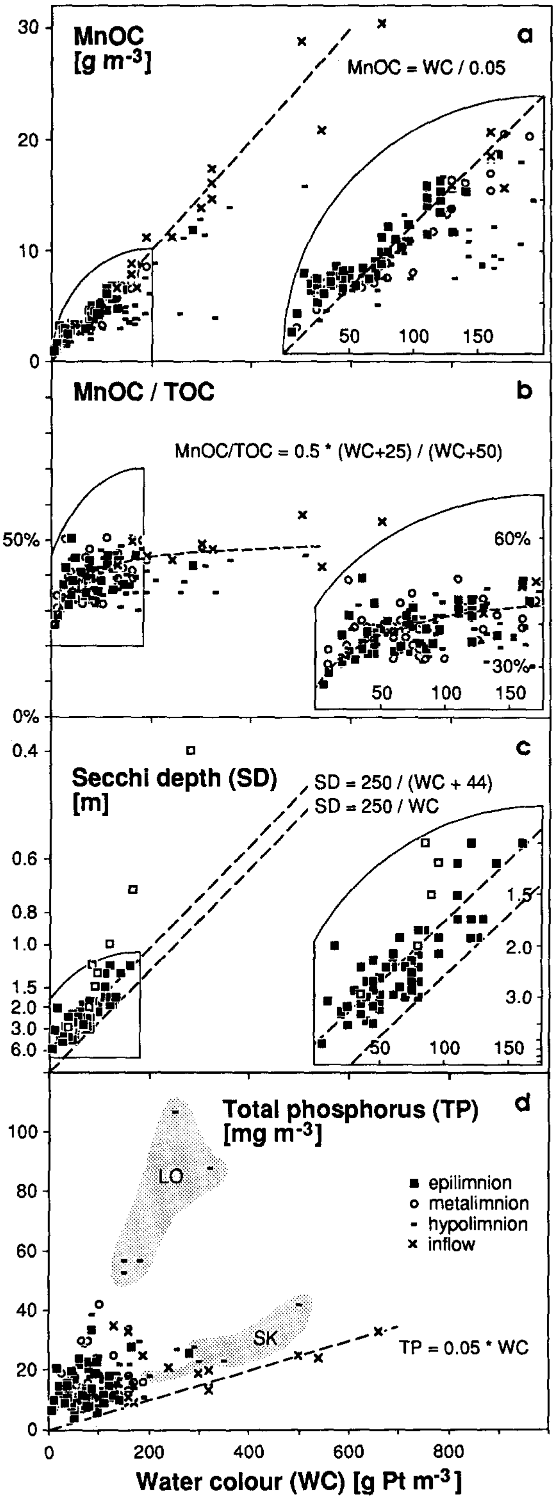

Fig. 2. Correlation of optical and chemical water characteristics with water colour in 18 Swedish forest lakes and streams 1985–1986. Enlarged insets show the lake data in more detail. See also Fig. 1.

from TOC (open symbols in Fig. 1c). A closer examination of the data revealed that these lakes belong to a group of four lakes with a very low mean depth (0.8–1.4 m), whereas the mean depth of the other lakes is 2.4–5.8 m. In addition, the four lakes have a surface area of 0.21–0.55 km^2 and are thus not among the smallest of the study lakes. This results in a high dynamic ratio, a relative measure for the potential impact of wind-induced mixing forces (Table 1). Consequently, it is highly probable that the decreased transparency is a result of periodic resuspension of sediments, a large proportion of which consists of inorganic clay particles (typically 40–80% of dry weight assuming C = 50% org. dw; Meili, 1991b). Deviations were often observed on windy days and were accompanied by unusually high concentrations of organic matter and nutrients in the water samples. Consequently, Secchi depth measurements are unsuitable for estimating TOC in lakes sufficiently large and shallow for sediment resuspension to significantly increase particle concentration in the water column. When excluding these lakes, however, predictions with this convenient method are satisfactory ($R^2 = 0.83$, $n = 43$).

Phosphorus content of organic matter

In contrast to MnOC, water colour and Secchi depth, the concentrations of total phosphorus were not correlated with TOC when comparing all samples. Especially the values for lake surface water show a pattern similar to random scatter (Fig. 1d). However, a more detailed analysis of the relationship between total phosphorus and TOC revealed interesting patterns about the C/P-ratio [$g\,g^{-1}$] in different types of waters. The highest C/P-ratios were found in stream waters, where most values were around 2000 (Fig. 1d). On the other hand, values on the order of 100 were found in the hypolimnion of mesotrophic lake Loppesjön. In surface lake waters, all samples except one showed an C/P ratio between 350 and 1500. Higher values were typically observed in dystrophic lakes, and lower values in lakes with low water colour and varying concentrations of total phosphorus, where most production is autochthonous. Evidently, the C/P-ratio reflects qualitative aspects of the organic matter in lakes, suggesting that in oligo-mesotrophic lakes, the C/P-ratio is basically dependent on the influence of allochthonous humic matter from the drainage area and can thus be used as a measure of dystrophy.

In humic waters, concentrations of total phosphorus (TP) were high and increased with water colour, most prominently in stream waters. In polyhumic waters, low phosphorus concentrations are very rare. A lower threshold appears to apply (cf. 987 Finnish lakes in Kämäri *et al.*, 1990), which is similar to the relationship of TP [$mg\,m^{-3}$] with TOC [$g\,m^{-3}$] (Fig. 1d) and colour [$g\,Pt\,m^{-3}$] (Fig. 2d) found in stream samples, and which may represent the proportion of recalcitrant phosphorus in decomposed organic matter:

$$TP = 0.05 \cdot WC \approx 0.5 \cdot TOC \qquad (6)$$

High phosphorus concentrations in humic lakes as well as positive correlations of TP with TOC or light attenuation have been reported previously (Åberg & Rodhe, 1942; Jackson & Hecky, 1980; Wetzel, 1983; Pennanen, 1988; Kämäri *et al.*, 1990). Other studies indicate that planktonic productivity or biomass in humic lakes is lower than expected from relationships with TP established for non-humic lakes (Chow-Fraser & Duthie, 1987; Jackson & Hecky, 1980). In humic waters, total phosphorus by itself is thus most probably of little value as an indicator of trophic state or primary productivity. Instead, it rather turns into a measure of humic content in heavily stained waters.

