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Differences in the eutrophication dynamics of Ammersee and Starnberger See (Southern Germany), reflected by the diatom succession in varve-dated sediments*

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Abstract

Diatom assemblages in the annually laminated sediments of two neighboring, pre-alpine lakes (Ammersee and Starnberger See, Southern Germany) were analyzed and compared year by year. Within both varve records of the last decades, the same 4-phase-succession of planktonic diatom species is preserved, consisting of 1. a dominance of *Cyclotella* species 2. assemblages of *Fragilaria crotonensis*, *Asterionella formosa* and *Stephanodiscus minutulus* 3. a mass bloom of *Aulacoseira islandica*, and 4. a dominance of *Stephanodiscus* species. This diatom sequence is considered as a model of a 'basic species sequence of eutrophication'. Time lags and differences in the duration of the phases between both lakes show evidence of an earlier start for nutrient loading in Starnberger See than in Ammersee, and a faster development to a higher trophic state level in the latter. The different reactions of the lakes are attributed to hydrological differences such as the existence or lack of a major tributary, the size of the catchment area, and the water residence time. The reconstruction of the eutrophication dynamics appears to be reliably hindcast by the inference of total phosphorus (TP) concentrations using weighted averaging regression and calibration techniques. Remarkable differences in the occurrence of some diatoms in both stratigraphies, which are not related to the general changes of the 'basic species sequence of eutrophication' model, may be due to the epilimnetic silica content (e.g. *Fragilaria crotonensis*) or competitive weaknesses (e.g. *Tabellaria flocculosa*).

Introduction

Paleolimnological interpretations of aquatic microorganisms preserved in annually laminated lake sediments have provided powerful data for reconstructing past lake changes (Simola et al., 1990; Zeeb et al., 1994; Bennion et al., 1995; Lotter et al., 1998). Changes in paleoindicator assemblages reflect the response of biota to natural climatic variability (Schmidt et al., 1990; Anderson et al., 1996) and direct anthropogenic impact (Klee & Schmidt, 1987; Cumming et al., 1994). In sedimentary records of non-remote lakes eutrophication (and reoligotrophication) of the last decades entails the majority of shifts in the phytoplankton community, and can obscure any climatic signal (Anderson et al., 1990, 1996; Liukkonen et al., 1993). But there lies a problem: continuous monitoring of lake water quality usually first starts, when pollution and signs of eutrophication become apparent. There fore, only the periods of recovery are well documented by limnological measurements. In the case that varves are preserved in lake sediments, high-resolution analyses on an annual time-scale are then the ideal base to improve the knowledge about the onset and early dynamics of eutrophication (Alefs et al., 1996a; Lotter,

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1998). Additionally, the precise dating of the sedimentary record with varves allows one to investigate the relationship between preserved bioindicator assemblages and measured environmental variables year-by-year.

Ammersee and Starnberger See, two neighboring pre-alpine lakes comparable in size, differ strongly with respect to their catchment and their water residence time (Grimminger, 1982). The increased nutrient loading in the last decades is accompanied in both lakes by the formation of diatom-rich varves in the profundal sediments (Alefs, 1997). The lakes, therefore, are promising sites for a paleolimnological investigation with the following aims:

1. reconstruction of the eutrophication histories by examining the sedimentary diatom assemblages with an annual resolution.
2. insights into the influence of hydrologic parameters on the eutrophication dynamics by an inter-lake varve-by-varve comparison of the diatom stratigraphies.
3. separation of the role of environmental variables such as TP, silica and resource competition on diatom assemblages by interpreting intraspecific differences of occurrence in both records.
4. testing, if the diatom-inferred TP concentrations support the reconstructed eutrophication scenarios.

Sites

Ammersee and Starnberger See are two neighboring pre-alpine hardwater lakes near Munich, Germany, with a surface area of 4.660 ha and 5.636 ha and a maximum water depth of 81.1 and 127.8 m, respectively. In Table 1 the main hydrologic parameters of both lakes are listed according to Grimminger (1982). The main differences in the hydrologic situation of both lakes are the existence of the strong tributary Ammer, a large catchment and a short residence time of 2.7 yrs for Ammersee and the lack of a main inflow, a small drainage basin and a long water renewal time of 21 yrs for Starnberger See. Both lakes have experienced pronounced eutrophication and – due to lake restoration programs – subsequent reoligotrophication during this century. Around Ammersee a sewage collecting and disposal system was installed in 1971, and around Starnberger See in 1976. In the 1980s the sewage treatment plants at the tributary Ammer started to eliminate phosphate, and lower limits of phosphorus concentrations in detergents were fixed by law. Continuous monitoring of lake water quality started in the 1970s (Steinberg, 1978; Lenhart & Steinberg, 1982; Lenhart, 1987) and showed a decrease in the phosphorus loading for both lakes (Lenhart & Steinberg, 1986; Henschel et al., 1992).

Table 1. Hydrologic parameters of Ammersee and Starnberger See after Grimminger (1982)

Hydrologic parameter	Ammersee	Starnberger See
Mean water level:	533 m a.s.l.	584 m a.s.l.
Surface area:	46.6 km^2	56.4 km^2
Volume:	$1.750 \times 10^6 m^3$	$2.999 \times 10^6 m^3$
Maximum water depth:	81.1 m	127.8 m
Mean water depth:	37.6 m	53.2 m
Length:	16.2 km	20.2 km
Mean width:	2.9 km	2.8 km
Catchment:	993 km^2	315 km^2
Water residence time:	2.7 yrs	21 yrs
Mixis:	mono/dimictic	mono/dimictic

Materials and methods

Two gravity cores (Meischner & Rumohr, 1974) from the profundal areas of Ammersee (81 m water depth) and Starnberger See (120 m water depth) were recovered in 1993 and 1994. Both cores were cut longitudinally. From one half of each core a series of overlapping thin sections was prepared for microscopically determination of the annual character of the laminations and of the varve boundaries. These boundaries were transferred to the respective second half of each core, giving the sample intervals for diatom slide preparation according to the techniques described by Klee & Steinberg (1987). Five hundred to 600 diatom valves were counted per slide with a magnification of 1000× using phase contrast optics. The diatom taxonomy generally follows Krammer & Lange-Bertalot (1991) and Klee & Steinberg (1987). Due to separation problems of the very thin varves of 1959/60, 1962–66, and 1973/74 in the sediments of Starnberger See, mixed samples were taken of these three periods. These periods, therefore, show constant values in the diatom stratigraphic plots (Figures 2 and 3).

