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IMPORTANCE OF INTERNAL NITROGEN RECYCLING ON WATER QUALITY AND CYANOBACTERIAL BIOMASS IN A SHALLOW POLYMICTIC LAKE (LAKE LANGER SEE, GERMANY)

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ABSTRACT

More than 70% of shallow lakes in Germany did not meet good ecological status according to the EU-Water Framework Direktive in 2015. Reasons for this are too high nutrient inputs and high efficiency of internal nutrient recycling and transformation into phytoplankton biomass. In our NITROLIMIT-project (nitrolimit.de) it has been proven that nitrogen is a crucial control variable for the majority of shallow lakes and its reduction is ecologically meaningful. This was checked by a balance approach in a polymictic eutrophic lake for nitrogen input (external inputs from surface inflow, atmospheric deposition and nitrogen fixation by nostocalaen cyanobacteria), output by surface outflow and internal turnover processes (primary production, release of ammonia from the sediment). Lake Langer See is part of a riverine system in lake chain of Scharmützelsee region (Brandenburg, Germany). It is a very shallow and eutrophic lake with theoretical water retention time of 30 days. Dominant nitrogen input is the surface inflow consisting more than 80% of organic nitrogen. During vegetation period, input of dissolved inorganic nitrogen (DIN) and lake concentration are very low and primary production is limited by availability of inorganic nitrogen. Despite of this low DIN concentration pelagic primary production is high and phytoplankton is dominated by cyanobacteria resulting in a poor ecological quality of the lake. We could prove that short cycling of nitrogen by ammonification in the pelagic water and in the surface sediment are the main drivers for the high intensity of phytoplankton primary production. An intensive short-term recycling of freshly settled detritus can compensate the relatively low external nitrogen inputs. Although N_2 fixation during late summer is low compared to sediment release of ammonia by ammonification, we suggest a relevant short-term competition for nostocalean cyanobacteria. N_2 fixation can contribute to stabilization of high level of phytoplankton primary production as an additional nitrogen input during summer. Management measures should include a reduction of organic nitrogen input rather than nitrate load reduction for these lake types. Moreover, possibilities of top down control should be complemented with top down mechanisms like macrophyte competition and grazing by zooplankton and mussels.

Keywords: shallow lakes, nitrogen, balance, phytoplankton, eutrophication, ammonification, management

1 INTRODUCTION

Aquatic ecosystems are important sinks for anthropogenic nitrogen inputs. Quantification of nitrogen elimination is given for estuaries, rivers, wetlands and groundwater but also for lakes (Seitzinger et al. 2006; Billen et al. 1986; Durand et al. 2011). N cycling in these systems is controlled by energy sources, redox conditions and trophic status because of nutrient loads. Durand et al. (2011) identified the residence time as the main factor differentiating N turnover rates in the different types of freshwater systems. The highest variability in residence time was found in standing waters (from days to decades) varying widely in space and time. This parameter is sensitive to changes in climate, land use and management.

Nitrogen elimination is influenced besides hydraulic parameters as water residence time by trophic conditions. This was described by Jensen et al. (1992) for Danish eutrophic shallow lakes and by Finlay et al. (2013) for lakes covering a wide trophic and morphometric range. According to Finlay et al. (2013), the absolute amount of nitrogen elimination is increasing across a trophic gradient with increasing nitrogen load and efficiency of nitrogen retention depending on water residence time. The authors mention the special relevance of phosphorous availability for nitrogen turnover and retention in lakes.

Eutrophic shallow lakes with low water residence time have a high potential for denitrification (Jensen et al. 1992). But, intensity of denitrification does not depend on in-lake nitrate concentration, rather on nitrogen loads and total nitrogen concentration (TN) in the lake and sediment turnover of nitrogen. High sedimentation of organic material resulted in high ammonification rates at the sediment. Consequently, an intensive coupling of nitrification of ammonia to nitrate and following denitrification of nitrate a high nitrogen elimination was observed.

According to Durand et al. (2011), an important part of nitrogen transferred by surface waters is in the form of organic N (dissolved organic N (DON) and particulate organic N (PON)). The spatial and temporal variations of the N forms, the processes controlling the transport and transformation of N within freshwaters, require further investigations of the role of nitrogen influencing ecological freshwater quality.

