Climate Change Effects on Runoff, Catchment Phosphorus Loading and Lake Ecological State, and Potential Adaptations

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Climate change may have profound effects on phosphorus (P) transport in streams and on lake eutrophication. Phosphorus loading from land to streams is expected to increase in northern temperate coastal regions due to higher winter rainfall and to a decline in warm temperate and arid climates. Model results suggest a 3.3 to 16.5% increase within the next 100 yr in the P loading of Danish streams depending on soil type and region. In lakes, higher eutrophication can be expected, reinforced by temperature-mediated higher P release from the sediment. Furthermore, a shift in fish community structure toward small and abundant plankti-benthivorous fish enhances predator control of zooplankton, resulting in higher phytoplankton biomass. Data from Danish lakes indicate increased chlorophyll *a* and phytoplankton biomass, higher dominance of dinophytes and cyanobacteria (most notably of nitrogen fixing forms), but lower abundance of diatoms and chrysophytes, reduced size of copepods and cladocerans, and a tendency to reduced zooplankton biomass and zooplankton:phytoplankton biomass ratio when lakes warm. Higher P concentrations are also seen in warm arid lakes despite reduced external loading due to increased evapotranspiration and reduced inflow. Therefore, the critical loading for good ecological state in lakes has to be lowered in a future warmer climate. This calls for adaptation measures, which in the northern temperate zone should include improved P cycling in agriculture, reduced loading from point sources, and (re)-establishment of wetlands and riparian buffer zones. In the arid Southern Europe, restrictions on human use of water are also needed, not least on irrigation.

On average, global surface temperatures have increased by about 0.74°C over the past 100 yr (Trenberth et al., 2007), with the majority of the increase (0.55°C) occurring over the past 30 yr. We may expect marked changes to occur in the global climate during this century (IPCC, 2007). Increasingly reliable regional climate projections are available for many regions of the world, but fewer projections are available for many developing countries than for the developed world (Christensen et al., 2007). The warming generally increases the spatial variability of precipitation with reduced rainfall in the subtropics and increases at higher latitudes and in parts of the tropics.

The changes in temperature and rainfall lead to changes in agricultural land use and management, including changes in soil cultivation and in the rates and timing of fertilization (Howden et al., 2007). These changes have cascading effects on the P cycling, directly and indirectly, that affect the aquatic environment. The direct effects are related to the increased temperatures, increased rainfall intensity, and changes in winter rainfall that are expected to enhance the P loading to freshwaters in the temperate zone (IPCC, 2007) and the Arctic (Arctic Climate Impact Assessment, 2002) and to reduce the loading, but not the concentrations, in streams and freshwater lakes in the Mediterranean region. However, a few quantitative studies are available (Chang, 2004; Andersen et al., 2006). The indirect effects are related to changes in the choice of crops, crop rotations, use of catch crops, and agricultural practices, including tillage and fertilization. In northern temperate areas, new heat-demanding, warm-season crops (e.g., maize and sunflower) will replace many of the present grain cereals and oilseed crops (Olesen and Bindi, 2002). At the same time, changes occur in planting and harvesting times (Olesen, 2005) and in fertilization rates and strategies (Olesen et al., 2007). Crop rotation must be adapted to changes in crop choices, in crop maturing, and in the need to control weeds, pests, and diseases. This will affect the amount of P released to freshwaters and its seasonal pattern. More-

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Abbreviation: TP, total phosphorus.

Table 1. HIRHAM modeled changes in mean temperature and precipitation extracted from the 25 × 25 km grid covering each of the 10 catchments modelled (lowland streams of Denmark).

Name of stream	Temperature control period (1961–1990)	Temperature A2 scenario period (2071–2100)	Change in temperature	Precipitation control period (1961–1990)	Precipitation A2 scenario period (2071–2100)	Change in precipitation
	°C			mm yr^{-1}		
Bolbro Bæk	7.7	10.8	3.1	1136	1142	6
Ellebæk	7.5	10.7	3.2	997	1117	120
Lyby-Grønning grøft	7.2	10.4	3.2	915	1030	115
Odderbæk	7.3	10.5	3.2	818	881	63
Ølholm Bæk	7.5	10.7	3.2	908	982	74
Lillebæk	8.1	11.3	3.2	736	804	68
Østerbæk	7.8	11.2	3.4	748	804	56
Maglemose Å	7.6	10.9	3.3	695	735	40
Højvads Rende	8.1	11.3	3.2	701	779	78
Bagge Å	7.6	11.1	3.5	806	908	102

over, an earlier harvest of crops and later planting of winter crops may result in a prolonged period of bare soil in autumn, which increases the risk of P loss (Olesen et al., 2004), particularly in connection with intense precipitation in the temperate region.

Lakes respond to these climate-driven changes in P loading (Vollenweider, 1968; Schindler, 1977; Jeppesen et al., 2005). Moreover, they are affected directly by changes in climate due to changes in mixing regime, including lake stratification, oxygen saturation by increase in temperature, and the frequency of extreme wind events (Mooij et al., 2005; Blenckner et al., 2007; Kernan et al., 2009); by changes in trophic structure determined by temperature (Gyllström et al., 2005; Meerhoff et al., 2007a,b; Beklioglu et al., 2007; Jeppesen et al., 2007b); and by complex interactions between temperature, nutrients, and physical forces (Jeppesen et al., 2009).

In this paper we discuss the impact of global warming on runoff and transport of P to lakes, how such changes may affect the ecological state of lakes, and potential mitigation measures to counteract the likely negative effects of climate change. We use the HIRHAM-NAM-statistical P loss model chain as a first attempt to analyze climate change impacts on hydrology and diffuse P loss in Denmark. We finally discuss how direct effects of climate change, by interacting with changes in nutrient loading, may reinforce eutrophication symptoms in lakes.

Climate-Driven Changes in Stream Hydrology and Nutrient Losses in Denmark

To illustrate the effect of climate change on runoff and nutrient loading, we coupled a series of models established for Danish streams and catchments with contrasting soil types and hydrological regimes. Climate change projections by the ECHAM4/OPYC General Circulation Model (IPCC A2 scenario) were dynamically downscaled by the Danish HIRHAM regional climate model (25-km grid) for two time periods: 1961 to 1990 (control) and 2071 to 2100 (scenario).

The IPCC A2 climate emission scenario was used for the periods 1961 to 1990 (the control period) and 2071 to 2100 (the scenario period) as input to the hydrological NAM model. A2 is a high-emission scenario (IPCC, 2001) and was chosen for this study to illustrate the worst case scenario. The global climate projections were the A2 climate scenario generated from ECHAM4/OPYC, a General Circulation Model developed by the Max-Planck Institute of Meteorology, Germany. Prediction of regional climate change was established using model runs from the regional HIRHAM model (e.g., Christensen and Christensen, 2003). Daily climate data were simulated for a 25 × 25 km grid covering the entire Denmark. HIRHAM daily model simulations were transformed as input to the hydrological model (NAM) using a three-step procedure as that thoroughly described in Andersen et al. (2006).