‘WACALIB 2. 1’ (Line & Birks, 1990) was used to infer past total phosphorus (TP) concentrations based on 17 planktonic diatom species (Figure 1) and 16 measured, epilimnetic TP concentrations in Ammersee, and 13 planktonic diatom species (Figure 2) and

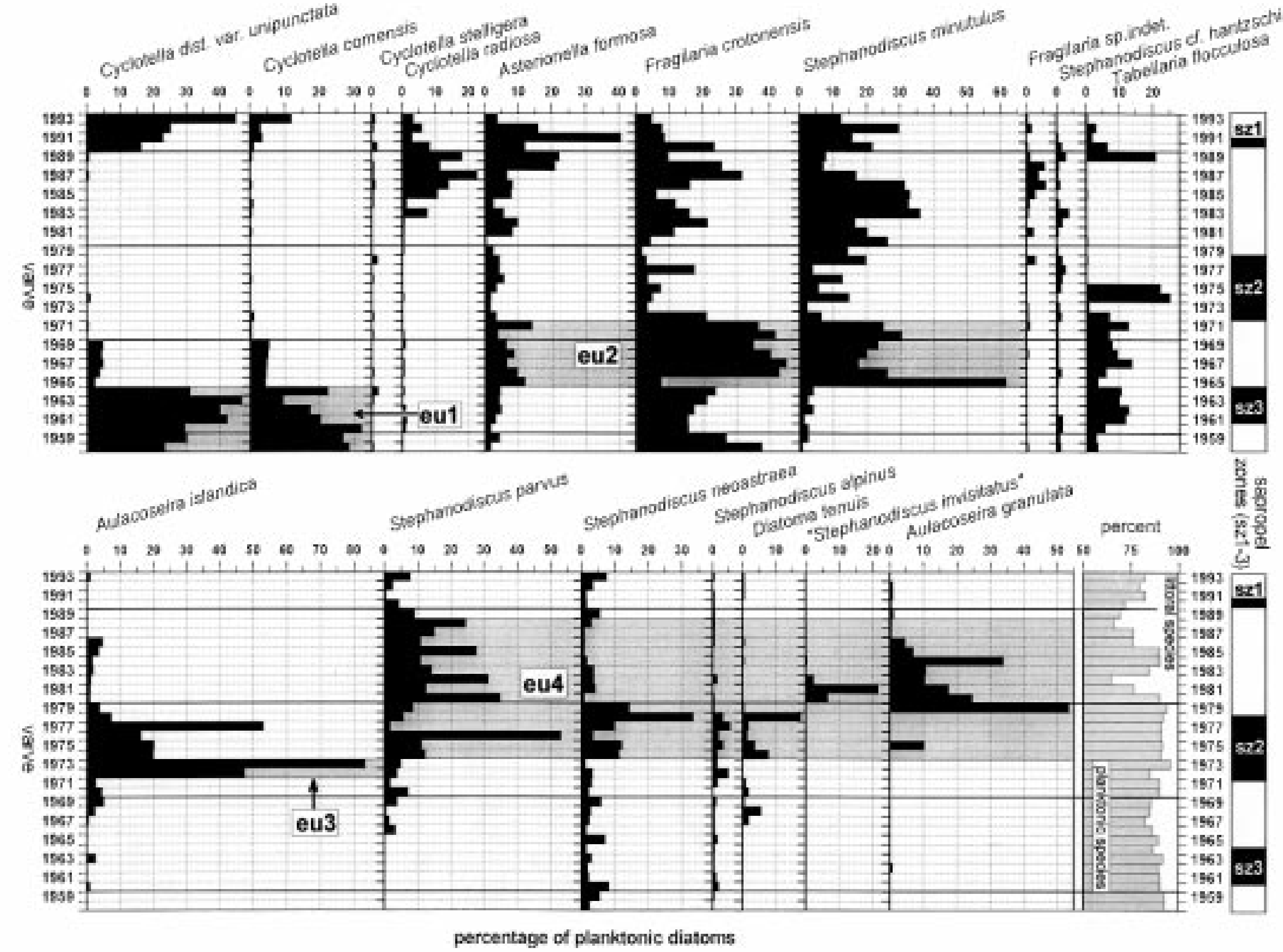

Figure 1. Relative frequency of planktonic diatoms in the varves of Ammersee (expressed as percentage of total planktonic diatoms) and the relative frequency of planktonic and littoral diatom species. Shaded zones 'eu 1' to 'eu 4' represent the four phases of the 'basic species sequence of eutrophication' model (see text). On the right side, three varve periods with sapropel formation are marked (sz 1 to sz 3).