Phosphorus can be part of organic or inorganic compounds, which may occur in particulate or dissolved state. Roughly half of total dissolved phosphorus both in streams (Olofsson, 1989) and oligotrophic lakes (Tranvik, 1988) of the boreal forest region is typically MRP. Particulate phosphorus is roughly half of TP in forest streams (e.g. Olofsson, 1989), but is the dominant fraction in many lakes (Wetzel, 1983). In humic waters, particulate phosphorus as defined by various filtration procedures may include part of colloidal organic phosphorus (cf. Wetzel, 1983). To assess the phosphorus content in different types of organic matter, chemical analyses of molybdate-reactive phosphorus (MRP) and total phosphorus (TP) were applied and compared to different measures of organic matter.

In contrast to TP (Fig. 1d and 2d, see above), MRP was correlated with water colour in all types of water (Fig. 3a). The influence of humic substances on the chemical reactivity of phosphorus becomes obvious when considering the MRP/TP ratio (Fig. 3b). Whereas in oligohumic lakes both the concentration and proportion of MRP were very low, the vast majority of TP in polyhumic stream waters was MRP. This indicates an efficient biotic fixation of labile phosphorus in clear-water lakes, whereas in humic waters, phosphorus is strongly interacting and to a large extent associated with humic substances (cf. Jackson & Hecky, 1980; Jones *et al.*, 1988).

In the lake water samples of this study, MRP was typically 5–40% of TP, whereas in stream water, the proportion was typically 30–90% (Fig. 3b). This difference could lead to the conclusion that in runoff water, most phosphorus occurs as inorganic orthophosphate (PO_4^{3-}). However, PO_4^{3-} has many times been reported to be almost completely absent in humic waters (cf. Pennanen, 1988), and MRP values from this study probably represent dissolved organic phosphorus (cf. Stainton, 1980). Humic matter alone has no capacity to bind PO_4^{3-} (Young & Comstock, 1984) and is only interactive in the presence of ferric iron (Koenings & Hooper, 1976). In polyhumic waters, both iron and phosphorus are almost exclusively associated with high molecular weight humic substances, which are also responsible for most of the brown water colour (Pennanen, 1988). Consequently, the correlations in lake and stream water between TP and colour (Fig. 2d) as well as MRP and colour (Fig. 3a) are most probably a result of chemical interactions between phosphorus and colloidal humic matter, whereas truly dissolved low molecular weight substances, which constitute the majority of the organic matter in polyhumic waters and soil solutions (Pennanen, 1988; Cole *et al.*, 1984; Jackson & Hecky, 1980, see also below), contain little phosphorus.

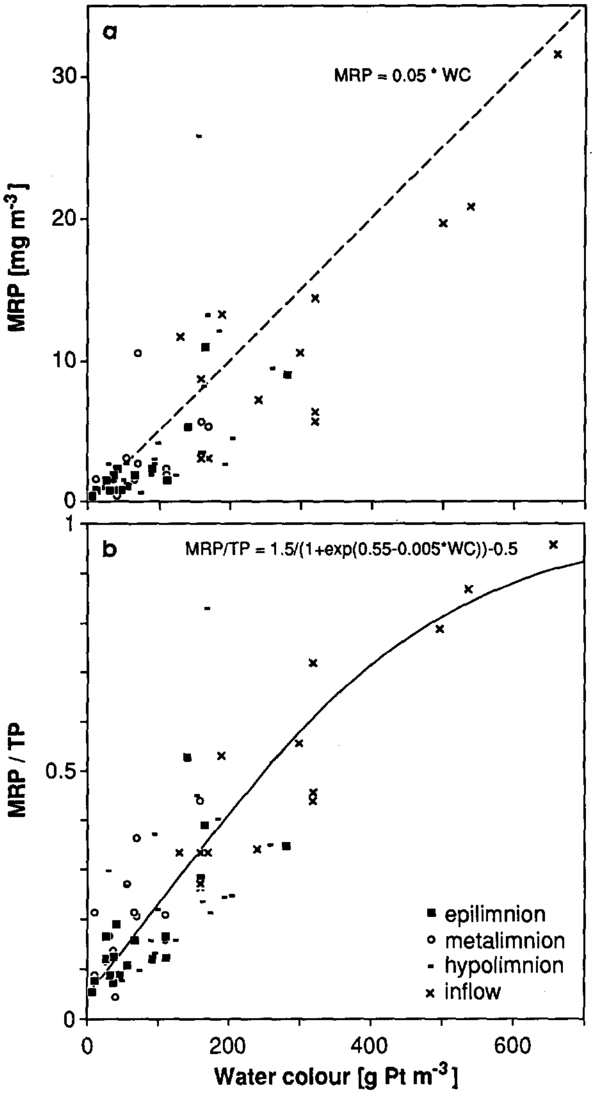

Fig. 3. Correlation of molybdate-reactive phosphorus (MRP) (a) and its proportion in total phosphorus (TP) (b) with water colour in 18 Swedish forest lakes in August–September 1985. The line in Fig. 3a is the same as in Fig. 2d.

Source-related estimates of TOC

Oligo- and eutrophic lakes are usually little stained by brown dissolved compounds (Åberg &

Rodhe, 1942; Hutchinson, 1957; cf. Fig. 2d). Water colour is enhanced in the presence of metals, especially iron and manganese (Gjessing, 1976) which, like humic substances, are supplied to forest lakes almost exclusively by surface runoff. Consequently, water colour can be regarded as an indicator of the concentration of allochthonous carbon. This view is also supported by the inverse relationship between colour and water residence time (Fig. 4, Table 1) and by the temporary increase of colour in lakes during periods of high water flow (Meili *et al.*, 1991).