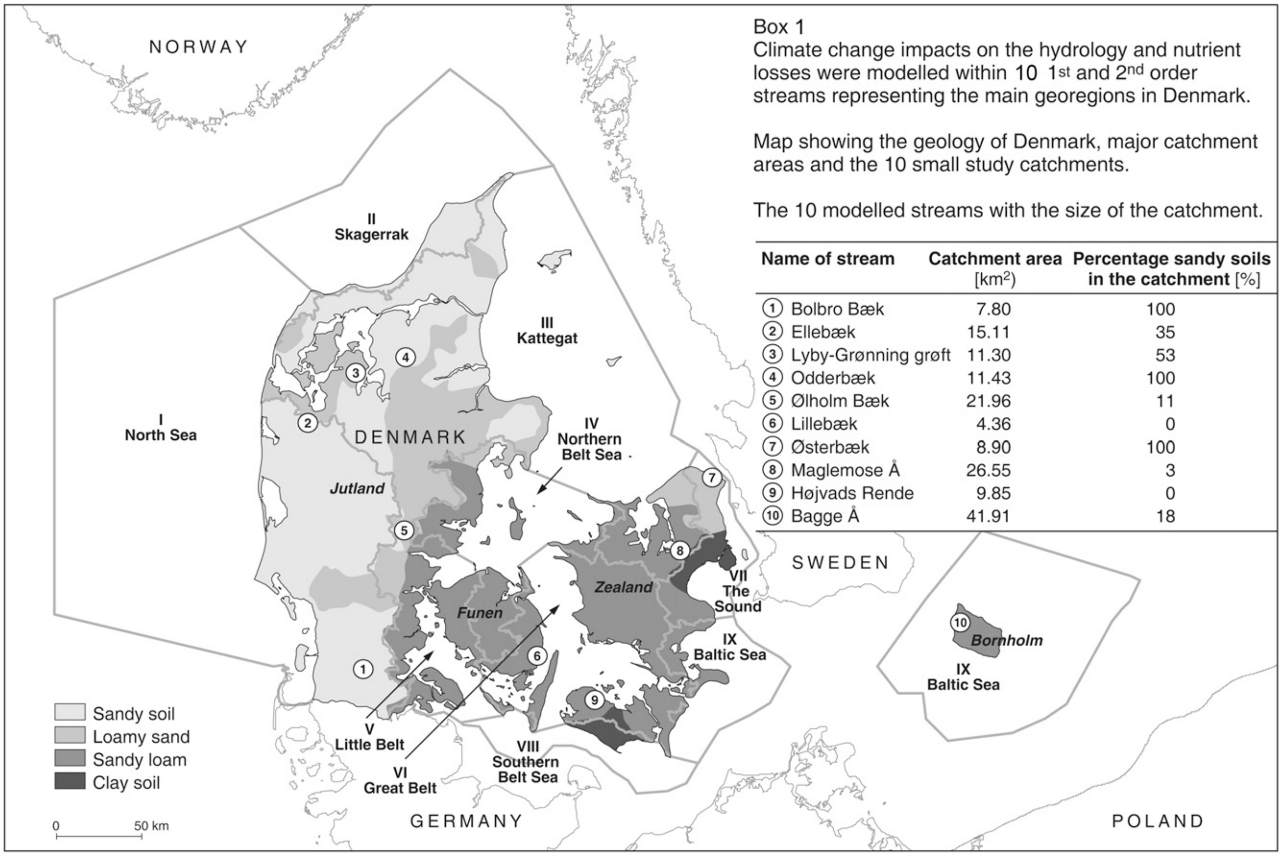
The HIRHAM regional climate model generated daily climate values for 360 d (12 × 30 d) for each period. For all years, extra days were added manually in between the existing 15th and 16th day in the months of January, March, May, July, August, October, and December.

Daily climate observations of temperature and precipitation from a 10-km grid covering each catchment were used to adjust the HIRHAM downscaled precipitation, evaporation, and temperature monthly means. This was done for the control and the scenario periods using a bias correction method.

We applied changes between 3.1 to 3.5°C and 6 to 120 mm yr^{-1} in annual mean temperature and annual mean precipitation, respectively, in the 25 × 25 km grids covering the 10 catchments to be modeled with the NAM model (Table 1).

Water discharge was modeled using the NAM rainfall-runoff model (DHI Water and Environment, 2003). NAM is a deterministic, conceptual, nondistributed hydrological model describing the hydrological system in a catchment by routing water with a daily time step through four linear reservoirs: snow storage, surface storage, root-zone storage, and groundwater storage. The NAM model was calibrated to 10 first- and second-order streams for an analysis of climate change impacts on stream hydrology in different regions of Denmark.

Because the catchments modeled are situated in different regions of Denmark, they represent all main landscape and soil types (Fig. 1). All catchments have a high proportion of agricultural land (>50%), which is typical of the intensively managed agricultural landscape in Denmark. Autocalibration of the NAM model was performed using daily discharge data for the period 1989 to 1996, and the NAM model was validated via daily observations for the period 1997 to 2004 (Table 2). After autocalibration, the final parameter settings were checked for being within the normally accepted intervals for the NAM model. The



Box 1
Climate change impacts on the hydrology and nutrient losses were modelled within 10 1st and 2nd order streams representing the main georegions in Denmark.

Map showing the geology of Denmark, major catchment areas and the 10 small study catchments.

The 10 modelled streams with the size of the catchment.

Name of stream	Catchment area [km^2]	Percentage sandy soils in the catchment [%]
① Bolbro Bæk	7.80	100
② Ellebæk	15.11	35
③ Lyby-Grønning grøft	11.30	53
④ Odderbæk	11.43	100
⑤ Ølholm Bæk	21.96	11
⑥ Lillebæk	4.36	0
⑦ Østerbæk	8.90	100
⑧ Maglemose Å	26.55	3
⑨ Højvads Rende	9.85	0
⑩ Bagge Å	41.91	18

Fig. 1. Map showing the 10 small study catchments, a description of the catchments, and the main soil types in Denmark.

Table 2. NAM model results of the auto-calibration of daily stream discharge during the period 1989–1996 and the validation period 1997–2004 shown as the squared correlation coefficient (R^2) and the water balance error as a percentage for the entire period (same catchments as in Table 1).

	Calibration period (1989–1996)		Validation period (1997–2004)	
Name of stream	**R^2**	**Water balance error**	**R^2**	**Water balance error**
		%		%
Bolbro Bæk	0.768	−14.8	0.773	−5.8
Ellebæk	0.800	0.3	0.632	3.0
Lyby-Grønning grøft	0.879	0	0.690	−6.6
Odderbæk	0.840	−3.0	0.763	9.4
Ølholm Bæk	0.862	0	0.737	14.4
Lillebæk	0.761	0	0.745	9.1
Østerbæk	0.763	0	0.698	7.1
Maglemose	0.793	0	0.800	−5.0
Højvads Rende	0.897	0	0.845	−20.9
Bagge Å	0.823	3.4	0.712	−10.4

calibration results of the NAM model were above 0.7 (R^2) for the calibration period in all 10 streams and above 0.6 for all streams in the validation period (Table 2). The water balance error was very low in the calibration period (−14.8 to 3.4%) but increased in the validation period from −20.9 to 14.4% (Table 2).

The NAM-calculated changes in annual mean runoff between the control and the scenario period showed an increase of 7 to 78 mm yr^{-1} or 9 to 34% for the 10 streams (Table 3). A much stronger seasonal change in runoff was observed in all 10 streams (Fig. 2). Monthly runoff generally increases in winter (December–March) and decreases in the late summer (August–October). The modeled reduction in monthly runoff during the summer was most extreme and lasted for a longer period in streams draining loamy catchments (Fig. 1 and 2). The reason for the less extreme summer flow conditions predicted in the streams draining dominantly sandy catchments is the impact of higher baseflow conditions due to higher net precipitation in winter, thus recharging the ground water in the catchment. The modeled summer flow conditions in the streams Bagge Å on the island of Bornholm and Højvads Rende on the island of Lolland do not change as markedly as in similar streams draining loamy catchments in Jutland in the western part of Denmark (Fig. 2). The reason is that HIRHAM simulates a regional increase in precipitation in July and August in the scenario period for the southeastern part of Denmark, which results in a higher summer flow only in this region.