Lake Langer See in Brandenburg (Germany) has been investigated since 1993 to analyse the water quality development and to establish a detailed nitrogen balance. The lake is a typical example of common very shallow lakes in the ecoregion of German lowlands as a part of a riverine system with low water residence time. Phytoplankton growth during vegetation period is limited by nitrogen (Kolzau et al. 2014), which was identified to predominate in shallow polymictic and riverine lakes by statistical analyses (Dolman et al. 2016). Phytoplankton in these lakes is dominated by cyanobacteria (Rücker et al. 2016). Ecological water quality according to Water Framework Directive (EU - European Union, 2000) concerning phytoplankton is low (Mischke et al. 2016). The lake belongs to the water bodies with worst assessment for German lakes: more than 80% do not reach good ecological status (Rücker et al. 2015). Reasons for poor water quality are too high primary production (PP) and dominance of cyanobacteria at a high level of phytoplankton biomass. Therefore, improved knowledge about trophic metabolism and management measures are of special interest for management strategies.

We analysed nitrogen balance for the Lake Langer See from 2000 to 2015 based on monthly averages of input and output data. Loads and seasonal dynamics of total nitrogen as well as seasonal net export of nitrogen and nitrogen losses were quantified to focus on following aspects and questions:

- Seasonal changes of water residence time and ecological relevance for phytoplankton growth
- Input-output-balance approach for Lake Langer See – Sink or source for nitrogen?
- Which lake internal nitrogen turnover processes are relevant for lake water quality in Lake Langer See compared to the nitrogen input?

2 STUDY SITE AND METHODS

Lake Langer See is a polymictic very shallow lake (mean depth 2.1 m and maximum depth 3.8 m). Area is 1.3 km² and volume 2.84 Mio. m³. Catchment size is 392 km², mean daily discharge 1.13 $m^3 s^{-1}$ and water residence time 0.08 (0.06 – 0.12) years. A bathymetric map is given in Kleeberg et al. (2013). The lake belongs to lake type 11.2 according to the German lake classification system (very shallow hard water lake with relative high catchment area, Mischke et al. 2016). Although nutrient concentrations have been reduced by about 50 % the lake does not reach target values for good ecological status or TN concentration (now: 952 µg L^{-1}, target: 710 (520 – 880) µg TN L^{-1} and TP now: 63 µg L^{-1}, target: 41 (32 – 51) µg TP L^{-1} according to Dolman et al. 2016). Phytoplankton concentration during vegetation period is high (Chl a: 58-77 µg L^{-1}, biovolume 9.3 – 12.3 $mm^3 L^{-1}$ and Secchi depth between 0.6 and 0.8 m) resulting in poor water quality according to the assessment of phytoplankton (Mischke et al. 2016).

Nitrogen balance was estimated quantifying the main N input and output parameters from 2000 – 2015. Loads for different N-forms (total nitrogen (TN), nitrate + nitrite nitrogen = NOg-N, NH_4-N, DIN = NOg-N + NH_4-N, organic nitrogen Norg = TN - DIN) were calculated from monthly values of nitrogen concentrations of the surface input (data from: LUGV Brandenburg) which were multiplied with monthly averages of discharge. Daily discharges were estimated from area-specific discharge based on discharge rate at two points in the catchment of Lake Langer See (data from: WSA Berlin, LUGV Brandenburg) considering the area of the sub catchment. Nitrogen surface output was calculated in the same way using the monthly averages of lake nutrient concentration. Atmospheric deposition was estimated according to European model MAPESI (1300 mg $m^{-2} a^{-1}$, Builtjes et al. 2011). Nitrogen input by N_2 fixation was measured 2012 with C_2H_2 reduction method (Capone 1993; Hardy et al. 1968) and in 2013 and 2014 with $^{15}N_2$ stable isotope method (Montoya et al. 1996), respectively. Monthly nitrogen losses were quantified by the difference between N input and N output. Corrections were done according to Sas (1989) considering the changes of lake N-content analogue to calculation of the net sedimentation of phosphorous for lakes. Positive values of the calculated nitrogen losses mean that the lake functions as nitrogen sink, negative values indicate nitrogen source.

Release of ammonia from the sediment was measured as *in situ* nitrogen flux with benthic chamber (volume 39 L; area 0.126 m^2) during vegetation period between 2012 – 2015. Additionally, results of N-diffusion flux from 11 analyses with dialyses sampler were measured as flux enhancement. To calculate an *in situ* flux these values were multiplied by 4.2. Values for periods without measurements (November to February) were obtained by interpolation.