In temperate lakes, the correlation of autochthonous production with the concentration or the availability of phosphorus is well established (e.g. Carlson, 1977). Whereas most organic matter in oligohumic lakes originates from primary production in the lake, a large proportion of TOC in humic lakes is produced in the catchment and transported to the lake, where it is mixed with carbon from autochthonous production in the lake. The latter causes a lower colour/TOC ratio in most lakes when compared to the inflowing water (Fig. 1b). Thus TOC in lake water is basically composed of strongly coloured allochthonous humic matter and weakly coloured but more nutrient-rich autochthonous matter such as algae and excreted dissolved compounds (Åberg & Rodhe, 1942; Hutchinson, 1957). Accordingly, it can be assumed as a first approximation that the concentration of TOC is proportional to both the concentration of phosphorus and to the water colour, each representing a different type of organic matter. Using only surface water data from the eight lakes which were sampled during the whole study period, empirical relationships from multiple linear regressions suggest the following TOC estimate for lake surface waters:

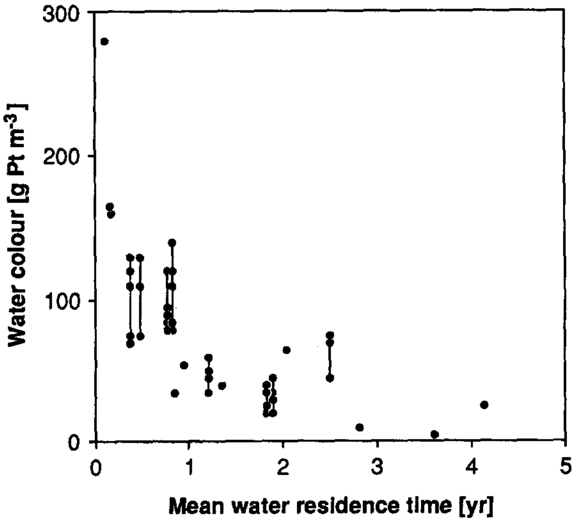

Fig. 4. Relationship of water colour and theoretical mean water residence time in 18 Swedish forest lakes 1985–1986.

$$\mathrm{TOC} = 0.085 \cdot \mathrm{WC} + 0.27 \cdot \mathrm{TP} \qquad (7)$$

where TOC = total organic carbon [$\mathrm{g\,m^{-3}}$], WC = water colour [$\mathrm{g\,Pt\,m^{-3}}$] and TP = total phosphorus [$\mathrm{mg\,m^{-3}}$]. This equation was derived from several regressions (usually $p < 0.0001$, $R^2 = 0.5...0.8$), where different periods (seasons, years) and lake types (morphological, hydrological, chemical) were included or excluded, and where the parameters in the equation varied interdependently within 0.074...0.099 and 0.35...0.17, respectively. 25% of the values observed in different seasons in the surface water of the lakes from which the model was derived were within ±5% of the model values, 40% were within ±10%, and 90% were within ±30% ($R^2 = 0.71$, $n = 41$).

However, Eq. (7) resulted in systematic overestimates for polyhumic lakes and especially streams. Moreover, the second term in the equation for the contribution of autochthonous carbon is conceptually not satisfactory, as it suggests a C/P ratio of 270 in autochthonous matter, which is lower than any of the observations from the study lakes, although part of them have a very low humus concentration and a long water residence time, suggesting that most production is autochthonous. According to Fig. 1d, the C/P ratio in epilimnetic waters is typically above 350, which is in agreement with data from other Swedish lakes of the meso-eutrophic type (Meili unpubl. data). In addition, Fig. 2d indicates that in humic waters, a large proportion of phosphorus is associated with humic substances and probably contributes little to primary production. Using Eq. 6, phosphorus associated with autochthonous matter (AP, mg m^{-3}) can be estimated as follows:

$$AP = TP - 0.05 \cdot WC \qquad (8)$$

Assuming that the C/P ratio of 350 is representative of organic matter from primary and secondary production in lakes, the concentration of autochthonous organic carbon (AOC, g m^{-3}) can be estimated from AP:

$$AOC = 0.35 \cdot AP \qquad (9)$$

Allochthonous humic organic carbon (HOC) can be calculated by subtracting AOC from the first TOC estimate (Eq. 7) and by assuming that the remaining phosphorus term represents detrital matter (C/P ratio $\approx$ 1000), which can be expressed in Pt-units according to Eq. (5):

$$\begin{aligned} HOC &= TOC - AOC \\ &= 0.103 \cdot WC - 0.08 \cdot TP \\ &\approx 0.103 \cdot WC - 0.008 \cdot WC \\ &\approx 0.095 \cdot WC \qquad (10) \end{aligned}$$

By including these considerations on the phosphorus content of humic matter and the C/P-ratio in oligohumic lakes, Eq. (7) can now be replaced by a new, more conceptual equation. It is based on the addition of one term representing the contribution of allochthonous humic carbon to TOC, and another term for the proportion of carbon from autochthonous primary and secondary production:

$$\begin{aligned} TOC &= HOC + AOC \\ &= 0.095 \cdot WC + 0.35 \cdot AP \\ &= 0.095 \cdot (WC + 3.7 \cdot AP) \qquad (11) \end{aligned}$$

where TOC = total organic carbon [g m^{-3}], WC = water colour [g Pt m^{-3}] and AP = available phosphorus from Eq. (8) [mg m^{-3}]. When applying this model to the surface water data from all 18 lakes, 40% of the observed values were within ± 10% of the model values, 70% within ± 20% and 90% within ± 30% ($R^2 = 0.75$, $n = 51$). When applying the model to all lake surface and stream data, 35% of the observed values were within ± 10% of the model values, 70% within ± 20% and 90% within ± 30% ($R^2 = 0.93$, $n = 65$).