Climate Change Impacts on Phosphorus Losses at the Catchment Scale

It is a complex task to analyze climate change impact on diffuse P losses in river catchments because these are influenced by multiple biogeochemical processes (e.g., Foy et al., 2003; Johnes et al., 2007). The statistical model developed and applied in this study for a catchment scale response to climate change

Table 3. NAM model results of changes in mean annual runoff in the 10 streams during the 30-yr control period (1961–1990) and the 30-yr A2 scenario period (2071–2100).

Name of stream	Runoff A2 scenario period (2071–2100)	Runoff control period (1961–1990)	Change in runoff between scenario and control period	Difference in runoff between scenario and control period
	mm yr^{-1}			%
Bolbro Bæk	602	524	78	15
Ellebæk	325	275	50	19
Lyby-Grønning grøft	180	151	29	20
Odderbæk	226	191	35	18
Ølholm Bæk	391	344	47	14
Lillebæk	214	179	35	20
Østerbæk	81	71	10	14
Maglemose	90	83	7	9
Højvads Rende	188	141	47	34
Bagge Å	292	262	30	11

on total phosphorus (TP) losses is based on an extensive dataset from 80 monitored Danish catchments covering a range in land use from predominantly agricultural to predominantly forested catchments. Such statistical models mimic all biogeochemical processes and pathways for P loss in an average and lumped way, and the simulations give reliable and robust results as long as the changes in forcing variables do not differ too much from the datasets from which the model was established. The climate change impact on monthly losses of TP in the study catchments was estimated with the following statistical model for diffuse TP losses from Danish catchments to surface waters (Eq. [1]):

$$\log(Y_{ij}) = \mu + \mu_i + \alpha_j + \beta_1 \cdot \log(Q_{ij}) + \beta_2 \cdot AL + \beta_3 \cdot SS + \beta_4 \cdot OS + \beta_5 \cdot WA \qquad [1]$$

where Y is TP in kg P ha^{-1}; μ is the intercept of the regression equation modified on an annual and monthly basis by μ_i and α_j, respectively, where i and j are the annual and monthly indexes; and the β parameters are slopes of the regression line relating to runoff (Q) in mm (β_1), the percentage of arable land (β_2), the percentage of sandy soils (β_3), the percentage of organic soils (β_4), and the percentage of wetlands in a catchment (β_5). The TP model was developed based on monitoring data from 93 streams, each draining a catchment area less than 50 km^2 (Andersen et al., 2006). The runoff, Q, was derived from the chained HIRHAM-NAM models. A detailed description of the models can be found in Andersen et al. (2006).

The modeled changes in average annual TP loss and TP concentrations from nine major regions of Denmark during the 30-yr control period and the 30-yr A2 scenario period are shown in Table 4. The increase in diffuse TP losses varied from 3.3 to 16.5% in the nine regions, being lowest in the Kattegat region and highest in the Southern Belt region (Fig. 1). The discharge weighted concentration of TP decreased in all regions as a result of the predicted higher annual discharge in rivers (Table 4). The modeled changes in TP losses showed pronounced seasonality (Fig. 3). Particularly, the changes in TP losses are expected to be highest in late winter (February and March) and early summer (May and June), whereas the TP losses decrease in autumn (September and October) (Fig. 3).

Our analysis with the HIRHAM-NAM statistical P loss model chain is the first attempt to analyze climate change impacts on hydrology and diffuse P loss in a distributed and spatial way in Denmark. Our model chain is not sufficiently advanced to incorporate climate induced changes in P retention in rivers, lakes, and wetlands caused by more frequent flooding events. More work has to be dedicated to developing hydrological and P model chains incorporating retention processes in river basins.

Riparian Zones

The documented increase in stream flow during winter affects the interaction between streams and their riparian areas. Estimations with the hydrodynamic model MIKE11 show a 50% increase in the average number of days per year with overbank flooding from the control period (1961–1990) to the scenario period (2071–2100) for the River Gjern in Central Jutland, Denmark (Andersen et al., 2006). The current intensive agricultural production of cereals in most Danish riparian areas is becoming increasingly difficult to sustain due to increased autumn and winter rainfall, leading to wet and often inundated conditions during periods of soil cultivation in spring and autumn. The problems will increase considerably under the projected climate change, and predictions are that in many riparian areas intensive agricultural production will cease in the future (Andersen et al., 2006). The predicted increase in the hydrological interaction between streams and riparian areas will consequently influence the sediment and P dynamics and transport in river systems because inundated floodplains act as sinks for sediment, carbon, nitrogen (N), and P (Mitsch et al., 1979; Walling, 1999; Kronvang et al., 2007). In situ measurements of sediment and P deposition on an inundated, permanently grazed riparian area showed that the deposition rate increases with the magnitude of the inundation event (Fig. 4). Thus, less intensive land use of riparian areas along the river corridors seems to be an important adaptation strategy to combat the impacts of climate change on the sediment and nutrient losses and dynamics in catchments.

Lake Response to Climate Change

Lakes are affected by changes in external nutrient loading, water temperature, mixing conditions, and trophic structure. In northern temperate regions, such as Denmark, higher annual nutrient loading to lakes is expected due to the higher runoff from the catchment and more extreme events. However, this may not necessarily lead to higher annual mean lake concentrations because the nutrient concentrations in the inlet water are

