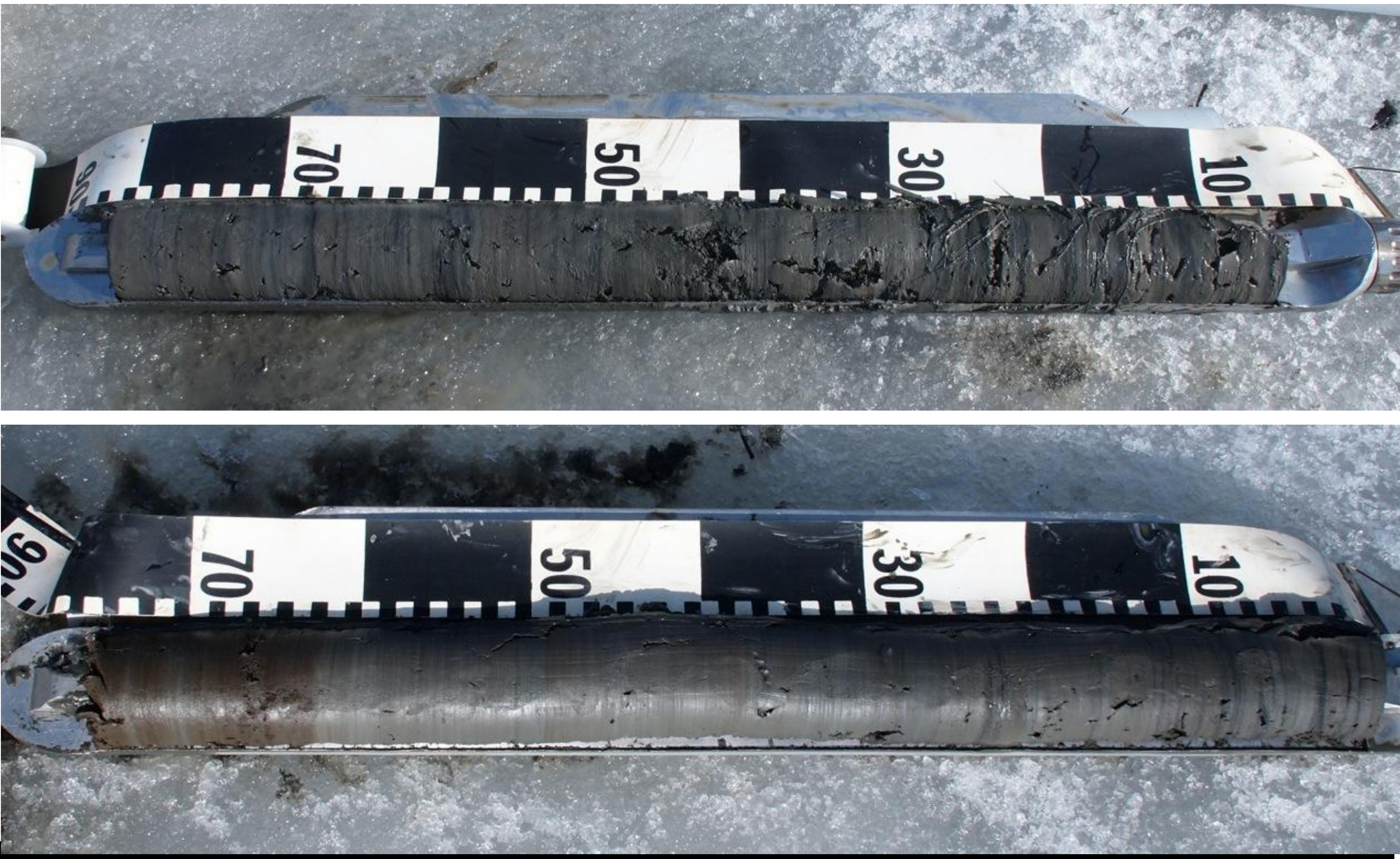

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Final report to Bioforsk

ECRC Research Report Number 162

H. Bennion, G. Clarke, B.J. Goldsmith, H. Yang, K. Roe, S. Goodrich & H. Borch

August 2015

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ECRC Research Report Number 162

Ensis Ltd.
Environmental Change Research Centre
University College London
Pearson Building, Gower St.
London, WC1E 6BT

Cover photo: Russian cores from Lake Vastadtjern. Håkon Borch, Bioforsk.