Phytoplankton primary production was estimated using Chl a - concentration and results of ^{14}C-measurements for the mixed water column according to Nixdorf et al. (2007). N-content of phytoplankton was calculated from C: Chla - relation of 30. Mass C/N-ratio of seston measured 2012 and 2013 using CHN-Analyser (Vario EL, Elementar) is relatively constant in our lakes and near Redfield ratio of six.

3 RESULTS AND DISCUSSION

3.1 Seasonal changes of water residence time and ecological relevance for phytoplankton

Lake Langer See is characterized as a lake with short water residence time: The discharge is high in relation to the lake volume, resulting in a mean hydraulic residence time of only 30.5 days (long-term annual mean 1994 – 2015). This value is at the boundary of 30 days which is used to differentiate between lake type 11.2 (very shallow lakes with mean depth < 3m) and type 12 (riverine lake) according to the German assessment system for WFD (see Mischke et al. 2016). Thereby, the lake belongs to the lake type with highest portion of moderate to bad lake water quality (Dolman et al. 2016) due to a low discharge in the vegetation period, and hydraulic residence time above 30 days (26.1 – 84.5 d, average 46.5 d; long-term annual mean 1994 – 2015). For calculations of nutrient budgets and matter turnover, it seems to be relevant which values for residence time are used. In Lake Langer See, this parameter is highly variable and is demonstrated in Figure 1 for the annual cycle of monthly averages between 2000 and 2014.

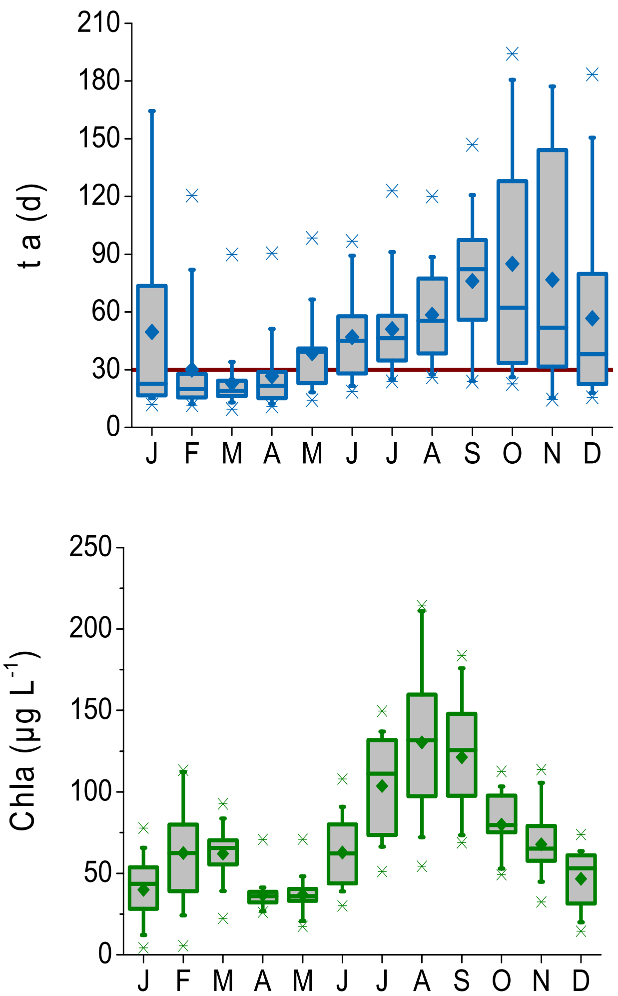

Figure 1. Water residence time in Lake Langer See as monthly average for the period 2000 to 2014 (top). Horizontal line indicates water residence time of 30 days, which is used for differentiation of riverine and very shallow lakes. Bottom: Chl a – concentration as monthly average for the same period (boxplots indicate medium and average values, 10 and 90% and 25 and 75% quantile and minimum and maximum)

During cold season and high discharges, the water residence time is mostly below 30 days from January to April. In this period, flushing can be assumed and the lake response on nutrient loading is rather comparable with a river or a riverine system. From June to October the lake has higher residence times than annual average of 30 days that was nearly doubled on average for this period. The increase is highly variable depending on discharge. For example, in 2002, a very wet year, water residence time did not exceed the summer average of 60 days. One year later, in 2003, a very dry year, followed with a period of 153 days when water residence time was larger than 60 days.

