

¹⁴C-PHOTOSYNTHESIS OF PHYTOPLANKTON IN AN OLIGOTROPHIC ALPINE LAKE (TRAUNSEE, AUSTRIA) AND ITS RESPONSE TO TURBIDITY CAUSED BY INDUSTRIAL TAILINGS

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Abstract. The influence of industrial tailings on the biological integrity of the phytoplankton was assessed from annual measurements of photosynthetic rates in the alpine lake Traunsee. The mean annual integral production of $21 \text{ mmol C m}^{-2} \text{ d}^{-1}$ corresponded to the oligotrophic nature of the lake. Effects of effluents were tested by comparing photosynthesis at a station close to the industrial outlet (EB) and at a reference site with a maximum depth of 190 m (VI). Between-site optical properties (vertical attenuation coefficient, euphotic depth) were statistically significant different. The euphotic zone at the impacted station was on average 2 m shallower than at the reference site, owing to turbidity emanating from the industrial plant. The adaptation to low light intensities by the algal community at this station was evident from a high maximum light utilisation coefficient (α^*) at low light saturation (E_K). Algae at the deep reference site were photosynthetically less efficient but adapted to high light intensities. Photosynthetic adaptation to different light climates in the euphotic zone without significant quantitative biomass alterations at the impacted site gave a clear signature of biological integrity of the phytoplankton in the oligotrophic Traunsee.

Keywords: bioindication, biological integrity, light, overall loss rates, primary production

1. Introduction

Studies on photosynthesis or primary production refer to the function of phytoplankton in two ways: the formation of algal biomass and the adaptive strategy of algal species composition. Limitation of growth by nutrients, mainly phosphorus and nitrogen, is often classified and predicted from primary production or photosynthetic rates (Smith, 1979; OECD, 1982; Felföldy, 1987; Likens, 1975). Photosynthesis is interpreted as potential growth of algae and usually significantly higher than apparent growth rates calculated from the net changes in algal biomass (Tilzer, 1984; Horn and Horn, 1986; Garnier and Mourelatos, 1991). Effects of light adaptation on photosynthetic rates and efficiencies suggest that size related adaptive strategies underpin algal communities (Koschel and Scheffler, 1985; Happey-Wood, 1993; Frenette *et al.*, 1996; Teubner *et al.*, 2001).

With a maximum depth of 191 m and a water volume of $2302 \times 10^6 \text{ m}^3$, Traunsee is the deepest Alpine lake in Austria. Industrial salt and alkaline sludge have



TABLE I

Averages for optical properties and phytoplankton parameters for VI and EB. K = vertical attenuation coefficient, z_{eu} = euphotic zone, $\Sigma Chl-a$ = integral chlorophyll- a , P = photosynthetic rate, ΣP = integral photosynthetic rate per hr; $\Sigma \Sigma P$ = annual average of integral primary production per day; P^* = specific primary productivity per chlorophyll- a ; $\mu - k$ = overall loss rate, α^* = maximum light utilisation coefficient (initial slope of P versus E curve), E_K = light saturation index. P -values from paired t -test (n.s. = non-significant, $p > 0.05$), averages from December 1997 to October 1998 for $\Sigma \Sigma P$, from April 1998 to October 1998 for all other parameters

		VI	EB	P -value
K	(m^{-1})	0.387	0.456	$P = 0.001$
z_{eu}	(m)	12.2	10.2	$P = 0.004$
$\Sigma Chl-a$	($mg\ m^{-2}$)	28.4	24.6	n.s.
P	($\mu mol\ L^{-1}\ hr^{-1}$)	0.226	0.292	n.s.
ΣP	($mmol\ C\ m^{-2}\ hr^{-1}$)	2.036	2.410	n.s.
$\Sigma \Sigma P$	($mmol\ C\ m^{-2}\ d^{-1}$)	21	–	–
P^*	($mol\ C\ (g\ Chl-a)^{-1}\ hr^{-1}$)	0.099	0.149	$P = 0.002$
α^*	(10^{-3}) ($mol\ C\ (g\ Chl-a)^{-1}\ (mmol\ photons)^{-1}\ m^2$)	0.212	0.534	$P = 0.008$
E_K	($mmol\ photons\ m^{-2}\ hr^{-1}$)	1379	1099	n.s.
$\mu - k$	(d^{-1})	3.16	3.28	n.s.

calculated from the vertical attenuation coefficient (K), the mixing depth (z_{mix}) from the depth with maximum relative thermal resistance against mixing (RTR, Wetzel, 2001).

Integrated samples for scanning electronic microscopy (SEM) were prepared from all four seasons by critical point drying.