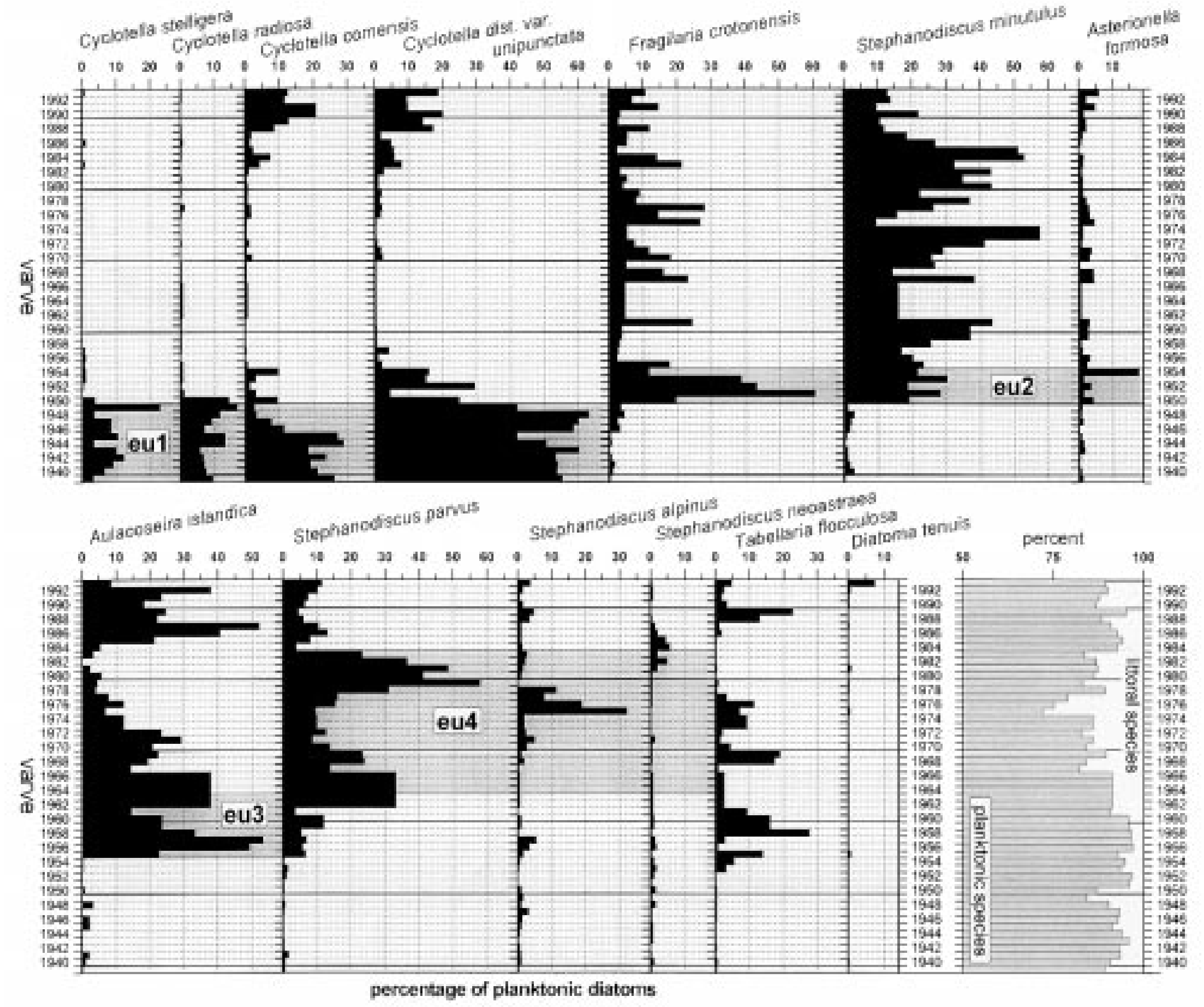

Figure 2. Relative frequency of planktonic diatoms in the varves of Starnberger See (expressed as percentage of total planktonic diatoms) and the relative frequency of planktonic and littoral diatom species. Shaded zones ‘eu 1’ to ‘eu 4’ represent the four phases of the ‘basic species sequence of eutrophication’ model (see text).

13 measured TP concentrations in Starnberger See. All these species reached at least once an abundance of over 1% in the calibration samples (years with a measured TP value). Littoral species are excluded from the inference model, because they are redeposited at the core sites and can be eroded from older sediments. The measured annual mean TP concentrations are calculated from monthly values provided from the Wasserwirtschaftsamt Weilheim (WWA Weilheim) and the Bayerische Landesamt für Wasserwirtschaft in Munich (BLW Munich). In Ammersee four to six months are measured in 1980–1983, and eight to twelve months in 1976, 1977 and in 1984–1993. In Starnberger See twelve values per year exist for 1978 and 1979, and six data for 1983–1993. The range of the monthly epilimnetic TP concentrations is 7–80 $\mu g \cdot l^{-1}$ in Ammersee, and about 5–50 $\mu g \cdot l^{-1}$ – with one very unusual high value of 83 $\mu g \cdot l^{-1}$ – in Starnberger See. All TP values used in the inference model are not log-transformed. The correlation coefficient (r) between observed and inferred TP is 0.91 in Ammersee, and 0.77 in Starnberger See. The root mean square error of prediction (RMSE) is 4.1 in Ammersee, and 4.5 in Starnberger See.

The Bayerische Landesamt für Wasserwirtschaft in Munich and the Wasserwirtschaftsamt Weilheim kindly provided the measured TP and silica data.

Results

Dating

The uppermost, partly sapropelic 20 cm of the profundal sediments of both lakes exhibit a light-dark lamination in the range of millimeters. We could prove the annual cyclicity of the diatom rich lamination in thin sections by the seasonal succession of diatom species, by coarse and fine grained calcite layers representing calcite precipitation in spring and summer, and by redeposition of coarse biogenic and minerogenic detritus from the littoral during turnover periods (Alefs, 1997). This fabric is very similar to that found in other lake sediments (e.g. Geyh et al., 1971; Lotter, 1989; Zolitschika, 1989; Lotter et al., 1997). To establish an absolute varve chronology, we compared the sedimentary record with sediment trap data, observed phytoplankton blooms in the water column, flood events, radioisotopic dating (^{137}Cs), and years with mass production and release of bisaccate pollen grains (Alefs, 1997). In Ammersee the sequence of varves comprises the years 1958–1993; in Starnberger See 1939–1993.