Executive summary

This project reports on analysis of a set of sediment cores collected from Lake Vastadtjern in Norway in 2013-2014, spanning a total sediment depth of c. 600 cm. Multi-proxy palaeoecological techniques, principally diatoms, macrofossils and Cladocera, were employed to assess environmental change at the lake over the last c. 6000 years. The project aims to determine ecological and chemical reference conditions of the lake to help inform the setting of reference conditions for catchments dominated by clay-rich soils.

Radiometric methods were applied to the cores in order to date the recent sediments but unfortunately ^{210}Pb activities in the upper 50 cm were low and hence there is great uncertainty in the dates assigned. Owing to poor diatom preservation in some core sections, only twelve samples could be analysed for diatoms. A diatom-TP transfer function was applied to the diatom data to reconstruct trophic status. For the macrofossil analysis a total of 25 levels was examined and for chitinous Cladocera remains a total of 20 samples was analysed.

The diatom results suggest that the site has experienced three major changes in environmental conditions. In its early history (below approximately 500 cm) the presence of species characteristic of brackish and marine environments indicates a period when the site was saline. In its middle history (c. 500 to 125 cm) the diatom flora is relatively stable and indicates freshwater and moderately rich conditions, typical of a naturally productive lake. In the recent history, the diatoms change markedly and indicate a shift from pelagic productivity to more benthic production. The macrofossil data suggest that this may be a result of higher plant biomass in the site. Furthermore, it would appear that there was a period of increased nutrient input between approximately 1850 and 1960 which has since been alleviated. The macrofossil data suggest a marked change from dominance by Nymphaeaceae in the lower core to the presence of broad leaved *Potamogeton* spp. in the central section of the core (130-20 cm), followed by a slight increase in Nymphaeaceae again in the uppermost sediments. There were marked changes in the Cladocera remains from a diverse assemblage of pelagic and plant-associated taxa to an assemblage comprising smaller taxa and several species indicative of higher productivity. The causes of the shifts are uncertain but a combination of nutrient increase, alterations in lake habitat (macrophyte coverage) and water depth, and changes in fish predation pressure are all likely drivers.

Based on the multi-proxy palaeoecological study, the reference conditions of Lake Vastadtjern can be described as those typical of a naturally mesotrophic lakes with a macrophyte community dominated by floating-leaved Nymphaeaceae, a diverse Cladocera assemblage comprising *Daphnia* spp., *Bosmina* spp. and several benthic and plant-associated taxa and a diatom community comprising of *Aulacoseira* spp and *Tabellaria flocculosa*. The data indicate that there was a major change in the lake at c. 150 cm depth with a very different flora and fauna above this depth from that of the lower core. There appear to be no ecological shifts associated with the increase in organic matter in the central part of the record (c. 130-190 cm in VASTR). While the exact causes of the ecological shifts cannot be established, there is a suggestion that the changes may at least in part be a result of recent nutrient enrichment.

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1. SPECIFICATION

1.1 Statement of understanding, purpose and aims of project

The aim of this project was to investigate the history of Lake Vastadtjern, Norway using palaeoecological methods as part of a larger project on 'Reference conditions for phosphorus runoff from forested areas with arable soil properties' led by Bioforsk - Norwegian Institute for Agricultural and Environmental Research. In south-eastern and central Norway the soils in the main agricultural areas consist of marine clays. The marine clay deposits contain apatite-phosphorus (P), and waters in these areas are, therefore, expected to have high reference levels for total P (TP) (Borch *et al.*, 2008). The project employs multi-proxy palaeoecological techniques, principally diatoms, macrofossils and Cladocera, to assess environmental change at the site over the last c. 6000 years and determine ecological and chemical reference conditions of the lake to help inform the setting of reference conditions for catchments dominated by clay-rich soils.

