

# Recent changes in the nutrient status of a soft-water *Lobelia* lake, Hampen Sø, Denmark

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Nutrient-poor, low-productive (oligotrophic) soft-water lakes in the Atlantic areas of West and North-West Europe – the so-called *Lobelia* lakes – are of high conservation value as their low nutrient status favours a particular submerged macrophyte flora with isoetids, which are becoming increasingly rare or threatened due to nutrient enrichment (eutrophication) associated with landuse changes and urbanisation. European Union member states have a duty of care, under the Habitats Directive, to protect the biodiversity of oligotrophic to mesotrophic (moderately productive) standing waters.

In Denmark the majority of *Lobelia* lakes are located on sandy soils in central and western Jylland. These lakes are clear-water ecosystems poor in nutrients and organic carbon and with a unique macrophyte vegetation of predominantly *Lobelia dortmanna* (Water Lobelia), *Littorella uniflora* (Shore-weed) and *Isoetes lacustris* (Quill-wort). Severe deterioration of isoetid plant communities is reported from Denmark and many other European countries (e.g. Arts 2002; Pedersen *et al.* 2006). The isoetids are low and slow growing with relatively poor competitive capabilities. These characteristics make them more sensitive to decreased light levels than other macrophyte groups (Middelboe & Markager 1997) and consequently also particularly vulnerable to eutrophied and turbid waters.

In an ongoing project we are investigating the limnological development of two *Lobelia* lakes in mid-Jylland during the last 1000 years (Hampen Sø and Rævsø, situated 2.5 km apart). The Hampen Sø investigation is part of a Geocenter Denmark funded project with the title: *Lake response to climate change during the last 1000 years*. In this paper we present the first results from Hampen Sø with emphasis on changes in the nutrient status of the lake through the last *c.* 300 years as inferred from diatom and microfossil analyses. Today Hampen Sø is influenced by nutrient enrichment and has a mixture of two vegetation types that normally belong to two different lake types, namely the lake's original isoetid vegetation plus species of fast-growing and tall elodeids, the latter being favoured by increased nutrient levels (Moeslund 2000). Palaeolimnological methods are used to explore the timing and possible causes of the nutrient enrichment. These are of significance for understanding the environmental threat to the lake ecosystem, and for determining

its baseline, or reference conditions, defined by the European Water Framework Directive (WFD) as conditions under minimal anthropogenic disturbance.

## Material and methods

Hampen Sø is located in mid-Jylland on sandy soils just west of the Main Stationary Line (Fig. 1). The lake has a surface area of 76 ha, a mean water depth of 4.3 m, a maximum depth of 13.1 m, and a topographic catchment area of 916 ha (Moeslund 2000). The lake is a seepage lake, i.e., a closed lake without natural inlets or outlets. In 2009 a *c.* 2 m long sediment core with humic, slightly silty and sandy gyttja was retrieved from the lake at a water depth of 9.66 m. The uppermost 1 m of the sediment sequence, which spans approximately the last 1000 years, has been dated by accelerator mass spectrometry (AMS)  $^{14}\text{C}$ -age determination (one sample) and the  $^{210}\text{Pb}$  dating method (Appleby 2001); here we focus on the period between *c.* AD 1750 and today. The nutrient status of the lake during this time period is inferred from diatom and microfossil analyses, and changes in the catch-



Fig. 1. Map of Denmark with the location of the study site, Hampen Sø. Sandy soils dominate west of the Main Stationary Line.