Diatom stratigraphy of Ammersee (Figure 1)

Mainly 17 planktonic species compose the diatom stratigraphy of Ammersee (Figure 1), with a roughly symmetric arrangement of their percentages around an imaginary axis in the mid to late 1970s. Obvious changes in the assemblages until the 1980s, often occurring from one varve to the following, allow a structuring of the diatom record into four phases ('eu 1' to 'eu 4' in Figure 1). Dominance of *Cyclotella* species, mainly *Cyclotella distinguenda* var. *unipunctata* (Hustedt) Håkansson & Carter and *Cyclotella comensis* Grunow until 1964, accompanied by considerable cell numbers of *Fragilaria crotonensis* Kitton and *Tabellaria flocculosa* (Roth) Kützing, characterize the lowermost phase 'eu 1'. After a drastic decline in the *Cyclotella* population in 1965, *Asterionella formosa* Hassall, *F. crotonensis* and *Stephanodiscus minutulus* (Kützing) Cleve & Möller dominated the diatom plankton until 1971 (= phase 'eu 2'). The sudden mass bloom of *Aulacoseira islandica* (O. Müller) Simonsen, preserved in the 1972 varve marks the beginning of the phase 'eu 3', which only lasted two years. The ex–pansion of the genus *Stephanodiscus* with *S. parvus* Stoermer & Håkansson, *S. neoastraea* Håkansson & Hickel and '*S. invisitatus'* (see taxonomic remarks in Alefs et al., 1996a) and the presence of *Aulacoseira granulata* (Ehrenberg) Simonsen characterize phase 'eu 4', contained in varves 1974–1988. Since the 1980s, we found the opposite development in species abundance, but with smooth transitions instead of abrupt breaks, considering the high percentages of *S. minutulus, F. crotonensis* and *A. formosa* in the mid to late 1980s, and the final resurgence of *C. comensis* and *C. distinguenda* var. *unipunctata* in the 1990s.

The percentage of benthic diatom species, redeposited from the littoral zone, varies between 4 and 35% (Figure 1), with the lowest values during periods of sapropel formation , i.e. 1961–1964 and 1972–1978.

Diatom stratigraphy of Starnberger See (Figure 2)

The varves of Starnberger See contain almost the same planktonic diatom species spectrum as Ammersee, and a very similar sequence of assemblages substituting one another (Figure 2). The same four phases ('eu 1' to 'eu 4') can be found. A distinct break from

1949–1950 ended the dominance of *Cyclotella* species (= phase 'eu 1'), which existed since the onset of varve preservation in 1939. During this phase, *C. distinguenda* var. *unipunctata* dominated by far over *C. comensis, Cyclotella radiosa* (Grunow) Lemmermann and *Cyclotella stelligera* Cleve & Grunow. Between 1950 and 1954, most of the diatoms present belong to *F. crotonensis, S. minutulus* and *A. formosa* (= phase 'eu 2'). The sudden appearance of *A. islandica* in 1955 (= phase 'eu 3'), together with the maximum abundance of *T. flocculosa,* caused the next abrupt change in the stratigraphy. High percentages of *S. parvus, Stephanodiscus alpinus* Hustedt and *S. minutulus* between 1964 (exact dating according to the thin section) and 1983 are typical for phase 'eu 4'. *A. granulata,* which was very abundant in Ammersee, is missing in the Starnberger See record. Phase 'eu 4' is the last unit before the recolonization of Starnberger See by *C. distinguenda* var. *unipunctata* and *C. comensis.* In contrast to Ammersee, this phase is here accompanied by a second mass development of *A. islandica.*

The percentage of benthic diatoms oscillates between 3 and 28% (Figure 2).

Year-by-year comparison (Figure 3)

The inter-lake varve-by-varve comparison of every diatom species in Figure 3 clearly illustrates time differences between the two lakes with respect to the beginning and the duration of the above described 4-phase-succession ('eu 1' to 'eu 4'). The step from phase 'eu 1' (dominance of *Cyclotella)* to 'eu 2' (dominance of *S. minutulus, F. crotonensis* and *A. formosa)* and the beginning of phase 'eu 3' (sudden massbloom of *A. islandica)* took place 15–17 yrs earlier in Starnberger See than in Ammersee. It is interesting that even the formation of organic varves – a result of enhanced sedimentation and decomposition of organic material – started 19 yrs earlier in Starnberger See (1939) than in Ammersee (1958). With phase 'eu 3' the development accelerates in Ammersee indicated by the following three points:

1. a continuous decrease of *A. islandica* within only 8 yrs in this lake against 27 yrs in Starnberger See,
2. a shorter time lag of 10 yrs at the beginning of phase 'eu 4' (dominance of *Stephanodiscus* species)
3. a shorter interval (7 yrs earlier in STA) with regard to the reoccurrence of the *Cyclotella* species in the respective sedimentary record.

However, other species:

a) show completely different patterns of occurrence in both lakes *(Diatoma tenuis* Agardh, *C. radiosa*);
b) exhibit time congruent appearances, maxima and declines (*T. flocculosa)*; and
c) are restricted in their occurrence to only one lake (*A. granulata*, *C. stelligera*, '*S. invisitatus*').

D. tenuis (Figure 3) was present up to 20% abundance in the Ammersee varves between 1967 and 1978. In Starnberger See only varve 1993 contained a noticeable number of cells. *C. radiosa* (Figure 3) is restricted to the lowermost section ('eu 1') in Starnberger See, and in Ammersee to the sediment dated to 1983 onwards.

A very similar distribution is characteristic for *T. flocculosa,* with a simultaneous maximum (1989) and a congruent gap from the late 1970s to the second half of the 1980s (Figure 3), and which also lacks the generally observed 15–17 year time shift in its first occurrence in the sediments.

A. granulata (Figure 3) is the species with the most evident restriction to only one record (Ammersee) with its high values of over 50% in 1979 and over 30% in 1984. In the Starnberger See core, not a single cell was found. Instead, *C. stelligera* is one of the members of the *Cyclotella* dominated phase 'eu 1' in this lake, but never reached considerable abundances in Ammersee.

Another remarkable difference in the distribution pattern is that of *F. crotonensis* (Figures 1, 2 and 3): in Ammersee it reached values between 15 and over 20% in phase 'eu 1', but was nearly absent in the same stage of Starnberger See.