3. Results

The seasonal dynamic and mean values of photosynthesis and physico-optical properties for both sites are shown in Figure 1 and Table I. The annual average integral photosynthetic rate ($\Sigma \Sigma P$) measured at the reference site VI in Traunsee was $21\ mmol\ C\ m^{-2}\ d^{-1}$, mean photosynthetic rate (P) at EB and VI were 0.29 and $0.23\ \mu mol\ L^{-1}\ hr^{-1}$, respectively (Table I). The integral photosynthetic rate (ΣP) showed a pronounced spring peak in May–June and a second, weaker autumn peak in September for VI and EB (Figures 1A and B). At both sites, the integral chlorophyll concentration showed the same trend as for integral photosynthetic rates (Figures 1A and B; VI: $r = 0.738$, $p < 0.05$; EB: $r = 0.714$, $p < 0.05$). The annual average of integral photosynthesis was $2.036\ mmol\ C\ m^{-2}\ hr^{-1}$ for VI and 18% higher for EB (Table I). The annual integral chlorophyll a for VI was $28.4\ mg\ m^{-2}$ but 13% lower at EB. These differences between VI and EB, however, were

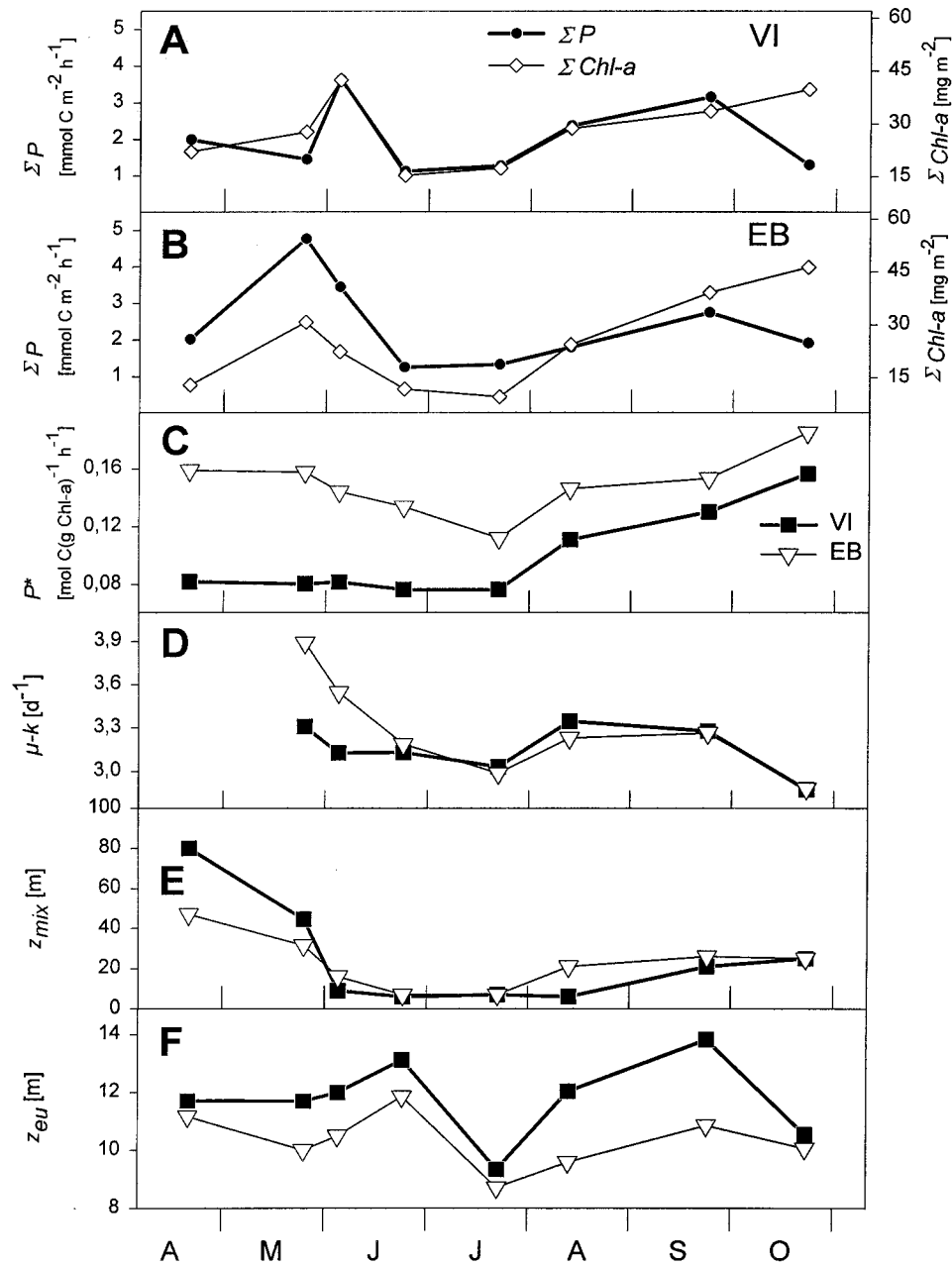


Figure 1. Dynamic of the integral chlorophyll *a* ($\Sigma \text{Chl-}a$) and photosynthetic rate (ΣP) for VI (A) and EB (B), specific photosynthetic rates (P^*) in C, overall loss rates of phytoplankton ($\mu - k$) in D, mixing depth (z_{mix}) in E and euphotic depth (z_{eu}) in F for both sites (legend in C for D-F).