The model can be illustrated with a set of parallel lines in a nomogram for the dependence of TOC on water colour and phosphorus concentration (Fig. 5a). The model accounts for the fact that low phosphorus concentrations at high water colour are very rare, which is illustrated in Fig. 5a by the bold line derived from the left term in Eq. (11). Systematic deviations of the predicted values from the observations occurred only in some meta- and hypolimnion samples (Fig. 5b). Prediction statistics and confidence intervals were therefore calculated for each sample type separately (Fig. 6a). In lake water samples, an increasing overestimation of TOC with water depth was observed, but only in hypolimnion samples was the median ratio of predicted/observed values significantly different from one. This can be attributed to anoxia in the hypolimnion of deep lakes, where excess colour is created from the accumulation of inorganic Fe-compounds, and where decomposition of settling matter and the presence of Fe-compounds results in an accumulation of inorganic phosphorus. In some deep and oligohumic lakes, however, the ratio was largest in the metalimnion. Speciation of phosphorus (Fig. 3b) and organic carbon (Fig. 2b) both indicate that the organic matter in the metalimnion of these lakes was dissolved, either diffusing from the hypolimnion or remaining after spring overturn, whereas in the lowest layer of the hypolimnion, settling detrital particles including precipitated humic colloids were more common.

As samples were collected during a year with unusually variable conditions with respect to hydrology and water chemistry, systematic seasonal deviations from predicted values were considered separately (Fig. 6b). In the northern study area, high water fluxes occurred as a result of unusually heavy rainfall and soil erosion in autumn 1985 and 1986, and a rapid snowmelt in spring 1986, whereas the summer period was rather dry (cf. Meili *et al.*, 1991). However, seasonal effects on the TOC predictions were small in epilimnion

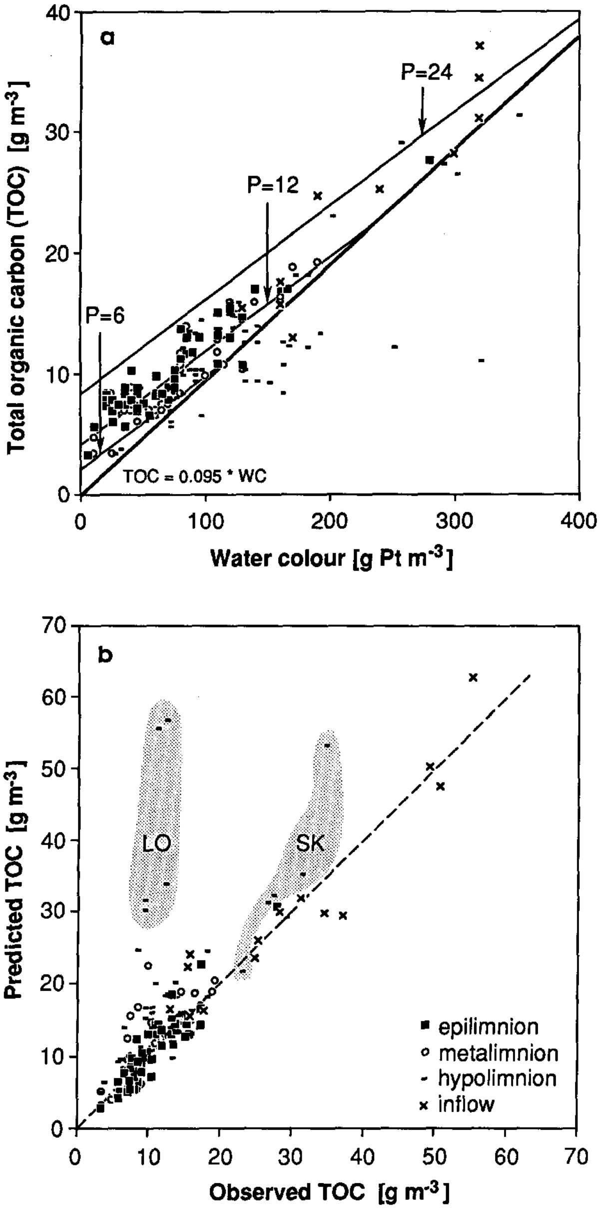

Fig. 5. a) Relationship of TOC and water colour in 18 Swedish forest lakes 1985–1986, and a nomogram for predicted TOC in softwater lakes of different water colour and phosphorus concentration (P = 6, 12, 24 mg m^{-3}). b) Relationship of predicted (= 0.095·(WC + 3.7·AP)) and observed concentrations of TOC.

samples, although periods of destratification and peak-flow events were included in the study during which TOC, water colour and TP varied dramatically. This robustness of Eq. 11 improves its value as a potential predictive tool for surficial