Discussion

Changes in fossil and recent diatom assemblages are normally interpreted as responses to shifts in nutrient supply (Klee & Schmidt, 1987; Liukkonen et al., 1993), pH-conditions (Birks et al., 1990), salinity (Juggins et al., 1994) and resource competition (Sommer, 1994; Kilham et al., 1996) and – especially in longtime records reaching back to the 'pristine' time before human impact – climate variability (Schmidt et al., 1990; Anderson et al., 1996). For diatoms, phosphorus, silica and the Si:P ratio are the most influential nutrients (Sommer, 1994). With the varve-by-varve comparison of the diatom stratigraphies of Ammersee

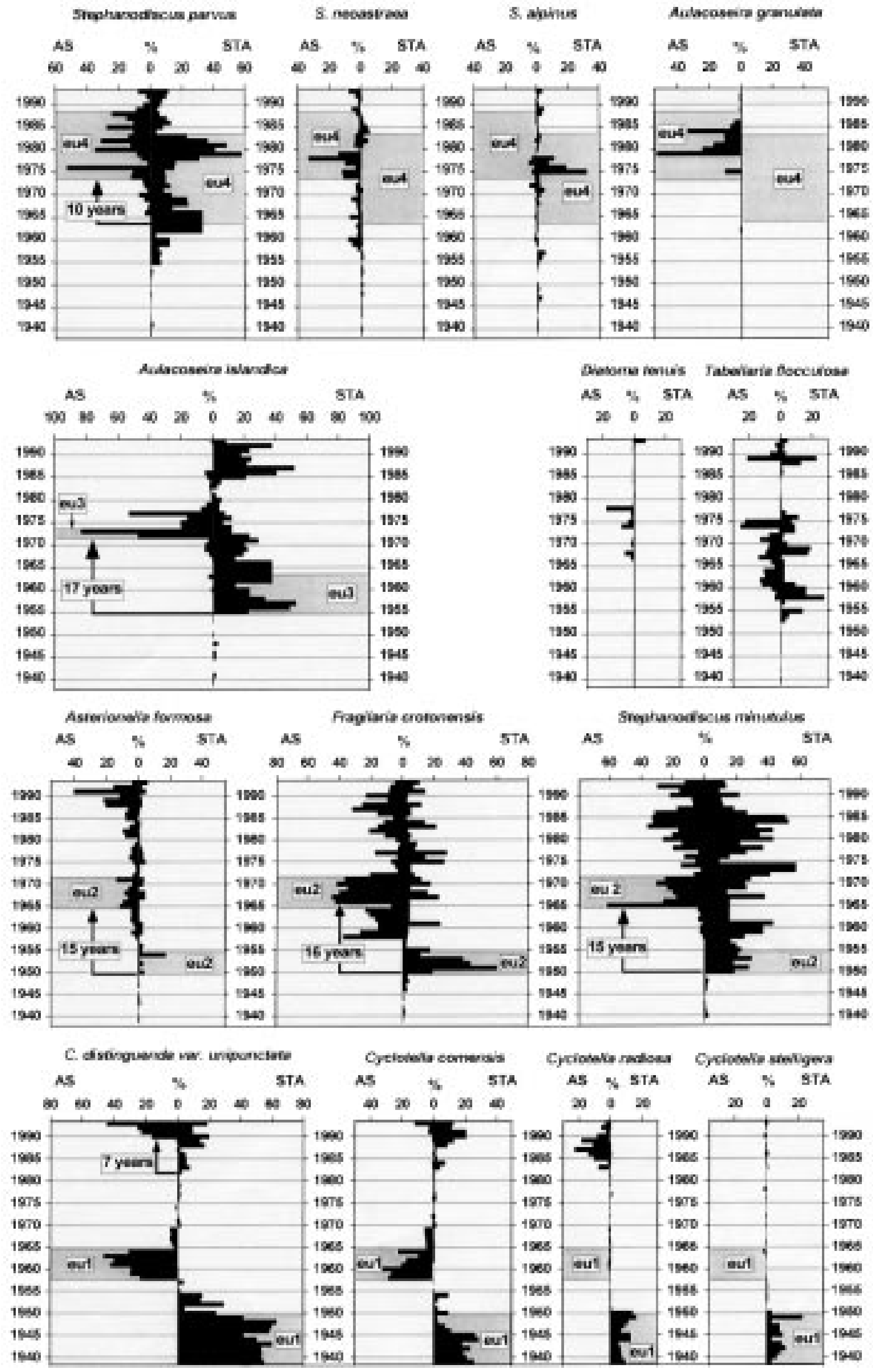

Figure 3. Inter-lake varve-by-varve comparison of the diatom stratigraphies of Ammersee (‘AS’) and Starnberger See (‘STA’). On the left side of each diagram the percentage of one diatom species in the varves of Ammersee, on the right side the percentage of the same species in the varves of Starnberger See is plotted. The shaded zones ‘eu 1’ to ‘eu 4’ representing the varves with the same basic assemblage of planktonic diatom species in both lakes show distinct time lags between the lakes.

and Starnberger See, we are somewhat able to separate the various effects on the diatom successions.

Since climatic effects, which would have affected both neighboring lakes in the same years, cannot be responsible for the qualitatively equivalent, but non-simultaneous, changes in the diatom assemblages preserved in both varve sequences, these observed main shifts can most likely be related to nutrient enrichment. Acidification is impossible in these well buffered hardwater lakes. As in many other lakes, phosphorus is the limiting nutrient and thus is controlling eutrophication in Ammersee and Starnberger See (Steinberg, 1978; Lenhart & Steinberg, 1982). We, therefore, consider the above described 4-step species sequence, which both lakes have in common, to reflect the increasing phosphorus supply. We refer to it as '*basic species sequence of eutrophication*' model. The intraspecific differences modifying this framework are related either to the different silica concentrations between the respective epilimnia or to the competition between species.

Basic species sequence of eutrophication

The 'basic species sequence of eutrophication' is characterized by the following four units, named 'eu 1' to 'eu 4' in Figure 3:

1. dominance of *Cyclotella* species ('eu 1')
2. assemblage of *Stephanodiscus minutulus, Fragilaria crotonensis* and *Asterionella formosa* ('eu 2')
3. sudden mass bloom of *Aulacoseira islandica* ('eu 3')
4. dominance of *Stephanodiscus* species, mainly *Stephanodiscus parvus* ('eu 4')

The genus *Cyclotella* is indicative of oligo- to slightly eutrophic conditions in the alpine and pre-alpine region (Wunsam et al., 1995), and is normally replaced by *Stephanodiscus,* which is 'the most faithful indicator of high productivity associated with culturally enriched lakes' (Battarbee, 1986), during eutrophication. Vice versa, the resurgence of *Cyclotella* at the expense of *Stephanodiscus* in the surface sediments parallels the reduction of nutrient loading (Alefs et al, 1996a). However, Stoermer (1993) emphasizes that the occurrence and abundance of the oligotrophic *Cyclotella*-association is, to a certain degree, governed by its strong adaptation to a subthermocline habitat. This habitat can be 'shaded out' in eutrophic but silica-limited lakes by the expansion of chlorophyte and cyanophyte populations in the epilimnion (Moll & Stoermer, 1982).