TABLE II

Summary of P vs. E characteristics for the sites Viechtau (VI) and Ebensee bay (EB). P_m^* = maximum photosynthetic rate ($\text{mol C (g Chl-}a)^{-1} \text{ hr}^{-1}$); E_K = light saturation index ($\text{mmol photons m}^{-2} \text{ hr}^{-1}$); α^* = maximum light utilisation coefficient (initial slope of P versus E curve) ($\text{mol C (g Chl-}a)^{-1} (\text{mmol photons})^{-1} \text{ m}^2$); r^2 = variance

Date	Site	P_m^*	E_K	α^* (10^{-3})	(r^2)
15-04-1998	VI	0.137	396	0.345	(0.98)
	EB	0.227	398	0.5720	(0.88)
19-05-1998	VI	0.180	1538	0.117	(0.92)
	EB	0.241	1631	0.148	(0.99)
29-05-1998	VI	0.111	178	0.625	(0.55)
	EB	0.255	102	2.498	(0.99)
17-06-1998	VI	0.182	2298	0.079	(0.79)
	EB	0.183	1012	0.181	(0.93)
15-07-1998	VI	0.139	2354	0.0590	(0.96)
	EB	0.392	1894	0.207	(0.99)
05-08-1998	VI	0.187	1196	0.156	(0.96)
	EB	0.232	1083	0.214	(0.99)
15-09-1998	VI	0.229	1498	0.153	(0.76)
	EB	0.293	1157	0.253	(0.97)
14-10-1998	VI	0.250	1572	0.159	(0.92)
	EB	0.300	1515	0.198	(0.93)

not statistically significant for either the integral chlorophyll concentrations or the integral photosynthetic rates (Table I). The integral photosynthetic rates for EB were relative high in relation to their respective integral chlorophyll concentration (Table I). The photosynthetic activity per unit chlorophyll a (P^*) was consequently higher at EB than at VI as shown in Figure 1C and as verified statistically from the t -test in Table I. The summary of photosynthesis versus light characteristics are given in Table II. The maximal specific photosynthetic rates (P^*) ranged from 0.18 to 0.39 $\text{mol C (g Chl-}a)^{-1} \text{ hr}^{-1}$ for EB and from 0.13 to 0.25 for VI. The mean onset of light saturation (E_K , Table I) was 20% lower in EB than compared with VI. The photosynthetic efficiencies (α^*) were consistently higher in EB than in VI (Table II). Therefore, statistically significant higher values of the maximum light utilisation coefficient (α^* , $p < 0.01$) at lower light saturation (E_K) were measured for EB than for VI (Tables I–II). The optical properties were significantly different between VI and EB as indicated by both vertical attenuation coefficients ($P <$

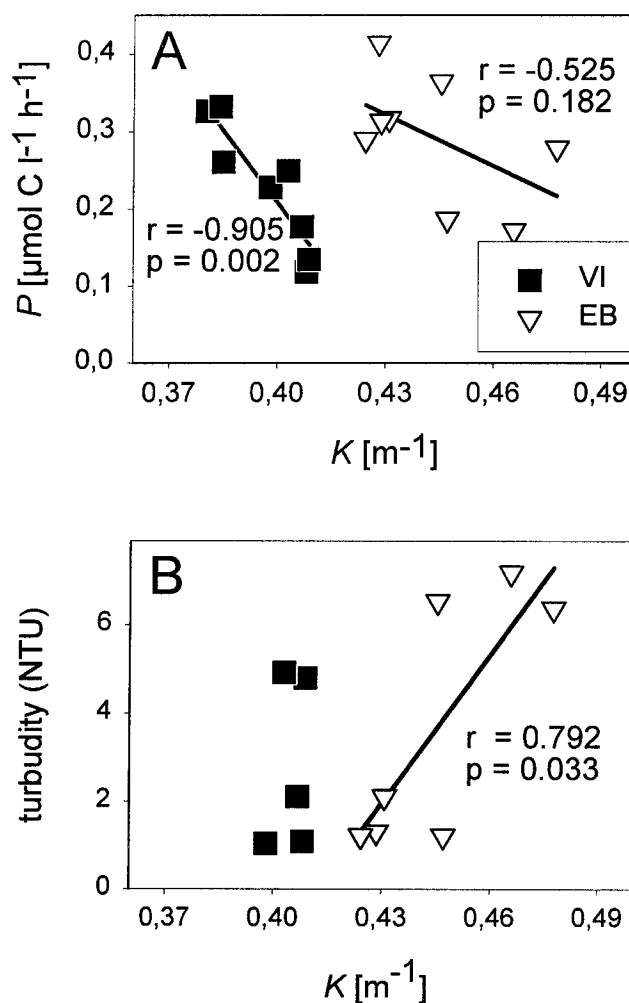


Figure 2. Photosynthetic rates (P) and turbidity (NTU) versus the vertical attenuation coefficient (K) in VI and EB. Pearson correlation coefficients and p -values.