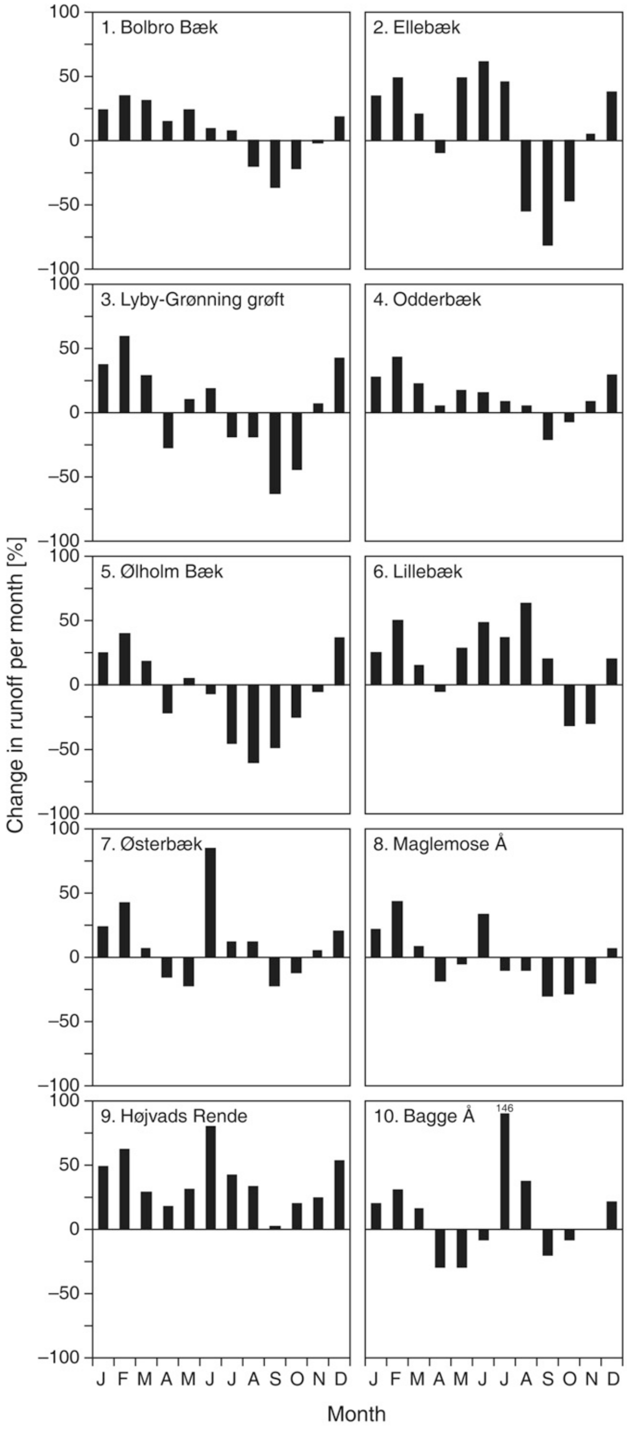


Fig. 2. Changes in mean monthly runoff from the control period (1961–1990) to the A2 scenario period (2071–2100) as modeled with HIRHAM climate data as input to the NAM model in 10 Danish streams.

predicted to decline due to dilution (Table 4). According to the commonly used simple lake model described by Vollenweider (1968), the annual mean lake TP concentration (P_{lake}) can be calculated from the discharge-weighted annual mean inlet TP concentration P_{in} as:

$$P_{lake} = P_{in}/(1 + TW^{0.5}) \qquad [2]$$

Table 4. Model estimated annual changes in diffuse total phosphorus (TP) losses and the discharge weighted phosphorus concentration in potential lakes from nine major coastal regions in Denmark during the control period (1961–1990) and the A2 scenario period (2071–2100).

	TP loss		Discharge-weighted TP concentration	
	Control period (1961–1990)	Scenario period (2071–2100)	Control period (1961–1990)	Scenario period (2071–2100)
	kg P ha^{-1}		mg P L^{-1}	
1. Nordsøen	0.343	0.365 (6.4%)	0.078	0.074 (−5.1%)
2. Skagerrak	0.240	0.258 (7.5%)	0.070	0.066 (−5.7%)
3. Kattegat	0.291	0.302 (3.8%)	0.089	0.087 (−2.2%)
4. N. Bælthav	0.265	0.285 (7.5%)	0.096	0.089 (−7.3%)
5. Lillebælt	0.334	0.345 (3.3%)	0.101	0.097 (−4.0%)
6. Storebælt	0.294	0.323 (9.9%)	0.128	0.117 (−8.6%)
7. Øresund	0.177	0.188 (6.2%)	0.093	0.088 (−5.4%)
8. S. Bælthav	0.236	0.275 (16.5%)	0.127	0.110 (−13.4%)
9. Østersøen	0.281	0.297 (5.7%)	0.120	0.115 (−4.2%)

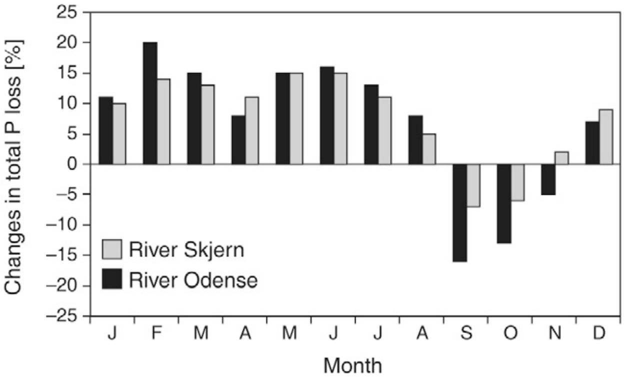


Fig. 3. Modeled average monthly changes in total phosphorus losses from diffuse sources to surface waters in two major river basins in Denmark from the control period (1961–1990) to the A2 scenario period (2071–2100).

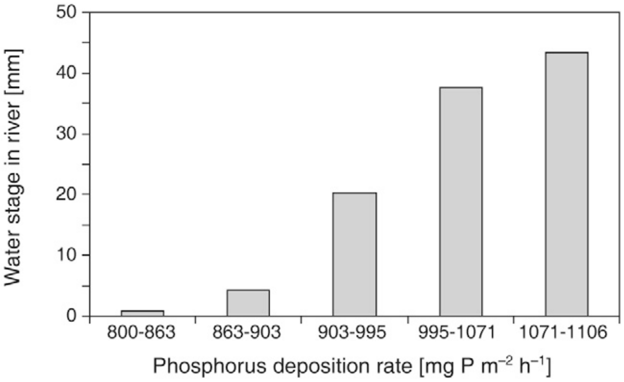


Fig. 4. Deposition of total phosphorus during inundation periods of increasing magnitude, as measured by the water stage in the River Gjern (Denmark).

where TW is the hydraulic retention time (years) in the lake.

Based on this relationship and using the data presented in Table 4, P_{lake} would decrease in the scenarios of climate change if the lakes are situated in the studied stream catchments (Fig. 5) because the effect of reduction in P_{in} is larger than the effect of reduced TW and the reduction becomes larger with decreasing TW. However, due to the expected higher nutrient loading, the net accumulation in the lake (and eventually in the sediment) will increase (Fig. 5), potentially leading to higher internal loading in summer (Søndergaard et al., 2003).

Several other factors may reinforce the eutrophication of lakes. Higher temperatures affect the physical properties of the water. In deep summer-stratified Danish lakes, the thermocline often occurs at lower depth (Closter, 2007), and the duration of stratification increases, which enhances the risk of oxygen depletion below the thermocline (Blenckner et al., 2007) and consequently the P release from the sediment, whereas polymictic lakes may become temporarily stratified. An analysis of data from five summer stratified Danish lakes, monitored biweekly during summers from 1989 to 2003 (Kronvang et al., 2005) when the lakes were subjected to nutrient loading reduction, showed a clear response to the loading reduction in the surface waters and strong interannual variations in oxygen and nutrients in the hypolimnion, depending on, for instance, summer temperature (Fig. 6). In the years with the highest summer temperatures, the depth where the minimum oxygen concentrations in the hypolimnion passed below 3 and 2 mg L^{-1} during the stratification period was lower than the average for the study period and much higher in the colder years. This also means that areas with low oxygen concentrations often, depending on lake morphometry, are larger in warm than in cold years, implying impoverished living conditions for benthic invertebrates and deteriorated foraging conditions for fish with increasing temperature. Maximum ortho-phosphate concentrations in the hypolimnion were overall higher in warm years, likely as a response to the lower oxygen concentrations leading to release of iron-bound phosphate. No clear effects of these changes were seen in the surface waters in the subsequent years. Total phosphorus responded more strongly to changes in external loading (loading data not shown). Chlorophyll *a* showed a tendency to a decline after nutrient loading reduction but was overall higher in warm years, whereas TP tends be lower in cold years. Enhanced P release in a larger hypolimnion