In Ammersee, the phase 'eu 2' seemed to precede the return of *Cyclotella,* leading to a highly symmetric diatom stratigraphy. The arrangement of the species in Figure 1, from the left side in the upper line to the right side in the lower line, therefore, tracks the observed eutrophic conditions in the 1970s. This is demonstrated by the advance of the percentage peaks symmetrically towards this period: *Cyclotella* was completely lacking during this timespan; *A. formosa, F. crotonensis* and *S. minutulus* dominated in the mesotrophic stage; and all species on the second line were fostered by higher nutrient levels (Alefs et al., 1996a). In Lough Augher (Northern Ireland), *A. formosa* and *F. crotonensis* are part of the mesotrophic diatom plankton (Anderson et al., 1990). In the comparison of the two separated basins of the lake Vesijärvi (Finland), a very small *Stephanodiscus* species (perhaps *S. parvus?)* was the dominant diatom in the more productive basin, together with *A. islandica, F. crotonensis* and *A. formosa.* In contrast, in the basin of lower trophic conditions *Stephanodiscus* was missing, *Cyclotella* was present and *F. crotonensis* prevailed (Liukkonen et al., 1993).

The basic species sequence of eutrophication reported here is in good agreement with the diatom records of other lakes in the alpine region, as for instance Chiemsee (Schaumburg, 1992), Zürichsee (Nipkow, 1927), Baldeggersee (Lotter, 1998) and Lake Constance (Mohaupt, 1994). The most striking differences between the diatom stratigraphies of the listed lakes are always related to *A. islandica* (phase 'eu 3'), which is completely missing in some records. In Chiemsee (Germany), *Cyclotella* dominates in deeper sediment sections, followed by a mass bloom and subsequent continuous decrease in *A. islandica.* Unfortunately, *F. crotonensis* and *A. formosa* were ignored in the analysis. A difference is the rapid increase of *Aulacoseira subarctica* (O. Müller) Haworth to a relative frequency of over 90% after 1986. This taxon is missing in both Ammersee and Starnberger See. The *Cyclotella* dominance in Zürichsee (Switzerland) is not as obvious as in the other lakes, but the diatom spectrum is enlarged by a series of 'invasions', beginning with *F. crotonensis, T. fenestrata, A. islandica* and ending with *S. hantzschii*. In Baldeggersee (Switzerland), a *Cyclotella*-dominated phase is followed by an assemblage of *F. crotonensis*, *A. formosa*, *T. fenestrata* and – some years later – *S. minutulus*. The final step of eutrophication is marked by *S. parvus* and *A. granulata* (Lotter, 1998). The phase with *A. islandica* (= 'eu 3') could not be found. In Lake Constance (Germany), the *Cyclotella*-phase is terminated by the increase in *F. crotonensis* and *T. fenestrata* (= *T. flocculosa*), followed by *S. minutulus*, *S. neoastraea* and finally *A. granulata*. *A. islandica* is also missing in this sequence. *T. flocculosa* shows a similarly unsteady and discontinuous appearance like in Ammersee and Starnberger See (see below).

Intraspecific differences

Diatom species of the family 'Fragilariaceae' such as *F. crotonensis*, *T. flocculosa*, *A. formosa* and *D. tenuis*, are reported to be strong competitors for nutrients if Si:P ratios are high (Sommer 1994: 150). The observation that *F. crotonensis* is a substantial component besides *Cyclotella* in phase 'eu 1' in Ammersee, but not in Starnberger See (Figures 1 and 2), may be explained by the higher supply of dissolved silica due to the allochthonous input by the river Ammer. The comparison of the measured epilimnetic silica concentrations between both lakes (Figure 4) indicate, that values were similarly low (< 1.5 mg·l^{-1}) only during the eutrophic period in the 1970s, due to the high consumption by mass diatom blooms. With decreasing trophic state level in the 1980s and 1990s, the concentrations remained low in Starnberger See, but rose constantly in Ammersee up to 3.5 mg·l^{-1} in spring. Extrapolating this situation to the pre-eutrophic state 'eu 1', we have to assume also higher silica concentrations in Ammersee in this time. Higher silica availability may also be the reason for the 'too early' occurrence of *T. flocculosa* in the Ammersee record (Figure 3), considering a lag of 15–17 yrs between both lakes as standard. Finally, the overall higher percentages of *A. formosa* and *D. tenuis* in Ammersee throughout the varve sequences may result from the same effect (Alefs, 1997).

That implies that in lakes with a considerable silica supply, *F. crotonensis* and *T. flocculosa* may react immediately and earlier to rising phosphorus loading with an increase in population size, than under poor silica conditions. The observation that *F. crotonensis* precedes *T. flocculosa* in the course of eutrophication has also been reported from Zürichsee (Nipkow, 1927), Lake Constance (Mohaupt, 1994), Mondsee (Klee & Schmidt, 1987) and Baldeggersee (Nipkow, 1927, Lotter, 1998), regarding *T. fenestrata* and *T. flocculosa* as conspecific. This may be explained by the observation made in culture experiments by Tilman & Sterner (1984): *T. fenestrata is* not able to invade an established population of *F. crotonensis,* when both have to compete for phosphate. Nevertheless, an increase in *T. flocculosa* during a time of high *F. crotonensis* frequencies is preserved in the sedimentary records of Ammersee and Starnberger See. Therefore, one may conclude that since then the competition for phosphorus ended, because phosphorus is available in excess. Anderson et al. (1995) assumed that *T. flocculosa* loses its competitive ability with continuous enrichment and is, therefore, subjected to *A. formosa* in Lake Kassjön (Sweden). Another indication to the weakness of *T. flocculosa* in highly competitive situations is its gap in the varves 1976–1988 of Ammersee (Figure 1). This gap is congruent with the occurrence of *A. granulata,* a species of the late summer and autumn plankton, like *T. flocculosa.* This same phenomenon can be seen in the Baldeggersee record (Lotter, 1998).