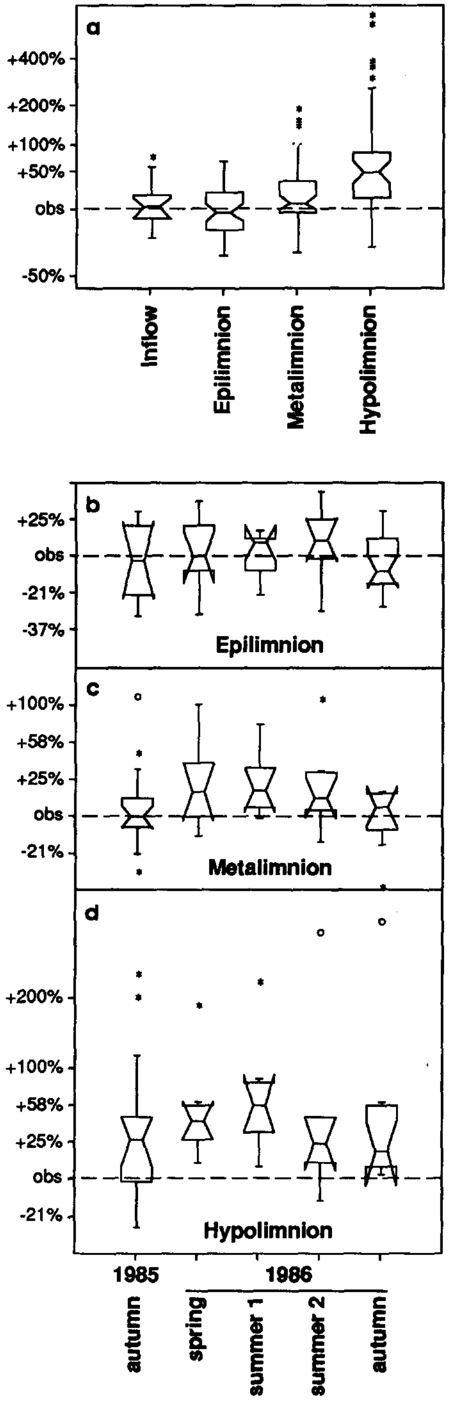

Fig. 6. Percentage deviation of predicted concentrations of TOC from observations at different sampling sites and occasions in 18 Swedish forest lakes 1985–1986. The notched box-and-whisker plot shows the median, lower and upper quartiles, min. and max. values (within 1.5 times the interquartile range from the quartiles), and extreme values ('*' = within and 'o' = outside 3 times the interquartile range from the quartiles). The medians of two boxes with notches that do not overlap are different at the 95% confidence level.

lake waters. On the other hand, the amplitude of seasonal variation increased with water depth, and in the deeper water strata of most lakes, the predictions usually yielded significant overestimates in summer. This confirms the effect of decomposition processes during periods of thermal stratification, during which predictions of TOC from Eq. (11) may only be valid for surface samples, especially in eutrophic lakes.

Sources, character and composition of organic matter

Organic matter in natural waters originates from biotic production and occurs in different states of decomposition, which results in a decreasing content of nutrients such as phosphorus. In the following section, an attempt is made to characterize different types of organic matter on the basis of their phosphorus content in order to identify their source and to quantify their quantitative importance in lake waters.

From the two components of Eq. (11), the proportions of allochthonous and autochthonous organic carbon in the water column can be roughly estimated. In Swedish forest lakes, the overall median phosphorus concentration is about 10 to 15 $\mathrm{mg\,m^{-3}}$, and the water colour about 70 to 80 $\mathrm{g\,Pt\,m^{-3}}$ (Meili *et al.*, 1991; SNV, 1986), which corresponds to a TOC concentration of 9 to 11 $\mathrm{g\,m^{-3}}$. According to the influence of AP in Eq. (11), autochthonous TOC (ca. 3 $\mathrm{g\,m^{-3}}$) constitutes about 30% of TOC. This indicates that the majority of TOC in a typical forest lake is of allochthonous origin. It can be estimated that in most unpolluted softwater lakes with a water colour of 50 $\mathrm{g\,Pt\,m^{-3}}$ or higher, more than half of the organic carbon in the surface water consists of allochthonous humic substances, and in polyhumic lakes (>200 $\mathrm{g\,Pt\,m^{-3}}$) more than 90%.

In oligo-mesotrophic lake waters, the concentration of dissolved inorganic phosphorus is usually very low, and it is the limiting nutrient for algal and bacterial production (Harris, 1986). While according to Harris, the C/P weight ratio in planktonic organisms is between 41 (Redfield ratio, zooplankton) and 64 (phytoplankton), the ratio in particulate organic matter in oligo-mesotrophic lakes is about 60–80 (*op. cit.*). This slight difference is most likely due to the influence of detrital P-depleted particles, which both agrees and disagrees with Harris who states that the C:N:P ratios of living fractions and detritus are indistinguishable, but also that settling detrital particles are nutrient-depleted. The character and amount of detrital particulate organic matter (DPOM) can be assessed in different ways. According to Wetzel (1983) and Harris (1986), roughly half or more of the POM in lakes is detrital, and about 10% are typically algae. Zooplankton accounts for a minor proportion of biotic matter in meso-eutrophic lakes (BPOM), but can exceed the phytoplankton biomass in oligotrophic lakes, especially when the input of allochthonous matter is high (cf. Wetzel, 1983). This is in accordance with data from Swedish oligotrophic lakes, where the biomass of phytoplankton, zooplankton and bacteria often is fairly equal (R. Bell, pers. comm.). For consistency with the C/P ratios given above, the C/P ratio in autochthonous DPOM in the epilimnion of lakes would have to be around 70–100. This ratio is similar to the C/P ratio (TOC/TP) around 100 which was found in the lowest part of the sheltered anoxic hypolimnion of mesotrophic oligomictic Loppesjön (Fig. 1d). This ratio may be representative of more heavily decomposed autochthonous DPOM settling in oligohumic lakes (cf. Boström, 1984) and for terrestrial DPOM occurring in forest streams (cf. Olofsson, 1989). In contrast, the hypolimnetic C/P ratio was up to 1300 in the oligotrophic polyhumic lake Skärhultsjön, which has a similar anoxic hypolimnion. This ratio is approaching the one found for humic matter in forest streams (Fig. 1d), indicating that organic matter settling in polyhumic lakes is dominated by humic colloids.