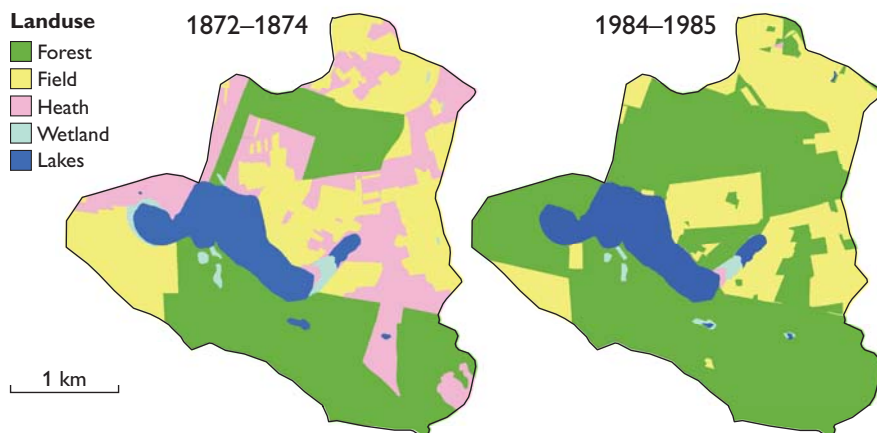


Fig. 2. Landuse in the topographic catchment of Hampen Sø in 1872–1874 (left) and 1984–1985 (right).

ment landuse are estimated from land classification on two cadastral maps from 1872–74 and 1984–85. Diatom data are presented as percentages and 300–400 valves (halves of their siliceous cell walls) were counted per sample. Macrofossils are presented as concentrations.

### Chronology

The uppermost 28 cm of the lake sediments were dated by  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  assay, estimated from 15 samples spanning the time period 1900–2009. A sample of deciduous leaf fragments found at 117 cm depth was AMS  $^{14}\text{C}$ -dated with the result cal. AD 910–1020 (range  $2\sigma$ ). An age–depth curve was constructed for the depth interval 0–117 cm by linear interpolation between the  $^{210}\text{Pb}$ - and  $^{137}\text{Cs}$ -dated sediments and the  $^{14}\text{C}$  date at 117 cm.

### Landuse change in the catchment area

According to the cadastral maps the most significant landuse change in the Hampen Sø catchment area since the end of the 19th century is the virtual disappearance of heathland (Fig. 2). Between c. 1870 and 1980 its area has decreased from c. 24% to less than 1%, while the forested area has increased from c. 36% to 64%. The area of arable land has stayed approximately the same during this time period. The former heathland has been planted with predominantly coniferous trees (pine and spruce) for timber.

### Development of the nutrient status over the last c. 300 years

There are two distinct changes in the Hampen Sø diatom assemblages: in the mid-18th century and around the 1940s (Fig. 3). The first change is defined by a clear decrease in planktonic taxa from c. 28% to 8%. Variations in the abun-

dance of planktonic species in temperate lakes are often associated with either changing water levels (Heinsalu *et al.* 2008; Laird & Cumming 2009) or eutrophication (Sayer *et al.* 1999; Bennion *et al.* 2004). *Cyclotella comensis*, an oligotrophic species, dominates the planktonic assemblages prior to the decrease, after which benthic taxa belonging particularly to the genus *Fragilaria* (including *Staurosira*, *Staurosirella* and *Pseudostaurosira*) increase. Such a change most likely signifies lowering of the water level. The macrophyte vegetation on the other hand does not show distinct changes, although an increase in carophytes (*Nitella* sp. and *Chara* sp.) can be observed and might suggest that they have been favoured by better light conditions due to shallower water. As the core was collected in the deepest part of the lake, the concentrations of littoral species such as *Lobelia* and *Isoetes* should be considered with some caution, due to their limited seed and spore dispersal.

The first forest plantations in the Hampen Sø catchment area date back to 1805. At first success was limited until the planting methods were changed in the 1830s. An increase in forest cover will increase evapotranspiration from the catchment area and hence could affect the water level in the lake due to a decrease in the ground water table. We initially assumed that the plantations may have affected the lake levels of Hampen Sø, however, the water-level decrease indicated by the diatom assemblages clearly occurs before the planting of trees. On the other hand, there is evidence from several studies based on a number of proxies that precipitation decreased in Scandinavia during the latter part of the Little Ice Age (e.g. Linderholm & Chen 2005; De Jong *et al.* 2009). Hence the diatom-inferred decrease in Hampen Sø water levels in the mid-18th century could reflect this suggested change in precipitation.