2. METHODS

2.1 Core collection and extrusion

A series of cores were collected from Lake Vastadtjern, Norway (Nxx, Exx- Hakon to add lat and long) on 10 April 2013. A short gravity core (VASTG), 30 cm in length, was taken to capture the most recent sediments and was extruded at 1cm intervals. Five Russian cores (VASTR) were taken as follows: core 1=0-65 cm, core 2= 65-140 cm, core 3=140-215 cm, core 4=205-280 cm, core 5=270-345 cm, with core 1 starting at approximately 30 cm sediment depth and thus continues from the bottom of the gravity core. Additionally a deeper Russian core (c. 270cm long) was collected on XX March 2014 which continues on from core 5, yielding a total sediment depth of c. 600 cm (Hakon to add/check).

2.2 Lithostratigraphic analyses

The percentage dry weight (DW) which gives a measure of the water content of the sediment, the percentage loss on ignition (LOI) which gives a measure of the organic matter content and the percentage carbonate (CO_3) content were undertaken using standard techniques (Dean, 1974; Heiri *et al.,* 2001) on every other sample from VASTG at UCL. DW and LOI were carried out on VASTR at Bioforsk.

2.3 Dating

Dried sediment samples from Lake Vastadtjern cores VASTG and VASTR were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Environmental Radiometric Facility at University College London, using ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector. ^{210}Pb (half-life 22.3 years) is a naturally-produced radionuclide, derived from atmospheric fallout (termed unsupported ^{210}Pb). ^{137}Cs (half-life 30 years) and ^{241}Am are artificially produced radionuclides, introduced to the study area by atmospheric fallout from nuclear weapons testing and nuclear reactor accidents. They have been extensively used in the dating of recent sediments (Appleby, 2001). ^{210}Pb was determined via its gamma emissions at 46.5keV, and ^{226}Ra by the 295keV and 352keV gamma rays emitted by its daughter isotope ^{214}Pb following three weeks storage in sealed containers to allow radioactive equilibration. ^{137}Cs and ^{241}Am were measured by their emissions at 662keV and 59.5keV (Appleby *et al.*, 1986). The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy gamma rays within the sample (Appleby *et al.*, 1992).

2.4 Diatom analysis

A total of 20 samples throughout VASTG and VASTR were prepared for diatom analysis following the methods of Battarbee *et al.* (2001). Where possible, at least 300 valves (siliceous component of the cell wall bearing the taxonomic features) were counted from each sample using a Zeiss research microscope with a 100x oil immersion objective and phase contrast. Principal floras used in identification were Krammer & Lange-Bertalot (1986-1991). All slides are archived at the ECRC. A summary diagram of the diatom stratigraphy (showing only those taxa present with a percentage relative abundance of >2 % in at least one sample) was produced using C2 (Juggins, 2003) – see Figure 7. All diatom taxa identified in the core are listed in Appendix 1.

Summary statistics of the diatom data were calculated for each sample in the core including the number of taxa observed and the Hill's N2 diversity score which is an estimate of the effective number of taxa (Hill & Gauch, 1980). Custer analysis was performed on the core data in an attempt to identify the major zones in the diatom record using ZONE v.1.2 (Juggins, 1991). ZONE is an MS-DOS program which employs a variety of constrained clustering techniques (ConsLink, ConISS, SplitLSQ and SplitINF) from which common splits can be identified. Unfortunately the wide spacing of the samples within the core and complications caused by dissolution and mineral contamination rendered this technique inconclusive and the results are not therefore presented.

Principal components analysis (PCA), an indirect ordination technique (ter Braak & Prentice, 1988), was used to analyse the variance downcore within the diatom assemblages using C2 (Juggins, 2003). The technique summarises the main changes in the data and helps to identify zones of change within complex species-rich data sets. The sample scores for PCA axis 1 are given. Where scores between two neighbouring samples in the core differ markedly this indicates that the assemblages have undergone substantial change between these two points in the core. The scores are also plotted in the stratigraphic diagram to illustrate the timing of any shifts and whether these were gradual or abrupt.