Phytoplankton biomass as Chl a – concentration is shown in Figure 1 (bottom). It becomes obvious that highest biomass occurred from July to September just in that period with highest water residence time. The phytoplankton biomass and portion of cyanobacteria are high and resulting in poor ecological quality, nevertheless, these values show a decreasing trend in the period investigated (Rücker et al. 2016). This change is also illustrated by a comparison of mean seasonal courses of the biomass of main phytoplankton groups. Cyanobacteria dominate the phytoplankton with 70 to 80% of total biomass. Among cyanobacteria, a drastic decline in *Planktothrix agardhii* after 2001 was striking. The biovolume of other fine filamentous cyanobacteria, such as *Pseudanabana spp., Planktolyngbya spp., Limnothrix spp.* and *Aphanizomenon gracile*, remained almost unchanged after 2001. Portion of Nostocales during the summer period (June to September) on total cyanobacterial biomass is between 13 and 33 % on monthly average. Whether Nostocales have competitive advantages due to their ability to fix atmospheric nitrogen is calculated in Chapter 3.3.

3.2 Lake Langer See – Sink or source for nitrogen? Input-output-balance approach

In Figure 2 the annual course of nitrogen load for Lake Langer See is shown for the period 2000 to 2014 (Boxplots of monthly averages): Maximum N-inputs are observed until March followed by a decreasing loading and a minimum during summer. In autumn, we measured an increasing areal N-loading. Dominant fraction of TN load is organic nitrogen, which is on annual average 70% of the total N-load in the inflow and more than 80% during vegetation period. This is a typical annual pattern for lake types in plankton dominated river – lakes - systems. The seasonal pattern of N-load is also reflected by the different components of N-concentration in the lake. Minimum in N-load and DIN-concentrations during summer lead to a distinct N-limitation especially in very shallow lakes (Kolzau et al. 2014; Dolman et al. 2016). Dynamics and seasonal patterns are explained by increased nutrient inputs during spring floods, efficient nutrient retention and elimination in upstream rivers and lakes in the riverine system of Lake Langer See during vegetation period.

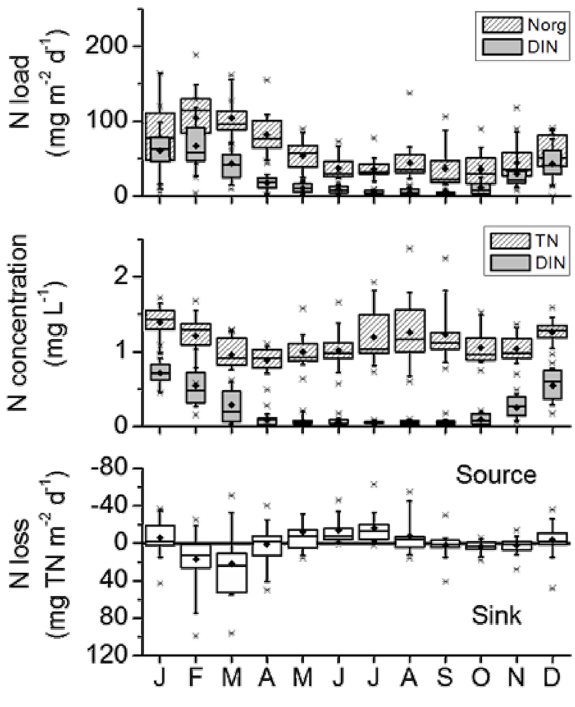

Figure 2. Annual course of load and in lake concentration of dissolved inorganic, organic and total nitrogen and losses of total nitrogen in Lake Langer See as monthly averages for the period 2000 to 2015

On average, in the period from 2000 - 2014 about 39 t a^{-1} TN were transported in Lake Langer See by the surface inflow. Maximum was measured in 2002 with 50 t a^{-1}, minimum in 2007 with 27 t a^{-1}. Portion of point sources by wastewater from the wastewater treatment plant was relatively low (10 %). Nitrogen is retained in the lake by a rate of 11 mg m^{-2} d^{-1} as a long-term average in the first quarter of the year (Figure 2). During summer the lake is a small nitrogen source, whereas during late summer and autumn net export of nitrogen is negligible because of high planktonic primary production. On a long-term average, no nitrogen will be retained in the lake.