The difference in the distribution pattern of *C. radiosa* between Ammersee and Starnberger See is presumably due to comparing two morphologically similar but ecologically different species. *C. radiosa* in Ammersee may be *Cyclotella praetermissa* Lund, *Cyclotella quadrijuncta* (Schröter) von Keissler, or *Cyclotella bodanica* Grunow (pers. commun. Wunsam). A detailed SEM investigation is in preparation.

Reconstruction of eutrophication dynamics

By comparing the dates of the significant changes in the basic species sequence of eutrophication, we can reconstruct the different eutrophication dynamics of both lakes and relate them to the main hydrologic differences, such as existence of a tributary, size of the catchment and length of retention time (Table 1).

The first signs of eutrophication, like varve preservation, and the decline in the genus *Cyclotella*, are archived 15–19 yrs earlier in the sediments of Starnberger See than in Ammersee. Limnological measurements in both lakes in the beginning of the 1940s by Gessner (1944) and in the 1950s by Wachter (1959) support this view, because lower chlorophyll concentrations, a threefold higher secchi depth, and less oxygen oversaturation in the epilimnion of Ammersee indicate lower phytoplankton production in this lake compared to Starnberger See. The immediate bordering area was undoubtedly responsible for the start of nutrient enrichment. Starnberger See is nearer to Munich and the stronger anthropogenic activity in its

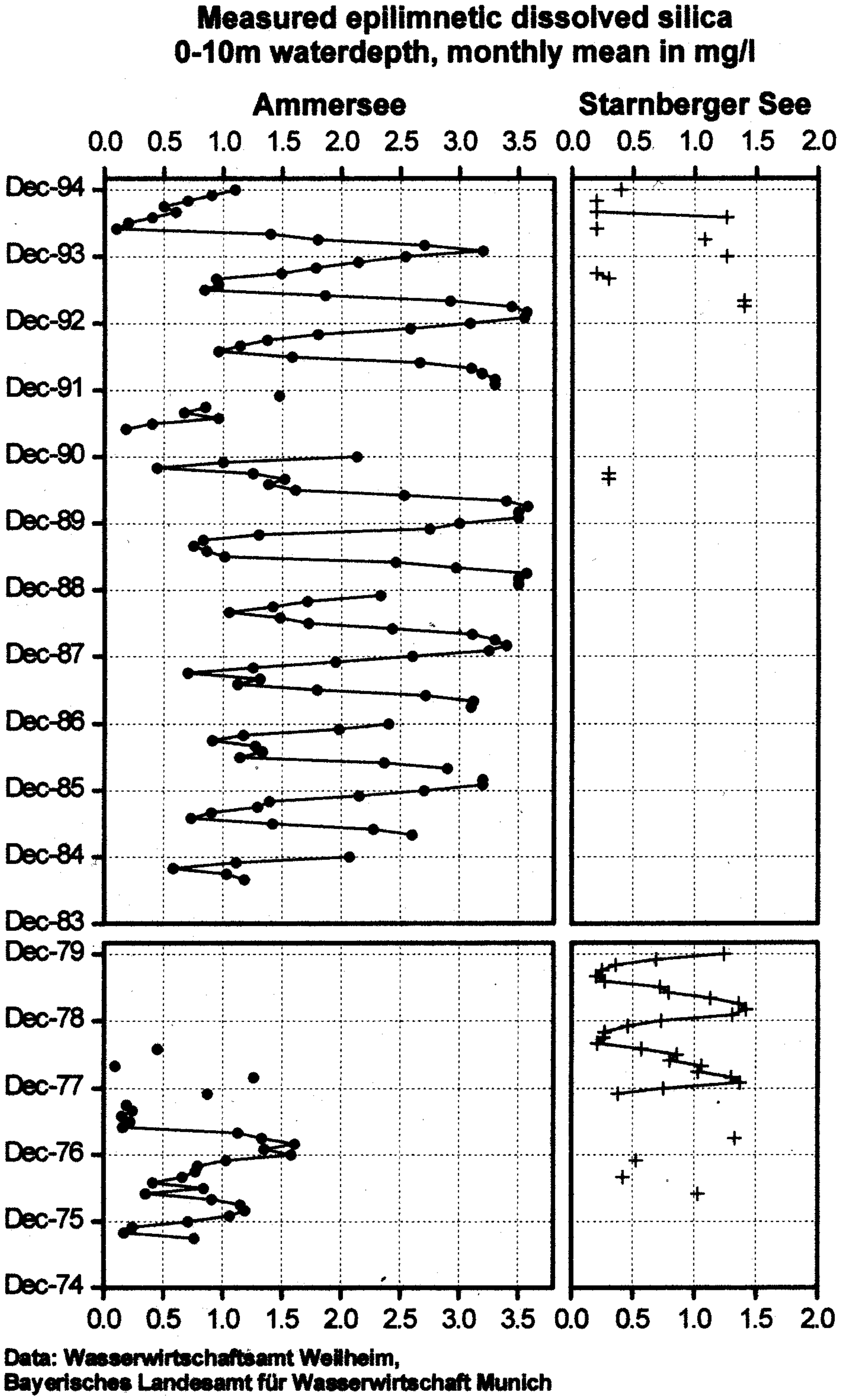

Figure 4. Measured concentrations of dissolved silica in the epilimnion of Ammersee and Starnberger See provided by the WWA Weilheim and the BLW Munich. The values represent monthly means of the 0–10 m water depth concentrations.

drainage basin resulted in more pollution. Additionally, there was also a higher possibility of waste water accumulation due to less inflow and a consequently high water residence time of 21 yrs. The inflow of relatively uncontaminated water through the river Ammer to Ammersee at this time, as well as its high water exchange capacity (residence time: 2.7 yrs), lessened the eutrophication influence of the nearby region.