A diatom-TP transfer function was applied to the diatom data to reconstruct trophic status using 1) a training set of 56 relatively large, deep lakes (> 10 m maximum depth) from Scotland, Northern Ireland, Cumbria, southern Norway and central Europe with annual mean TP concentrations ranging from 1-73 µg TP L^{-1} and a median value of 22 µg TP L^{-1} (Bennion *et al*., 2004); the best model was generated with simple weighted averaging and inverse deshrinking (ter Braak and van Dam, 1989); this model has a coefficient of determination (r^2) between observed and inferred values of 0.75 and a root mean squared error of prediction (RMSEP based on the jack-knifing cross validation method) of 0.25 $\log_{10}$ µg TP L^{-1}, and 2) a Northwest European training set of 152 relatively small, shallow lakes (< 10 m maximum depth) with annual mean TP concentrations ranging from 5-1190 µg TP L^{-1} and a median value of 104 µg TP L^{-1}, and an r^2 of 0.91 and a RMSEP of 0.21 $\log_{10}$ µg TP L^{-1} for the weighted averaging partial least squares two-component (WA-PLS2) model (Bennion *et al*., 1996). The training set containing the greatest percentage of taxa present in the fossil samples was judged to be the most appropriate. All reconstructions were implemented using C2 (Juggins, 2003).

2.5 Macrofossil and Cladocera ephippia analysis

For the macrofossil analysis a total of 25 levels were examined from VASTG and VASTR as shown in Table 1.

Table 1 Sample numbers and the corresponding depth in the gravity (G) and Russian (R) cores of samples analysed for macrofossils

Sample number	Depth (cm)	Actual depth (cm)
1	1G	1
2	6G	6
3	11G	11
4	16 G	16
5	21G	21
6	0R	30
7	11R	41
8	21R	51
9	41R	71
10	60R	90
11	80R	110
12	100R	130
13	125R	155
14	150R	180
15	175R	205
16	200R	230
17	225R	255
18	250R	280
19	300R	330
20	330R	360
21	452R2	452
22	454R2	454
23	502R2	502
24	552R2	552
25	602R2	602

A measured volume of sediment (~30 cm^3, the exact volume was assessed using water displacement) was analysed for each sample. Samples were sieved at 350 and 125 microns and the residues from each were transferred using distilled water to plastic vials for storage. The entire residue from the 350 micron sieve was examined under a stereomicroscope at magnifications of x10-40 and plant and animal macrofossils (zooplankton ephippia) were identified and enumerated. A quantitative sub-sample, approximately one fifth of the sample, from the 125 micron sieve sample was analysed for smaller remains such as leaf spines.

All plant material was identified by comparison with herbarium documented reference material held at UCL. It was not always possible to ascribe remains to species level, thus in some cases an aggregate group of species corresponding to the highest possible taxonomic resolution was used (for example, *Potamogeton pusillus* / *P. berchtoldii*). The data are presented as numbers of remains per 100cm3 of wet sediment.

Analysis of the sedimentary cladoceran record based on chitinous remains alone is incomplete due to the absence of ephippia, with a greater diversity of littoral chydorids being preserved compared to planktonic cladocerans (Hofmann 1987a, b, c; Hann *et al*., 1994). This arises because planktonic cladocera, particularly large bodied species, are most susceptible to fish predation (Brooks & Dodson, 1965). Developments in cladoceran based palaeolimnology have increasingly incorporated ephippia data (Jeppesen *et al.,* 2001) and have consequently demonstrated that the sedimentary assemblage is a good reflection of the population that formed it (Davidson *et al*., 2007). Thus, in order to determine the past effects of fish and record shifts in ecosystem function it is vital that ephippia are enumerated. The ephippial remains in this study were separated and counted alongside the macrofossil remains using a binocular microscope, thus the counts are based on the analysis of at least 30 cm^3 of sediment and are expressed as numbers per 100 cm^3. *Daphnia* ephippia were identified to the highest taxonomic resolution possible, with remains separated into three different groups. These were: *Daphnia hyalina* agg. (consisting of a number of smaller bodied species, including *Daphnia longispina*, *D. hyalina, D. cucullata),* *D. galeata* and *D. pulex*. *Simocephalus* spp and *Ceriodaphnia* spp. are the highest taxonomic resolution for the various *Ceriodaphnia* and *Simocephalus* species.