The second clear change in the diatom assemblages occurs around the 1940s, marked by a pronounced increase in the mesotrophic species *Cyclotella pseudostelligera* and *Fragilaria*

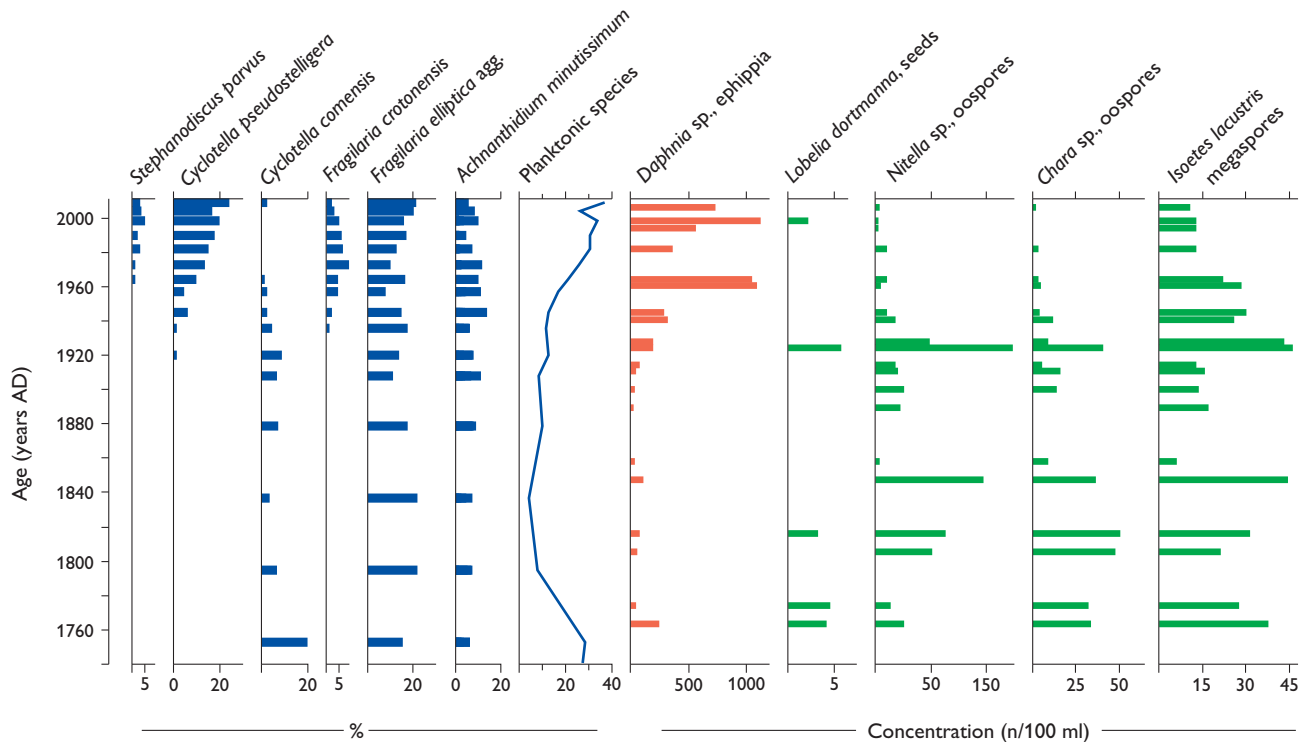


Fig. 3. Diatom and macrofossil diagram showing selected abundant species. Diatoms (blue) are given as percentages. Macrofossils (*Daphnia* ephippia (red) and submerged macrophyte remains (green)) are shown as concentrations (remains per 100 ml fresh sediment). Ages based on the constructed age–depth curve are given on the left of the diagram.