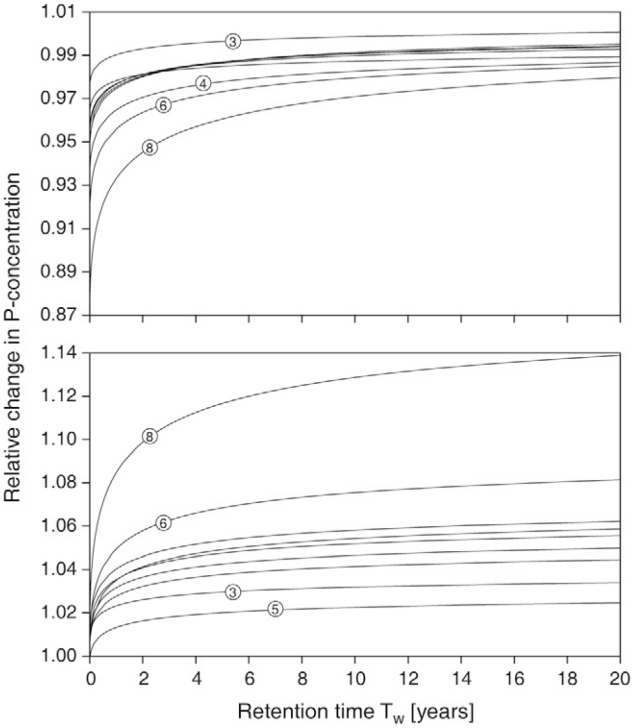


Fig. 5. Proportional changes in annual mean lake phosphorus concentrations from the control period (1961–1990) to the A2 scenario period (2071–2100) calculated from the Vollenweider equation (Eq. [2] in the text) in lakes with different hydraulic retention times using the simulated inlet total phosphorus concentration given in Table 3 (upper panel) and the proportional changes in retention of P in the lakes for the same types of lakes (lower panel). Numbers referring to those in Box 1 are given for the streams' deviation from the norm in the figures. No simulation exists for Bagge Å (No. 10).

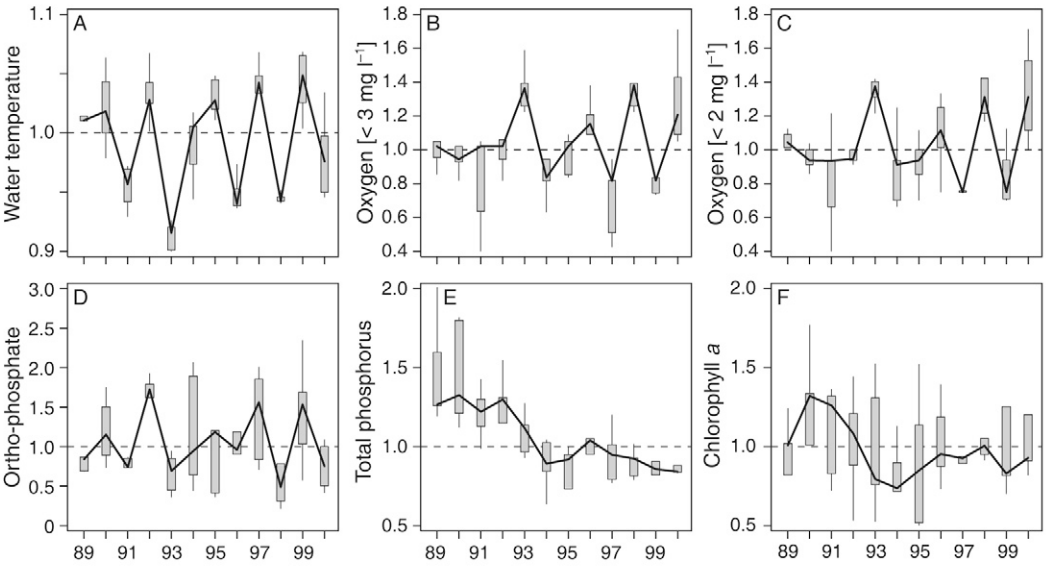


Fig. 6. Boxplot of various variables in each year normalized to the means for the period 1989 to 2003 in five stratified, eutrophic Danish lakes. The variables are interpolated summer mean (1 May to 30 Sept.) temperatures in the epilimnion (A), minimum depth where oxygen passes below 3 mg O_2 L^{-1} (B), and 2 mg O_2 L^{-1} (C), respectively, at any sampling date during stratification, maximum ortho-P (D), summer mean epilimnion concentration of TP (E), and chlorophyll a (F). Median, 25, 75, 10, and 90% percentiles are shown.

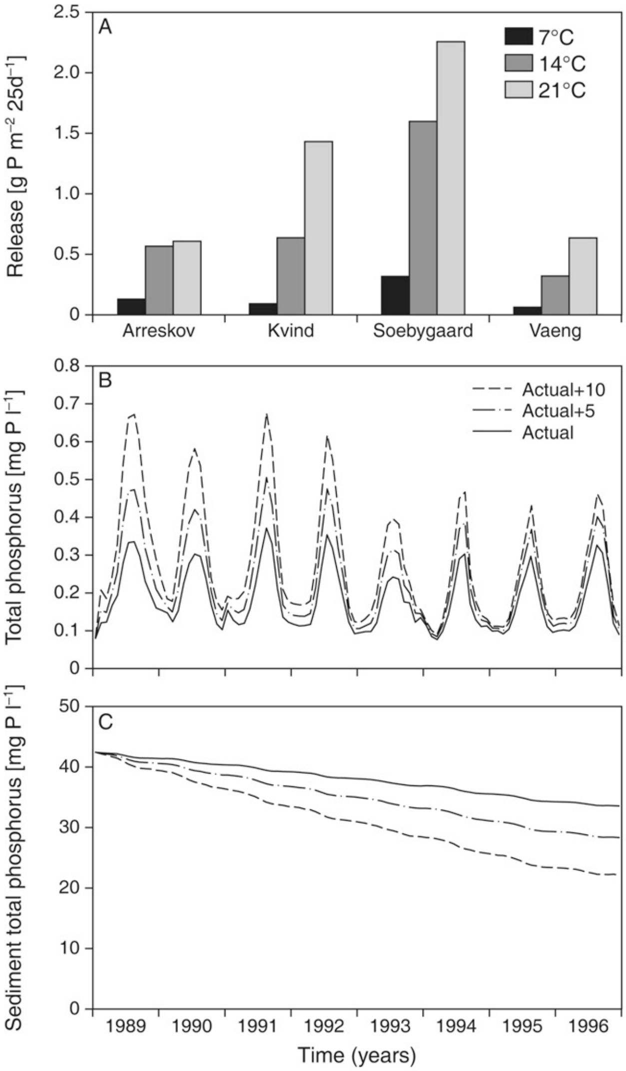


Fig. 7. Laboratory experiments showing release of phosphorus (P) in short-term experiments run at three different temperatures in four shallow Danish lakes (after Jensen and Andersen, 1992) (A). Simulated changes in P in shallow Lake Dons; Denmark (drainage area: 24 km^2; surface area: 0.36 km^2; Z_{max}: 1.5 m; Z_{mean}: 0.9 m), after nutrient loading reduction, during the period 1989–1996: water P concentrations (B), and change in the P pool in the upper 20 cm of the sediment (C) under three temperature scenarios (i.e., actual measured temperature and 5 and 10°C higher) using a simple model developed for Danish shallow lakes (Jensen et al., 2006) with minor changes, including permanent deposition in the sediment.