2.6 Chitinous Cladocera analysis

Cladocera remains were analysed from 20 levels throughout VASTG and VASTR (sample numbers 1-20 in Table 1) using an adaptation (Davidson *et al*., 2007) of standard techniques (Frey, 1986; Korhola & Rautio, 2000). Chitinous remains (head shields, carapaces and post abdomens) along with small ephippia were counted using a light microscope at 40× to 400×.Remains were identified using Frey (1958, 1959, 1964), Flössner (1972) and Alonso (1996). Counting of individuals followed the minimum number method, where head shields, carapaces and post-abdominal claws are tabulated separately, and the count for each species is the number of the most numerous remains. The occurrences of the various taxa represented by chitinous remains are expressed as percentages or relative abundances.

It should be noted that in the lower section of the core the samples were very hard to clean due to the clay content of the sediment making identification difficult. In particular this affected the identification of the *Bosmina* head capsules as identification of these remains relies on locating the position of the lateral head pore which is particularly hard if the sample is dirty. Five additional Cladocera samples will be selected for analysis from the bottom of the core and the analysis will be completed by spring 2016. The results for these will be reported separately.

The results of the macrofossil and Cladocera analyses were plotted as stratigraphic diagrams using C2 (Juggins, 2003).

3. Results

3.1 Lithostratigraphic analyses

The VASTG gravity core was inorganic throughout with LOI% ranging from ~5-9%, and carbonate content was low at 1-2% (Fig. 1). DW% was relatively high and more variable, fluctuating between 35 and 62%, with the higher values near the base of the core and a gradual trend towards lower values in the upper core (Fig. 1). Organic matter in VASTR was low in the section below 200 cm at <12% then sharply increased to a peak of 35% at 170 cm before sharply declining again to fluctuatiing values of 15-25% in the section 130-160 cm (Fig. 2 and Fig. 3). LOI% values were low and stable in the uppermost 130 cm of the VASTR core at 5-10%, being similar to those seen in VASTG, and reflecting the clay-rich nature of the soils.

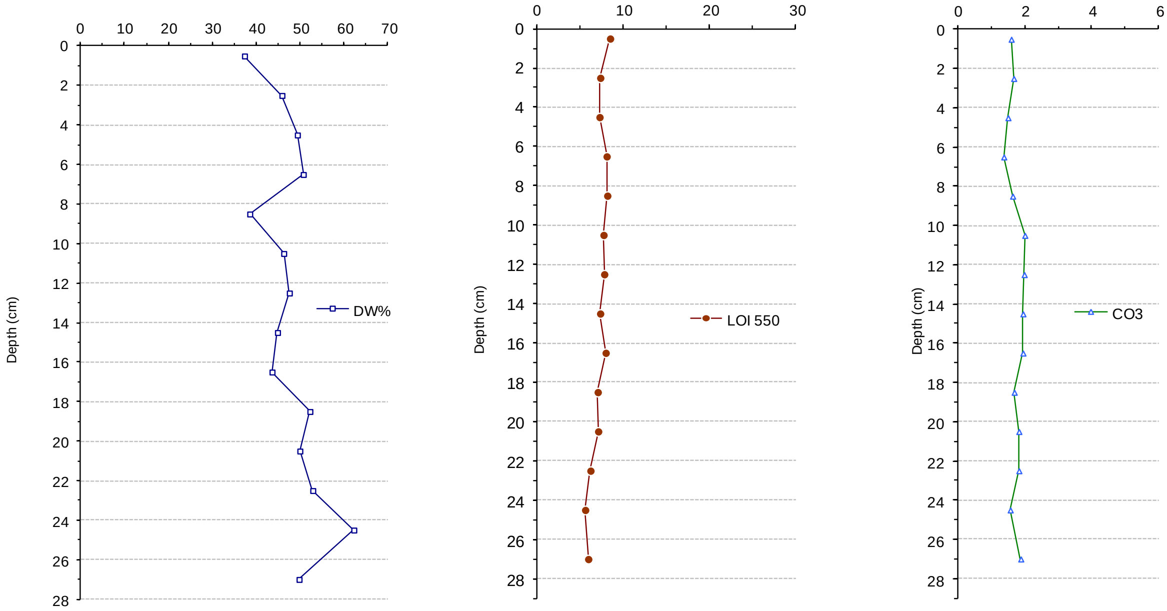


Figure 1 Percentage dry weight (DW), organic matter (LOI) and carbonate (CO_3) profiles of VASTG

Figure 2 Photograph of VASTR core 2, 65-140 cm, showing the change to more organic sediment at c. 130 cm.