*crotonensis* (up to 23% and 9%, respectively). Their increase is followed by the appearance of the eutrophic *Stephanodiscus parvus* in the early 1960s. These taxa indicate increased nutrient concentrations and, with higher phytoplankton productivity, also decreased transparency of the lake water. The charophytes *Nitella* sp. and *Chara* sp., which can occur at water depths of over 10 m, exhibit a decreasing trend from the 1920s (Fig. 3), whereas according to recent surveys (Moeslund 2000), tall elodeids, which occur in shallower water (such as *Potamogeton* and *Myriophyllum* species), have become more abundant. Many elodeids are scarce in sediment records (such as in Hampen Sø) due to lower seed production and limited dispersal compared to other macrophytes. The reasons for these changes are likely to be the increased nutrient load from the catchment area (intensified field fertilisation and particularly waste waters from a farm and summer houses near the lake, Moeslund 2000) which, with increasing phytoplankton productivity, also affect water transparency.

Concentrations of ephippia (resting eggs) of the water flea genus *Daphnia* began to increase around the same time as the change in macrophyte vegetation is observed with the highest concentrations from the 1960s onwards (Fig. 3). *Daphnia* resting eggs are generally produced when conditions dete-

riorate due to e.g. overcrowding, limited food availability, extreme changes in the environment or increased predation (Korhola & Rautio 2001). In Hampen Sø, we interpret the increased numbers of resting eggs as simply an indication of larger *Daphnia* populations due to a general increase in biological production. In addition, more suitable habitats could be represented by the tall elodeids, which function as refuge from fish predation (Jeppesen *et al.* 1997).

According to surveys made in Hampen Sø from 1971 to 1999, nutrient concentrations were high from the beginning of the survey until the mid-1980s (summer-time total phosphorus value  $c. 70\text{--}80 \mu\text{g l}^{-1}$  and total nitrogen  $c. 800\text{--}1000 \mu\text{g l}^{-1}$ ), after which concentrations decreased to present-day levels of  $<30 \mu\text{g l}^{-1}$  total phosphorous and  $<600 \mu\text{g l}^{-1}$  total nitrogen (Moeslund 2000). This decrease in concentrations is attributed to the cessation of waste water effluents (in particular animal manure) from the nearby farm. The decreased nutrient concentrations from the mid-1980s onwards are not reflected in the biota. This could be explained by the sediment nutrient pool which, due to its limited binding capacity (low iron:phosphorus ratio), releases particularly phosphorus back into the water. This is then taken up by phytoplankton and macrophytes (Moeslund 2000).

It is noteworthy that the abundance of planktonic diatoms slowly begins to increase before the appearance of the meso- and eutrophic diatom taxa (Fig. 3). This could suggest slightly increasing water levels from the late 19th century onwards, which may partly have been masked by the marked increase in the planktonic diatom taxa indicating eutrophication.

## Conclusions and future work

Distinct signs of anthropogenic disturbance in Hampen Sø can be seen in the 1920s (reflected in macrophyte vegetation and *Daphnia* abundance) indicating the onset of nutrient enrichment. Clear indications of eutrophication are evident from the 1960s onwards in all proxies. Although water-column nutrient concentrations have decreased since the mid-1980s, no change is observed in the biota. This could be attributed to increased internal loading of nutrients from the sediments. Compared to the majority of Danish lakes, which have been impacted by anthropogenic activities for centuries (Bradshaw *et al.* 2005, 2006), the timing of these changes is surprisingly late. It appears that sandy soils of central and western Jylland have been less intensively used for crop cultivation in the past and hence lakes located in such settings are less affected. According to our results, baseline or reference conditions at Hampen Sø, as defined by the European Water Framework Directive, could be set at the early 1900s. These reference conditions only define the state of the lake before intensified human impact. Our data show that climate exerts a notable influence on the groundwater-fed lake and its biota implying that the physical, chemical and biological status of the lake has changed naturally in the past. In the ongoing work the lake's response to climate change will be explored further.

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