This element ratio approach is also applicable to assess the characteristics and composition of autochthonous matter. A study of several hundred softwater lakes (Birge & Juday, 1934) showed that in clearwater lakes containing predominantly autochthonous matter, 80–85% of the organic matter in the surface water is typically dissolved, as defined by centrifugation. This dissolved organic matter (EDOM) is a product of excretion and decay of planktonic organisms (Cole *et al.*, 1984). As most phosphorus is associated with particles, the C/P ratio in autochthonous EDOM will be manyfold higher than in POM, probably between 350 which is the lower end of the C/P range of total organic matter (TOM) found in surficial lake waters (Fig. 1d), and infinity which is equivalent to complete P-depletion of EDOM. Given this potential range and a C/P ratio of 70 for POM which accounts for 15–20% of the organic matter, the C/P ratio in autochthonous total organic matter (TOM) including POM and DOM will be within a limited range of 200 to 500, which supports the assumption that the C/P ratio of 350 in fact may be representative of autochthonous matter in lakes.

From the proportion of dissolved carbon and the C/P ratios in TOM, POM, BPOM and DPOM, the partitioning of phosphorus and carbon into different fractions of autochthonous matter can be assessed by solving a system of 9 simple simultaneous equations:

$$
\begin{aligned}
&C\%(\mathrm{POM}) + C\%(\mathrm{EDOM}) = 100\% \\
&P\%\ (\mathrm{POM}) + P\%\ (\mathrm{EDOM}) = 100\% \\
&C\%\ (\mathrm{POM}) = C\%\ (\mathrm{BPOM}) + C\%\ (\mathrm{DPOM}) \\
&P\%\ (\mathrm{POM}) = P\%\ (\mathrm{BPOM}) + P\%\ (\mathrm{DPOM}) \\
&C\%\ (\mathrm{POM}) = 18\%
\end{aligned}
$$

$$
\begin{aligned}
&C\%\ (\mathrm{TOM})/P\%\ (\mathrm{TOM}) = 350 \\
&C\%\ (\mathrm{POM})/P\%\ (\mathrm{POM}) = 70 \\
&C\%\ (\mathrm{BPOM})/P\%\ (\mathrm{BPOM}) = 50 \\
&C\%\ (\mathrm{DPOM})/P\%\ (\mathrm{DPOM}) = 90
\end{aligned}
$$

The results are summarized in Table 3, which also shows that allochthonous and autochthonous matter differ both with respect to physical characteristics and regarding to nutrient content (C/P-ratio) of physically similar fractions. The equations suggest that about 90% of the phosphorus in the surface water of oligotrophic clearwater lakes is particulate, which is in agreement with Wetzel (1983) and Harris (1986). A comparison with the equation in Fig. 3b indicates that MRP analyses yield roughly half of the dissolved phosphorus in clearwater lakes (cf. Tranvik, 1988), but most of total phosphorus in polyhumic forest streams. This may be due to the different character of terrestrial and aquatic DOM. The majority of EDOM in lakes consists of high molecular weight substances, whereas the reverse is the case in polyhumic waters where low molecular weight compounds (fulvic acids, FDOM) account for around 70–90% of the organic matter (Cole *et al.*, 1984; Pennanen, 1988; Jackson & Hecky, 1980). Differences with respect to the type of phosphorus binding may also occur due to different contents of iron.

Table 3. General character and proportions (weight %) of organic carbon and phosphorus of different type and origin in the surface water of Swedish forest lakes. Values for autochthonous organic matter and estimates derived from oligohumic oligo-mesotrophic lakes. Values for allochthonous organic matter correspond to humic forest stream water after partial settling of particulate matter. See text for abbreviations, analyses, estimates and calculations.

	C/P	C %	P %
Autochthonous:			
TOM	350	100	100
POM	70	18	90
BPOM biotic	50	6	45
DPOM detrital	90	12	45
EDOM dissolved	3000	82	≤10
PO_4-P	–	–	≥0
Allochthonous:			
TOM	2000	100	100
POM detrital	≥100	2	≤40
DOM	3000	98	≥60
HDOM humic coll. + diss.	1000	20	40
FDOM fulvic dissolved	8000	78	≤20
PO_4-P	–	–	≥0

In combination with Eq. (11), the values in Table 3 can be used to estimate the proportion of carbon and phosphorus in organic matter of different type and source. In humic lakes, mean water residence times are typically short, of the order of a few months or less (cf. Meili *et al.*, 1991; Meili, 1991a). This results in a continuous or periodic supply of recalcitrant humic matter, and allows little time for biotic or chemical transformation in the lakes, except a partial settling of particles and heavier colloids. The composition of autochthonous organic matter may be subject to rapid transformations and vary seasonally, but can be regarded constant for the purpose of rough estimates, as spatial and temporal variations with respect to the distribution among biotic and detrital particles and dissolved compounds are not very large (cf. Birge & Juday, 1934), partly because of the slow turnover of most detrital and dissolve matter (Cole *et al.*, 1987). The high MRP/TP-ratios in humic waters, and its similarity in lakes and streams of the same water colour (Fig. 3b) also indicates that little of the phosphorus associated to humic substances is available for planktonic production. Thus assuming constant proportionality between organic fractions of the same origin (allochthonous and autochthonous), the relative contribution of each fraction to the organic matter in lake waters can be calculated for model lakes of different trophic state with respect to dystrophy and eutrophy (Fig. 7). Most of the organic carbon is dissolved, particularly in humic lakes, whereas the majority of phosphorus is associated with particulate or colloidal organic matter of different origin. In polyhumic lakes, humic substances may suppress primary production by competing with biota for phosphorus and by causing light limitation, but at the same time they may serve as an important long-term nutrient storage for primary producers and bacteria (Tranvik, 1988) by preventing phosphorus from settling out from the water column.