measurement of photosynthetic rates of total phytoplankton assemblages from EB and VI by Weisse and Mindl (2002). We could show elsewhere for Traunsee and Mondsee, that not only photosynthesis but also the pigment pattern is subject to adaptation to the prevailing light climate (Teubner *et al.*, 2001). High photosynthetic efficiency at low light saturation was in accordance with a high ratio of light-harvesting chlorophyll a to photo-protective β -carotene, by reducing chlorophyll content or providing photoprotective pigmentation of the light harvesting apparatus. Algae at high solar radiation were photosynthetically less efficient but high-light adapted having low ratios of chlorophyll a to β -carotene. These changes in the pigment composition due to light acclimatisation, substantiated in our earlier

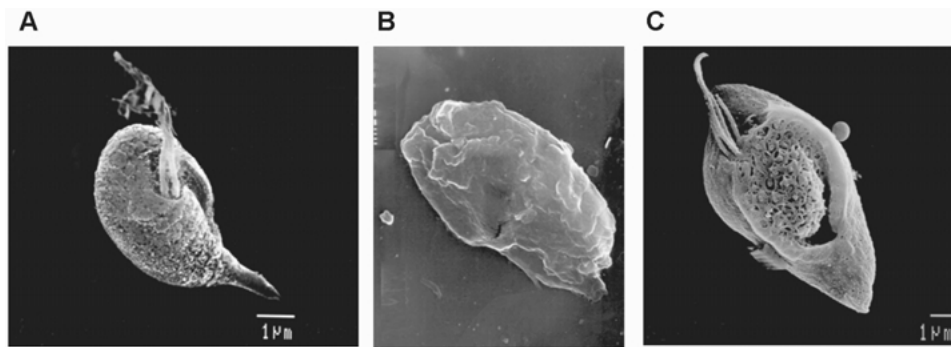


Figure 3. Flagellates from Traunsee with coating on the cell surface in EB (A, *Rhodomonas lacustris*, B-*Cryptomonas spec.*) and clean cell surfaces in VI. (C, Scanning electronic microscope).

studies, confirm the key function of photosynthetic light adaptation in Traunsee. In contrast to the total phytoplankton, the photosynthetic rates of picocyanobacteria under light-limited conditions ($10 \mu\text{mol m}^{-2} \text{s}^{-1}$) were significantly reduced at EB when compared with VI as shown by *in vitro* experiments by Weisse and Mindl (2002) and provide an example for an adaptive photosynthesis of single organisms or small fractions which can not compensate low-light intensity and/or can not cope with industrial contaminants.

The difference between the potential growth calculated from photosynthesis and the apparent growth as net changes of algal carbon is used as a measure of overall loss rates of phytoplankton. Grazing, sedimentation, wash-out and mortality contribute most to overall phytoplankton losses (Tilzer, 1984; Garnier and Mourelatos, 1991; Horn and Horn, 1986). The evidence of coating on cell surfaces of flagellates observed by SEM imply an enhanced sedimentation at the station impacted by industrial sludge. In fact, the overall phytoplankton losses at EB were higher, corresponding to higher turbidity and higher grazing pressure as deduced from the NTU's and the carbon ratio of certain fractions of the plankton community (Teubner, 2002). These losses at EB, however were not significantly distinct from the reference site. We could not find any further significant effects on species composition and on size-structure of phytoplankton as shown in Teubner (2002). Similar results were obtained for other pelagic organisms, e.g. heterotrophic bacteria (Klammer *et al.*, 2002), ciliates and flagellates (Sonntag *et al.*, 2002), and the abundance of picoplankton (Weisse and Mindl, 2002). Significant between-site differences, however, were evident from the vertical distribution patterns (Teubner, 2002). Both the higher portion of particulate organic phosphorus within TP and the shift towards P-enrichment in nutrient stoichiometry of TN:TP:SRSi verify an enhanced P-accumulation in the epilimnetic community at the open water reference site as a consequences of small pool-size of TP and stable stratification. The disturbances at the impacted site were indicated by: (i) up to 11% less P accumulation by organisms at the surface, (ii) no stoichiometric shift towards TP in the epilim-

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