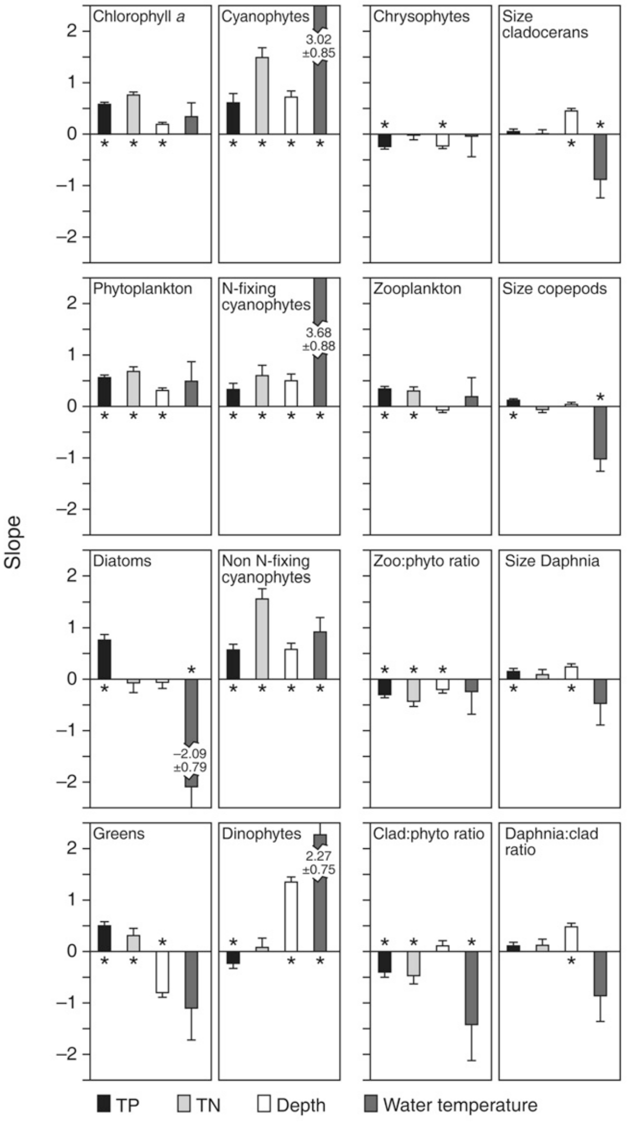


Fig. 8. Slopes of multiple regression relating various phytoplankton and zooplankton variables (log-transformed) to surface water total phosphorus (TP) and total nitrogen (TN), mean depth of the lake (Depth), and water temperature in surface (all log-transformed) in August in 250 lakes and >800 lake-years in Denmark. * Significant at $p < 0.05$. If more than one sample per month occurs for a given year, averages were calculated before analyses. Information about sampling and analyses is given in Kronvang et al. (2005) and Jeppesen et al. (2007b). Phytoplankton is biovolume; zooplankton is biomass; size of zooplankton is in μg dry weight ind^{-1}.

may therefore not necessarily translate into higher algal biomass in the following year.

Higher temperatures also imply a lower oxygen capacity in the water, which, combined with a higher temperature-mediated increase in metabolism, enhances the risk of oxygen depletion in the lakes (Søndergaard et al., 2003); however, temperature increases much less in the hypolimnion than in the epilimnion with warming (Closter, 2007; Jørgensen et al., 2008). In shallow, nonstratified lakes, P release may also be stimulated by the higher temperature (Fig. 7).

The risk of dominance by potential toxic cyanobacteria will increase and the period with blooming of cyanobacteria will likely be longer (Romo et al., 2005; Blenckner et al., 2007). Multiple regression analyses on data from 250 Danish lakes sampled in August showed higher dominance of cyanobacteria in terms of biovolume, most notably potential N-fixing forms and dinophytes at higher temperatures, and a tendency to an increase in chlorophyll *a* and phytoplankton biovolume, whereas diatoms become less important (Fig. 8).

Changes in the trophic structure in lakes may indirectly enhance the risk of turbid conditions and dominance of cyanobacteria by affecting the fish community (Jeppesen et al., 2007b). Thus, changes are to be expected in the trophic composition of fish stocks with higher dominance of zooplanktivorous and omnivorous fish, implying increased predation on zooplankton and, consequently, less grazing on phytoplankton (i.e., less top-down control) and a higher chlorophyll/TP ratio (higher yield). A study by Gyllström et al. (2005) of shallow European lakes along a latitudinal gradient from Northern Sweden to Spain showed that the ratio of fish biomass (expressed as catches per net in multi-mesh–sized gillnets) to zooplankton biomass increased from North to South and that the zooplankton/phytoplankton biomass ratio decreased substantially. Moreover, higher-latitude fish species are often not only larger but also grow more slowly, mature later, have longer life spans, and allocate more energy to reproduction than populations at lower latitudes (Blanck and Lamouroux, 2007). Even within species such changes are seen along a latitude gradient (Blanck and Lamouroux, 2007). Enhanced predation on zooplankton is also evident from multiple regression analyses of August data from Danish lakes, indicating a decrease in the average size of cladocerans and copepods with increasing temperature (Fig. 8). This usually suggests enhanced predation by fish. A tendency to a decrease in the zooplankton/phytoplankton biomass ratio and the proportion of *Daphnia* among the cladocerans provides further evidence of higher fish predation. With a lower proportion of large-sized *Daphnia* and a lower average size of zooplankton, grazing on large-bodied phytoplankton is likely to decline, which will further enhance the risk of dominance by filamentous cyanobacteria.

Comparative experimental studies with artificial plants in shallow lakes in Uruguay (warm temperate to subtropical) and Denmark (temperate) give further evidence of lower grazer control of algae in warm lakes compared with otherwise similar temperate lakes (Fig. 9). Notable differences in littoral trophic structure and dynamics were found between the two climate zones regardless of the gradients in water transparency, nutrient status, and lake area. The littoral food web seemed more complex and less hierarchically structured in the subtropical lakes. In particular, the structure of the littoral predator assemblies differed remarkably between the climate zones, with important effects on the lower trophic levels (Meerhoff et al., 2007a). Fish species richness was significantly higher in the subtropical South American lakes, with communities amply dominated by small-bodied and omnivorous cyprinodontids, whereas somewhat larger cyprinids and percids dominated in the temperate lakes. Moreover, the fish in the plant beds were on average 11-fold more abundant in the subtropics. By contrast, higher taxon richness and significantly higher densities of plant-associated macroinvertebrates were found in the temperate lakes: approximately 8-fold higher densities of predators, 10-fold of grazers, and 2-fold of collectors (Fig. 9). Cladoceran richness, density, and body size were also significantly higher among the plants in the temperate systems. The typical pelagic cladoceran community in the subtropical lakes was composed of small-bodied genera, and *Daphnia* was almost absent. The periphyton biomass in the subtropical lakes was much lower than expected by the lower density of grazing invertebrates and by the more positive environmental conditions for periphyton growth (i.e., more light and higher temperature). Thus, the observed 4-fold reduction in periphyton biomass in the subtropical lakes is probably the result of periphyton feeding by the fish and shrimps (possibly enhanced by apple snails in some of the lakes). These results indicate that submerged macrophytes in subtropical lakes fail to provide an effective refuge for macroinvertebrates and large-bodied zooplankton against fish predation, in contrast to temperate lakes (Meerhoff et al., 2007b). This was also confirmed by behavioral laboratory experiments, where *Daphnia* avoided subtropical plants even when exposed to fish cues (Meerhoff et al., 2006).