3.3 Which nitrogen inputs and lake internal turnover processes are relevant for lake water quality in Lake Langer See?

The balance approach for Lake Langer See includes nitrogen input (external inputs from the catchment by surface inflow, atmospheric deposition and nitrogen fixation by nostocalean cyanobacteria), output by surface outflow and internal turnover processes (nitrogen demand of primary production, release of ammonia from the sediment). The following nitrogen turnover processes are not considered in the balance approach: production of laughing gas, anammox and ammonification of nitrate because of negligible quantitative importance (Nitrolimit I 2014). Denitrification seems to be a loss process of minor importance in the first quarter of the year but without relevance for the nitrogen budget of the lake from late spring to late autumn. The lake was characterized in Chapter 3.2 as a lake without relevant nitrogen elimination on long-term average. During vegetation period, nitrate and ammonia concentrations are considerably below the limitation level of 100 µg L^{-1} (Kolzau et al. 2014) indicating either low intensity of nitrification and denitrification or intensive coupling and compensating effects of these processes. Nitrification and denitrification and its coupling could not have quantified in this study and are therefore, marked in Figure 3 by question marks.

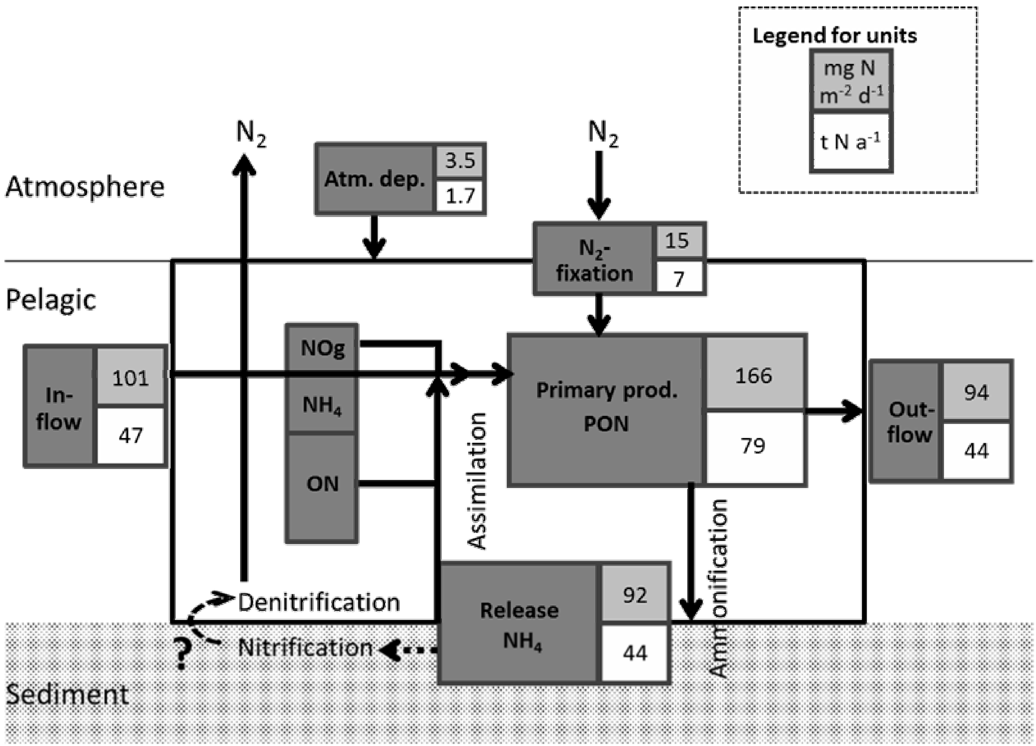

Figure 3. In- and output and relevant turnover processes for total nitrogen (TN) for Lake Langer See as daily rate per area (top: mg m^{-2} d^{-1}) and as annual loads (bottom: t a^{-1}) calculated from monthly averages for the period 2000 - 2015