The comparison of different analytical methods and calculations also provides a physico-chemical characterization of organic matter. MnOC, which yields 35 to 60% of TOC, seems to include mainly truly dissolved organic matter. Calculations based on data in Table 3 and Figs. 2b and 7 suggest that only about one third of the autochthonous DOC and about half of the allochthonous DOC are susceptible to permanganate oxidation. These proportions may be related to the proportions of low to medium molecular weight ($<10^4$ to 10^5)

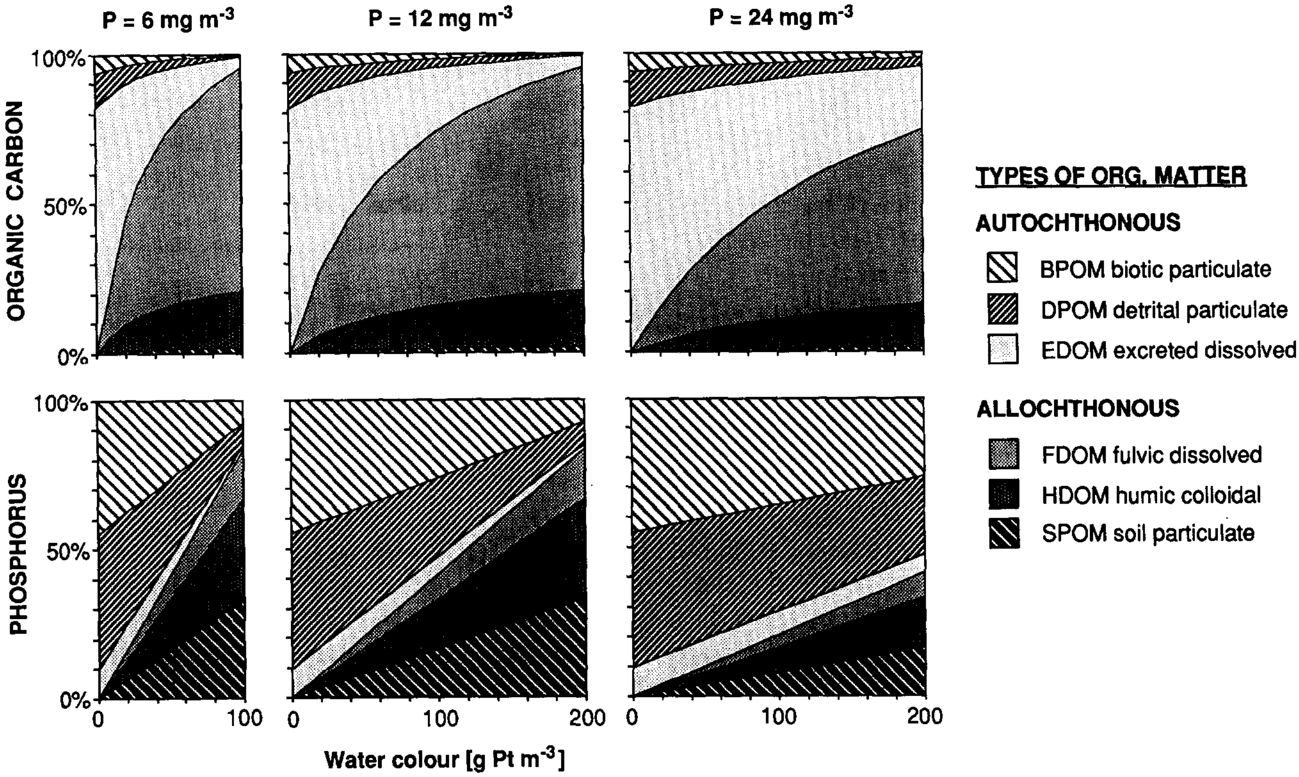

Fig. 7. Estimated mean composition of organic matter with respect to carbon (top) and phosphorus (bottom) in boreal forest lakes as a function of water colour (dystrophy) and phosphorus concentration (eutrophy).

compounds in DOM from the two sources (cf. Cole *et al.*, 1984). The higher chemical stability of lacustrine organic matter is also evident from the analysis of hypolimnion water, where the relative yield of MnOC was lower than in stream water at equal TOC (Fig. 1a) or water colour (Fig. 2a,b). These findings indicate that the permanganate method provides information about the molecular weight of the organic substrate, when combined with analysis of TOC.

Light attenuation by different types of organic matter

The transparency of lake water is highly dependent on the concentration of organic matter. In the range of Secchi depths (SD) of 1–5 m, reasonable estimates of TOC can be obtained from the inverse proportionality of TOC and SD (Fig. 1c, see above). SD is basically determined by the light absorption by dissolved compounds, the light scattering by particles, and the light absorption by the water itself. In waters with a SD of < 10 m, the absorption by the water can be neglected. In most softwater lakes $< 1\ \text{km}^2$ with a mean depth of > 2 m, the concentration of inorganic particles originating from e.g. sediment resuspension or calcite precipitation will be of little importance. The influence of humic matter on the light attenuation in lakes can be assessed from the linear relationship between 1/SD and water colour (Fig. 2c). Linear regression provided the following relationship (four extreme values were excluded from the calculation):

$$\begin{aligned} 1/\mathrm{SD} &= 0.0040 \cdot \mathrm{WC} + 1.76 \\ &= 0.0040 \cdot (\mathrm{WC} + 44) \end{aligned} \tag{12}$$

The slope describes the light extinction by humic matter, and the intercept accounts for the interference of autochthonous matter corresponding to 44 Pt colour units on average. The intercept can be replaced by a function of AP (from Eq. 8) which was derived from the relationship of SD with TP in a number of meso-eutrophic oligohumic lakes in the Stockholm area and in central Sweden (Meili, unpubl. reports):

$$1/\mathrm{SD} = 0.02 \cdot \mathrm{AP} \tag{13}$$

The coefficient is in good agreement with Carlson (1977) who proposed 0.0208 for summer data using the same formula. Combining the slope of Eq. (12) with Eq. (13) produces:

$$1/\mathrm{SD} = 0.0044 \cdot (\mathrm{WC} + 5 \cdot \mathrm{AP}) \tag{14}$$

The internal relationship between the allochthonous and the autochthonous term in Eq. (14) is similar to the one in the estimate of TOC (Eq. 11). This indicates that the extinction coefficient per unit carbon is similar for allochthonous and autochthonous matter, although the spectral behaviour may be quite different (Wetzel, 1983), and explains why SD is inversely proportional to TOC (Fig. 1c).