Supporting these findings, in shallow Florida lakes (USA) no differences were found in the chlorophyll/TP or Secchi depth/TP relationships in lakes with low, medium-high, or high plant coverage or plant volume infested (Bachmann et al., 2002), indicating that plants here, like in the Uruguayan lakes, are not an efficient refuge for zooplankton. It has been argued that macrophyte growth will be stimulated by climate warming (Scheffer et al., 2001) due to the higher temperature and in the Mediterranean region due to a reduced water table as well (Coops et al., 2003; Beklioglu et al., 2006). Moreover, unless compensated by higher precipitation-induced N loading, nitrate in summer will probably be lower in the future due to enhanced denitrification (Weyhenmeyer et al., 2007), which potentially may be beneficial for the richness and density of submerged macrophytes (James et al., 2005; González Sagrario et al., 2005). However, increases in the availability of nutrients may counteract the benefits of low water level for macrophyte growth (Beklioglu and Tan, 2008; Özen et al., unpublished data). Moreover, a recent cross-system analysis of data from lakes from the temperate zone to the tropics gave evidence for a lower probability of macrophyte dominance in warm lakes and lower nutrient thresholds for loss of these plants (S. Kosten et al., unpublished data). The results of the competition between submerged macrophytes and other potentially dominant groups, such as cyanobacteria and free-floating plants, under warmer climates are unclear. However, even when the submerged macrophytes are abundant, the positive effect of the plants on water clarity is much less pronounced at higher temperatures due to changes in fish community structure and consequent cascading effects (Jeppesen et al., 2007a).

The higher impact of fish and the lower effect of submerged plants on water clarity may result in higher sensitivity of the warmer lakes to external changes (e.g., increase in nutrient loading or water level changes). The current process of warming, particularly in temperate lakes, may thus entail increased sensitivity to eutrophication and constitute a threat to the high diversity, clear water state. Moreover, in northern temperate lakes, a higher disturbance of sediment is to be expected if cyprinids such as carp (*Cyprinus carpio*) become more abundant in a projected warmer climate (Lehtonen, 1996). With increasing warming it may therefore be more difficult to fulfill the present-day ecological state targets of the lakes without undertaking additional efforts to reduce nutrient loading to levels lower than the present-day expectations. Temperate and subtropical conditions may appear in cold winter, warm summer areas such as northern-mid Turkey and Greece, where the composition of the fish fauna is more northern-like but where the fish may exploit the warm summers for more frequent reproduction (Beklioglu et al., 2007; Jeppesen et al., 2007a).

In warm southern Europe, the expected lower precipitation and higher evaporation in the future will lead to reduced runoff, which

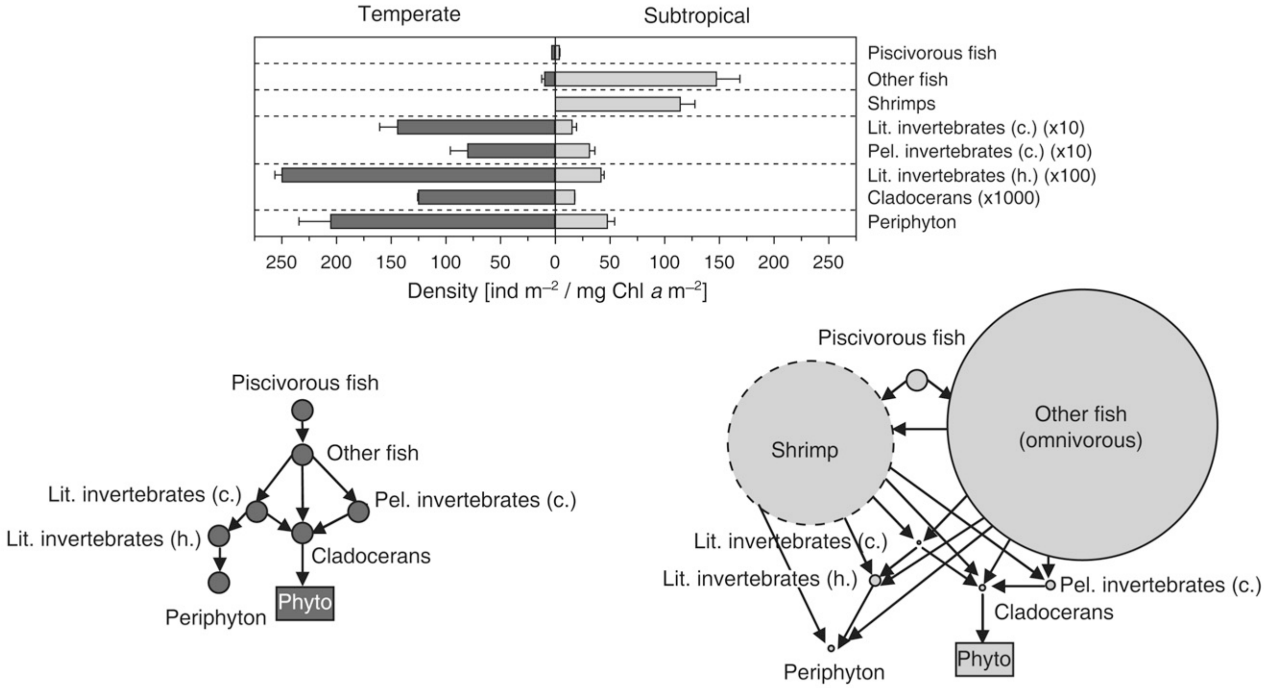


Fig. 9. Main littoral community structure in artificial plant beds in temperate (left) and subtropical (right) lakes. Above: Density of potentially piscivorous fish, all other fish, shrimps, littoral carnivorous macroinvertebrates, pelagic carnivorous invertebrates, littoral herbivorous macroinvertebrates, pelagic herbivorous cladocerans, and biomass of periphyton (as chlorophyll *a*). Below: Simplified scheme of trophic interactions among the same trophic groups showing the densities in the subtropics relative to those in the temperate lakes. Shrimps were absent in the temperate lakes, and, except fish, the same taxa received the same trophic classification in both climate zones. (c), carnivorous; (h), herbivorous; Lit., littoral; and Pel., pelagic. Data are sample means (±1 SE) of five lakes paired between climate regions in terms of phytoplankton biomass and physicochemical and morphometric characteristics (adapted from Meerhoff et al., 2007a).

is predicted to be as high as 30 to 40% in Mediterranean Europe and Asia, in which Spain and Turkey are predicted to be among the worst affected in the world, from the 20th century to 2040, and these areas are thus particularly threatened. Biodiversity will then decrease, and many endemic species may disappear. With lower runoff, the P loading from diffuse sources may be lower. However, concentrations in the inlet may increase due to enhanced evaporation and water loss (Beklioglu et al., 2007). A comprehensive mass balance study of Lake Mogan, a shallow Turkish lake, shows that TP increases in dry years when the water table is low, despite a major reduction in external loading due to reduced runoff during 2001 and 2005 to 2007 (Fig. 10). In those years, the lake TP concentration was substantially higher than predicted from the OECD equation (Eq. [2]), and the lake showed a net release of P (2005–2007) that more than balanced the much lower input, leading to higher TP concentrations. A likely explanation is the lower volume of water in the lake and lower oxygen concentrations in the water due to higher consumption and a lower saturation level of oxygen at higher temperature (Beklioglu and Tan, 2008; Beklioglu and Özen, 2008).

In Southern Europe, the risk of drought or low water input to inland waters will increase and salinization will become a more widespread phenomenon due to increased evaporation and enhanced consumption of water for irrigation purposes (Williams, 2001; Zalidis et al., 2002). A 3-fold increase in salinity in two shallow Mediterranean lakes has been recorded resulting from profoundly reduced inflow, prolonging the residence time (>10 yr) with enhanced evapo-transpiration (Beklioglu and Tan, 2008; Beklioglu and Özen, 2008). Less precipitation in these areas would likely mean lower nutrient loading to lakes, but this might not compensate for the negative consequences of water loss. Thus, contrary to expectations, P and N became concentrated in the two lakes due to internal mechanisms, including enhanced internal P release and oxygen depletion–induced ammonium accumulation (Beklioglu and Tan, 2008). This may result in a major increase in summer phytoplankton biomass dominated by cyanobacteria (Beklioglu and Tan, 2008). Moreover, at similar nutrient concentrations, saline lakes tend to be more turbid than freshwater lakes due to differences in trophic structure and in the zooplankton grazing capacity (Jeppesen et al., 1994, 2007b; Barker et al., 2008). Such lakes tend to be species poor (Williams, 1998).