A scheme for nitrogen in- and outputs in Lake Langer See demonstrates the relevance for the different pathways and processes (Figure 3) on an annual average. The dominant pathway of nutrient input was the inflowing river compared to atmospheric deposition and nitrogen fixation by cyanobacteria. It is obvious that beside of nitrogen in- and output assimilation of phytoplankton and release of ammonia from the sediment are the dominant processes for nitrogen turnover. The surface sediment in Lake Langer See is the most important compartment for denitrification. This process mainly causes the calculated loss of nitrogen in spring. During this period, concentration of nitrate is not limiting for denitrifiers because of higher discharges and intensive nitrification (Nitrolimit I, 2014). Denitrification in pelagic water is negligible during the year due to low nitrate concentration and very good oxygen supply in this polymictic lake. Finlay et al. (2013) quantified retention of nitrate across a trophic gradient as a linear dependency that lies just under the 1:1 level. Furthermore, they calculated the efficiency of nitrogen elimination and found a close relation to water residence time. Statistical scattering of this regression was lower in eutrophic lakes compared to oligotrophic systems. Our values for Lake Langer See fit into this scheme concerning nitrogen losses and the areal nitrogen load of about 35 g m^{-2} a^{-1} and a water residence time of 0.1 a. Lakes with water residence time below 1 year eliminate according to Finlay et al. (2013) between 0 and 50 % of imported nitrogen. On average, nitrogen losses in the period 2000 – 2014 were very low or negligible: -1.0 ± 11.5 (standard deviation) mg m^{-2} d^{-1} or -350.3 ± 4180.6 (standard deviation) mg $m^{-2}a^{-1}$.

Organic portion of imported nitrogen to Lake Langer See is very high during vegetation period (80 % of total nitrogen input, Figure 1). This component is metabolic relevant as a nutrient source for primary producers in the lake. The most important processes of nitrogen turnover are pelagic primary production, ammonification and release of ammonia from the sediment. These processes are characterised by a tight spatial and temporal coupling in this very shallow lake. In that period the input of inorganic nitrogen (nitrate and ammonia) is very low whereas 80 % of total nitrogen input is organic nitrogen consisting half of this by phytoplankton imported from the riverine system.

In Table 1 are shown the monthly averages for input of nitrogen by external surface inflow, atmospheric deposition and N_2-fixation, nitrogen demand of phytoplankton primary production (PP) and release of ammonia from the sediment in Lake Langer See for investigation period 2000 to 2015.

Table 1. Monthly averages for input of nitrogen by external surface inflow, atmospheric deposition and N_2-fixation, nitrogen demand of phytoplankton primary production (PP) and release of ammonia from the sediment in Lake Langer See for investigation period 2000 to 2015 (given in mg m^{-2} d^{-1}). Annual load of nitrogen, summer nitrogen inputs (June to September) and turnover are given in g N m^{-2}. Different processes are calculated as percentage of total N-input (sum of N-load by surface inflow, atmospheric deposition and N_2-fixation) and nitrogen demand of primary production as annual average and average for the summer period (June to September)

	Input surface inflow	**N demand PP**	**NH_4-release**	**atm. depos.**	**N_2-fixation**
month	**mg m^{-2} d^{-1}**				
January	142.9	58.1	20.5	3.6	0.0
February	177.1	110.7	27.2	3.6	0.0
March	151.6	131.6	33.0	3.6	0.0
April	104.0	87.8	52.6	3.6	0.0
May	67.9	98.0	62.7	3.6	0.0
June	60.3	180.8	70.1	3.6	10.2
July	124.9	299.9	124.6	3.6	79.9
August	118.0	349.6	177.6	3.6	64.7
September	64.5	282.6	230.7	3.6	18.1
October	52.5	151.8	126.1	3.6	2.5
November	77.9	106.2	67.9	3.6	0.0
December	98.9	64.5	36.9	3.6	0.0
annual load [g N m^{-2} a^{-1}]	**38**	**58**	**31**	**1**	**5**
% of all inputs	85	132	71	3	12
% of N demand PP	65		54	2	9
Sum Jun-Sept [g N m^{-2}]	**11**	**34**	**18**	**0.4**	**5**
% of all inputs	66	201	109	3	31
% of N demand PP	33		54	1	16

These values help to answer the question why the efficiency for trophic conversion of nutrients into phytoplankton biomass is so high in this lake type during summer. Furthermore, a differentiation between the impact of different inputs and internal turnover of nitrogen on annual average and during summer is possible.