Eq. (14) can be translated into a nomogram for Secchi disk transparency in softwater lakes of different trophic state with respect to dystrophy and eutrophy (Fig. 8a). A comparison of predicted and observed SD (Fig. 8b) shows a scatter of similar magnitude as the empirical relationship between SD and TOC (Fig. 1c).

Secchi disk transparency corresponds to the depth of around 10% of surface light, and is related to the extinction coefficient $[\mathrm{m}^{-1}]$ as follows (Idso & Gilbert, 1974):

$$E = 1.7/\mathrm{SD} \tag{15}$$

A combination of Eq. (4),(5),(9),(14) and (15) shows that the carbon-specific extinction coefficient is about 0.07 to 0.1 $\mathrm{m}^2\ (\mathrm{gC})^{-1}$ for allochthonous and autochthonous organic matter, respectively.

Conclusions

Organic matter in surface waters can be classified according to origin (allochthonous or autochthonous), physical state (particulate or dissolved) and nutrient content (carbon/phosphorus ratio). The character as well as the quantity of various organic fractions can be assessed with standard monitoring methods due to differential response

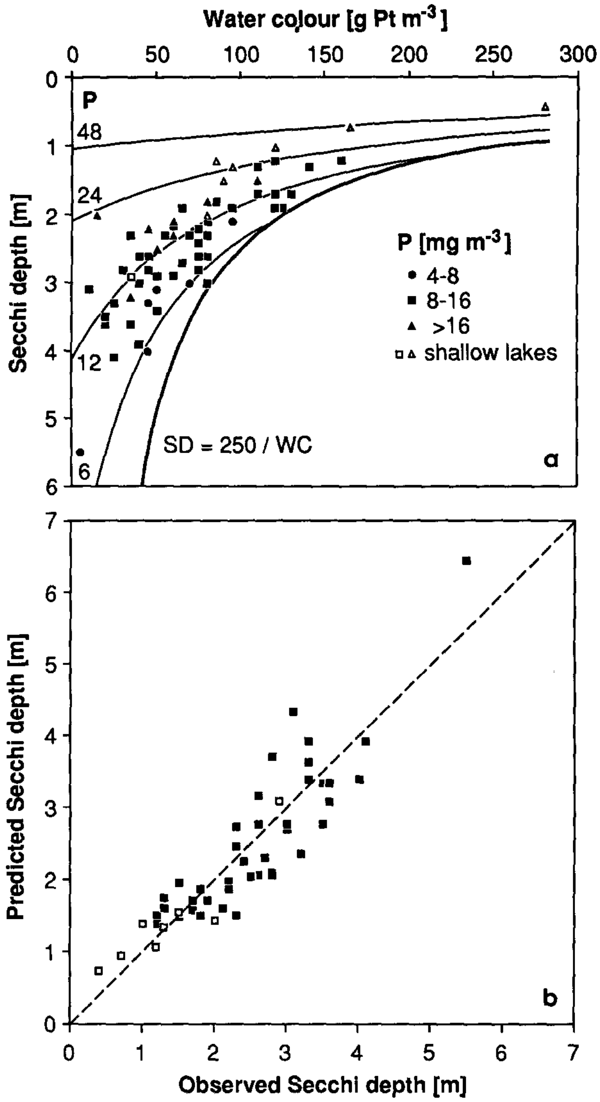

Fig. 8. a) Relationship of Secchi disk transparency and water colour in 18 Swedish forest lakes 1985–1987, and a nomogram for predicted SD in softwater lakes of different water colour and phosphorus concentration (P = 6, 12, 24, 48 mg m^{-3}). Shallow lakes with a mean depth of <2 m are highlighted. b) Relationship of predicted (= 250/(WC + 5·AP)) and observed Secchi depth.

to different analytical procedures (Table 4). Given constant proportions between organic fractions of the same origin (allochthonous or autochthonous, Table 3), Secchi disk transparency has a similar response to carbon from both sources. As a result, Secchi depths provide good TOC estimates which can be obtained with a single optical measurement (cf. Fig. 1c). Water colour on the other hand is the most selective tool with which allochthonous and autochthonous matter can be clearly distinguished, as most of the brown colour in forest lakes originates from an interaction between iron and humic substances, both of which originate from soils in the drainage area.

A large proportion of phosphorus is associated with biotic particles (Table 3, Fig. 7). Consequently, total phosphorus concentrations provide a rough measure of POM which is little influenced by the relative contribution from different sources. However, the results will vary seasonally

Table 4. Apparent relative response of different optical and chemical methods to quantitatively important types of organic matter in lake waters.

	Secchi depth	Water colour	Permangomate oxidation	Total phosphorus	Molybdate-R. phosphorus
Autochtohonous					
BPOM biotic particulate	+ +			+ +	
DPOM detrital particulate	+ +			+	
EDOM excreted dissolved	+		+		+
Allochthonous					
DPOM detrital particulate	+ +			+ +	
HDOM humic colloidal + dissolved	+ +	+ +		+	+ +
FDOM fulvic dissolved	+	+	+ +		

and depend on the productivity, the vertical mixing of the water column, and the abundance of iron and other chemical components. MnOC, which yields 35 to 60% of TOC, seems to include mainly truly dissolved organic matter, and when combined with analysis of TOC, the permanganate method provides information about the chemical character of the organic substrate.

The standard methods applied can be used not only to assess lacustrine organic matter with respect to physical and chemical character, but also with respect to the relative contribution from different sources (allochthonous or autochthonous). It is estimated that in most unpolluted softwater lakes of the boreal forest region, the majority of the organic carbon in the surface water consists of allochthonous humic substances, which in polyhumic lakes (>200 g Pt m^{-3}) constitute more than 90% of TOC.

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