Adaptation Measures to Counteract Negative Effects of Climate Change

Autonomous adaptation to climate change in the agricultural sector is likely to lead to intensified production in Northern Europe and less intensive production in Southern Europe, including forced reduced use of irrigation due to enhanced water scarcity (Olesen and Bindi, 2002; Alcamo et al., 2007). The intensification of North European agriculture under climate change will most likely lead to enhanced nutrient cycling and runoff. The higher winter rainfall will make current low-lying agricultural soils in riparian areas less attractive for cultivation, which could be exploited to lessen the negative consequences of climate change on the aquatic environment by promoting the establishment of (larger) buffer zones along river corridors.

Counteracting the climate-induced potentially enhanced P loading of freshwaters in Denmark will, in principle, involve measures to increase focus on: (i) reducing P losses from point sources, including stormwater outlet (higher storage capacity); (ii) reducing surplus P input to agricultural soils; (iii) reducing P losses from agricultural soils; (iv) enhancing P retention in buffer zones; (v) removing P from high-risk loss zones; and (vi) maintaining stream flow during the dry season.

To further reduce nutrient leakages from point sources, municipal sewage treatment plants and wastewater from rural houses with more or less mitigated runoff to streams may receive increased attention (Bowes et al., 2005). However, the major sources of P to be affected by climate changes are agricultural soils in river catchments. Because P losses from agricultural soils are related to soil P concentrations (Heckrath et al., 1995), efforts should be made to avoid P surpluses on agricultural soils and to further reduce P fertilization where the soil P status is high. The P loss from agricultural soils is affected by the extent to which P is mobilized and transported under high-intensity rainfall events. Having a ground cover of plant residues or catch crops during the rainy periods of the year and avoiding high-intensity tillage may serve as measures to protect the streams from receiving the P losses from agricultural soils (Deizman et al., 1989). However, some of these measures may increase the bioavailabilty of P in the runoff by increasing the proportion of dissolved P or easily degradable organic P through leaching of substances from plant residues on the soil surface (McDowell and McGregor, 1984); care must therefore be taken to ensure that this P is recaptured before reaching the freshwater systems.

Riparian buffer zones are generally very effective in capturing solids (and P) in runoff (Borin et al., 2005). The effectiveness depends on the buffer width and vegetation type, where especially grasses act as filters and encourage infiltration. These buffer zones may routinely be harvested to remove P from the soils near streams and thus avoid the risk of P saturation in the buffer zone (Richardson and Qian, 1999). Other types of filter zones for drainage water in the landscape using substrates with high P adsorption may be used for accumulation of P that can later be removed and possibly upgraded as P fertilizer. Constructed wetlands may serve as effective sites for reducing the P load into freshwater systems by affecting P sorption, precipitation, plant uptake (with subsequent harvest), and peat/soil accretion (Schulz et al., 2004; Vymazal, 2007). However, removal of P in all types of constructed wetlands is usually low, unless special substrates with high sorption capacity are used. An increased wetland area in a river catchment may serve to maintain base flows during the dry season and thus the ecosystem functioning during this period.

To reduce the risk of salinization, species loss, eutrophication, and lowering of the water table of shallow lakes in Southern Europe, restrictions on the human use of water are needed. Because more than 80% of the freshwater abstraction in most Mediterranean countries is used for irrigated agriculture, this implies less use of irrigation water, more effective irrigation and water distribution systems, and improved recycling of water, including wastewater, within catchments. This is likely to entail changes in water rights and water pricing (Brookshire et al., 2004). In critical areas, intensive irrigated agriculture will have to be substituted by less water demanding rain-fed agriculture or by grazing livestock systems, with important consequences also for local cultures and lifestyles. An example is Turkey, where already >500 km^2 of the freshwater lake area has been lost as a result of surface- and ground water abstraction for irrigated crop farming in the now drier climate. Lake Akşehir, Turkey, with an area of 361 km^2, has recently dried out completely, and three fish species (*Alburnus nasreddini*, which was only found in Lake Akşehir, and *Gobio gobio intermedius* and *Leuciscus anatolicus*, both endemic to the region) have been lost. It is likely that these losses will become more severe in the region with increasingly drier conditions due to climate warming. Interestingly, until the middle of the 20th century, the Anatolian plateau was famous for less water–demanding animal farming with herding animals at the edge of the wetlands, which earlier and during the last glaciations covered most of the plateau.

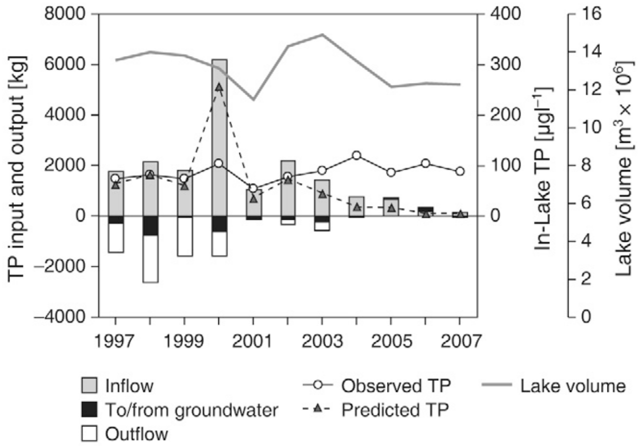


Fig. 10. Mass balance of total phosphorus (TP) on Lake Mogan, a large and shallow lake in Turkey (drainage area: 925 km^2; surface area: 5.4–6 km^2; Z_{max}: 3.5 m; Z_{mean}: 2.1 m) showing annual input, output, and retention of TP as well as the annual mean lake TP concentration and the lake volume. The mass balance is based on water samples collected fortnightly in spring, summer, and autumn and with monthly intervals in winter (Beklioglu et al., 2006), lake level recorded daily from a fixed gauge, flow rates in inlet and outlet, and ground water input calculations (General Directorate of Electrical Power, Resource Survey & Development Administration [EIE, 2007]). Monthly air temperature, rainfall, and evaporation data were recorded by a meteorological station located within the lake catchment.

Conclusions

The predicted climate change will most probably enhance the P loading to lakes and lead to an impoverished ecological status, with higher importance of cyanobacteria in eutrophic lakes, less grazer control by zooplankton due to higher fish predation, diminished effects of macrophytes as a refuge for zooplankton, and reduced water clarity. Because the critical nutrient loading for good ecological status according to the Water Framework Directive in EU will likely decline, a further reduction of the external nutrient loading is required to counteract this deterioration. Adaptations in the northern temperate zone should include more sustainable agriculture; improved nutrient and soil management with less loss of nutrients to surface waters; reduced loading from point sources; and, where appropriate, re-establishment of lost wetlands, riparian buffer zones, and re-meandering of channelized streams. In the arid Southern Europe, restrictions on human use of water are needed, in particular for the irrigated agriculture, and this will likely have to be obtained through changes in water markets and less intensive agriculture and drought control. The success of these measures will largely lay on the involvement and participation of local communities in the process of adaptation.

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