a) Surface inflow: On annual average, external total nitrogen load by surface inflow as the main external load covers 65% of phytoplankton nitrogen demand for primary production, whereas during summer only one third meets these demand. During the colder season TN load of the surface inflow is sufficient for pelagic primary production.
b) Atmospheric deposition is constant and very low (1-3 %) compared to other external N-inputs.
c) Nitrogen fixation is on annual average 12 % and 31 % of total nitrogen inputs during summer. Compared to the surface inflow, this process is half of the nitrogen load during summer. Input by nitrogen fixation is coupled with the occurrence of Nostocales which have their temporal appearance during summer and therefore, are negligible between November and May for the nitrogen balance of Lake Langer See. N_2-fixation contributes between 12 (annual) and 16 % (summer) to nitrogen demand of primary production at light intensities corresponding with that in mixed layer. Maximum rates for nitrogen fixation were measured in July 2014 with 111.9 mg m^{-2} d^{-1} and about 240 mg m^{-2} d^{-1} at saturating light intensity. Between July and September, this process can contribute to set the course as an additional nitrogen input to stabilize the high level of phytoplankton primary production (Rücker et al. 2016).
d) Ammonification – release of ammonia from the sediment: From Table 1 and Figure 3 it becomes apparent that ammonification of organic matter within short-term cycles is the key process supplying sufficient nitrogen for the high intensity of phytoplankton productivity. There is a close relationship between release of ammonia from the sediment and phytoplankton primary production indicating coupling and high intensity of mineralization of freshly settling detritus, ammonification and primary production. The time lag between primary production and ammonia release is about one month. This relatively short period pointed out the high turnover and short-term recycling of primary products during summer. Hargreaves (1998) specified a half-life period of settled organic matter in the sediment of 1 to 2 weeks. These results are supporting i) the evidence of sediments as short-term temporary storage for organic substances and particulate bounded nutrients and ii) the high velocity of ammonia release from the sediments in shallow eutrophic lakes during summer. This phenomenon of intensive internal matter turnover is also proved for aquatic systems with lower productivity (Small et al. 2013). Beside of ammonification the sediment is the compartment were intensive nitrification and denitrification occur as Jensen et al. (1992) showed previously for Danish lakes. We conclude from the negligible nitrogen retention in Lake Langer See a low relevance of denitrification and small coupling of nitrification – denitrification at the sediment-water-interface. Compared to Lake Langer See the investigated Danish lakes had much higher concentrations of nitrate.

These results show that ammonia release from the sediment is the most relevant process supporting high pelagic primary production during vegetation period. Besides bottom up effects there are also some top down mechanisms that can contribute to phytoplankton losses, remineralisation of organic matter and intensive nutrient recycling. Rücker et al. (2014) estimated phytoplankton losses due to filtration of mussels. These organisms cause 38 % of phytoplankton losses on an annual average corresponding to elimination of 2 – 20 mg m^{-2} d^{-1} of nitrogen in phytoplankton biomass (average of vegetation period 2011 – 2013). Nitrogen elimination due to zooplankton grazing can be even higher (45 and 95 mg m^{-2} d^{-1}, Nitrolimit I, 2014).

4 CONCLUSION

1. Lake Langer See is a typical representative for very shallow and productive lakes with short but varying residence time embedded in a riverine system. It is rich in total nitrogen, but characterized by low dissolved inorganic nutrient loads and in lake concentrations. Dominant external nitrogen input is by more than 70% organic nitrogen transported by the surface inflow. Therefore, inorganic nitrogen concentration in the lake during vegetation period is limiting for primary production and for denitrification. On long-term average, the lake does not retain nitrogen.
2. Phytoplankton primary production is very high and cyanobacteria are dominating by more than 80 % of the total biomass in vegetation period resulting in poor ecological quality. Short-term recycling of

imported organic material and ammonification of detritus in pelagic water and sediment enable the high intensity of primary production. Ammonia release from sediment is the most relevant source to maintain high primary production during summer when external nitrogen inputs are low. Thereby, fast mineralisation of dead biomass compensates low external inorganic nitrogen input. Release of ammonia from the sediment can be reduced by decreased TN inputs only. Decrease of organic nitrogen load into Lake Langer See is more efficient as a management measure compared to the reduction of nitrate load.

3. N_2-fixation by Nostocales is only relevant from June to September during main period of their occurrence. This process can contribute to set the course as an additional nitrogen input to stabilize the high level of phytoplankton primary production during summer.
4. Management steps - First step to improve water quality in shallow lakes with dominating organic nutrient loads and turnover is to reduce total nutrient inputs. Second step is the enhancement of biological control of trophic status. Management measures for competition and losses of phytoplankton due to filtration and grazing are recommended (improved food webs, macrophytes as competitors for nutrients, filtration by mussels and grazing of zooplankton)

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