In the 1970s the 'flushing effect' of the river Ammer ceased, and the increasing nutrients gathered from the large catchment area then caused the accelerated eutrophication and the higher trophic state level in Ammersee (phase 'eu 3' lasted only for 2 yrs in AS against 9 yrs in STA). *A. granulata,* which is reported to be an indicator for nutrient-rich environments (Klee & Steinberg, 1987; Krammer & Lange-Bertalot, 1991; Van Dam et al., 1994), occurs only in the varves of Ammersee and not in Starnberger See. Therefore, at Starnberger See, the installation of a sewage collection and disposal system proved to be effective in restoration, whereas at Ammersee the reoligotrophication was mainly induced in the 1980s by elimination of phosphate in the sewage treatment plants at the tributary Ammer and the stepwise reduction of phosphates in detergents (Lenhart & Steinberg, 1986). This

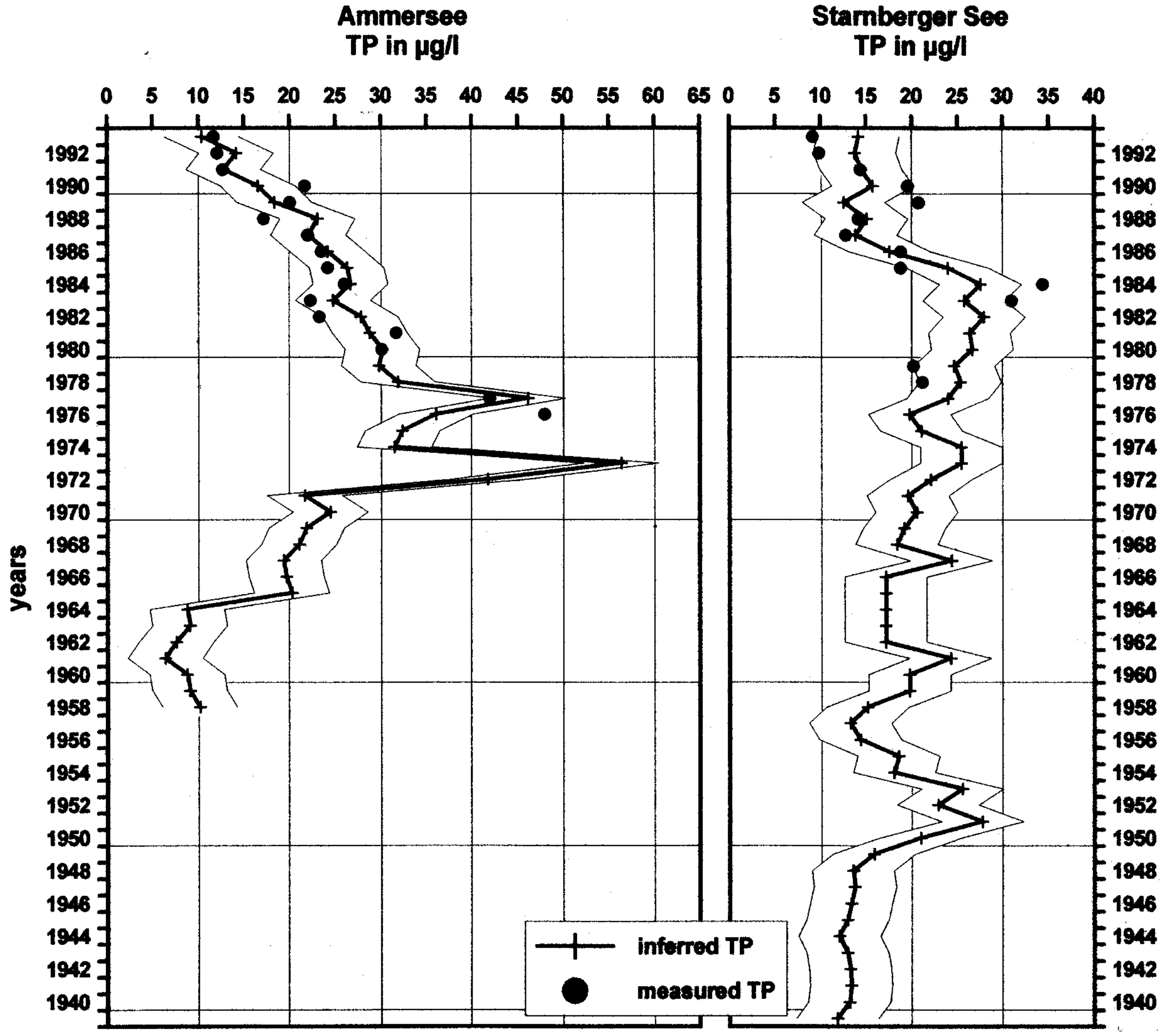

Figure 5. Diatom-inferred TP concentrations (WA-value, inverse regression) of Ammersee and Starnberger See with the respective error of prediction interval. Measured annual means of epilimnetic TP concentrations are plotted as dots. The correlation coefficient between measured and inferred TP is 0.91 in Ammersee and 0.77 in Starnberger See.

development coincides with the termination of heavy black sapropel formation (Figure 1, right side, sz 2, and Alefs et al., 1996a).

Inferred epilimnetic TP concentrations

The above scenario of eutrophication and reoligotrophication in Ammersee and Starnberger See appears to be accurately reconstructed by the curves of diatom-inferred epilimnetic TP concentrations (Figure 5). In Starnberger See, the first rise of inferred TP from around 13 $\mu g \cdot l^{-1}$ to over 25 $\mu g \cdot l^{-1}$ occurs in 1950, and the corresponding rise in Ammersee from under 10 $\mu g \cdot l^{-1}$ to 20 $\mu g \cdot l^{-1}$ is dated to 1964/65. Whereas in Starnberger See the inferred TP concentration then always remains under 30 $\mu g \cdot l^{-1}$ and decreases after 1984, the TP values in Ammersee suddenly climb to a maximum of 56 $\mu g \cdot l^{-1}$ in 1973 and never fall under the 30 $\mu g \cdot l^{-1}$ level during the 1970s (Alefs, 1996b).

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