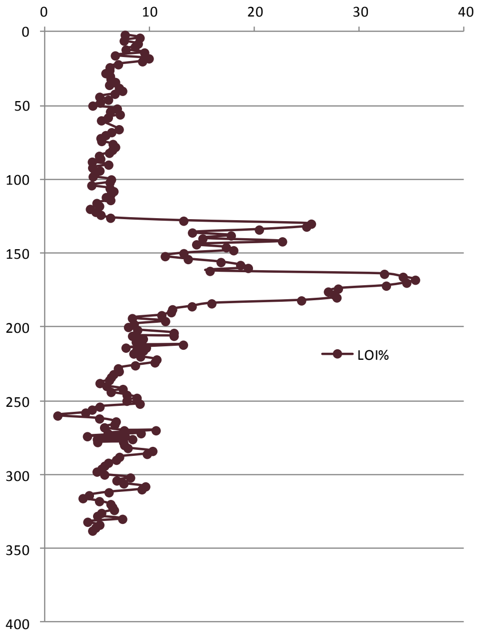


Figure 3 Percentage organic matter (LOI) profile of VASTR

3.2 Dating

VASTG (Gravity core)

^{210}Pb activities in the sediments are low and it is difficult to estimate at which depth total ^{210}Pb activity reaches equilibrium with the supported ^{210}Pb (Table 2, Fig. 4a). Unsupported ^{210}Pb activities, calculated by subtracting ^{226}Ra activity (as supported ^{210}Pb) from total ^{210}Pb activity, are low and decline irregularly with depth (Fig. 4b). In the 2-6 cm section and at 22.5 cm, unsupported ^{210}Pb activities are even close to zero, suggesting rapid sediment accumulation in those depths.

The ^{137}Cs activity versus depth shows a peak at 27 cm (sample 26-28 cm) (Table 3, Fig. 4c). This peak is likely to be derived from the atmospheric testing of nuclear weapons with maximum fallout in 1963.

Use of the CIC (constant initial concentration) model was precluded by the non-monotonic variation in unsupported ^{210}Pb activities. ^{210}Pb chronologies were calculated using the CRS (constant rate of ^{210}Pb supply) dating model (Appleby & Oldfield, 1978). The CRS dating model places the 1963 depth at 24 cm, which is not in agreement with the depth suggested by the ^{137}Cs record. Radiometric chronologies and sedimentation rates of the core were corrected by assuming that 27 cm was formed in 1963. The results are given in Table 4 and shown in Figure 5. Sedimentation rates in the core vary, with a mean of 0.38 g cm^{-2} yr^{-1} in the last 50 years. The highest sedimentation rate is 3.26 g cm^{-2} yr^{-1}.

VASTR (Russian core)

Similarly to VASTG, unsupported ^{210}Pb activities are very low in this core (Table 5, Fig. 6b). Relatively high counting errors make the unsupported ^{210}Pb activities little use in dating.

The ^{137}Cs activity versus depth shows a peak at 35.5 cm (sample 35-36 cm) (Table 6, Fig. 6c). Rapid change from a very low value in the deeper sediments to the peak value at 35.5

cm in the ^{137}Cs activities suggests that it is almost certain that the peak is derived from the 1963 maximum fallout of the atmospheric testing of nuclear weapons. This site might be affected by the 1986 Chernobyl accident, as there is a small peak in between 12 and 16 cm (Fig. 6c). However, uncertainty is high. It is impossible to use the unsupported ^{210}Pb activities of the core for dating. Based on the ^{137}Cs record of the core, 35.5 cm can be dated to c.1963.

Table 2 ^{210}Pb concentrations in core VASTG

Depth	Dry Mass	Pb-210						Cum Unsupported	
		Total		Supported		Unsupp		Pb-210	
Cm	g cm^{-2}	Bq Kg^{-1}	±	Bq Kg^{-1}	±	Bq Kg^{-1}	±	Bq m^{-2}	±
0.5	0.2437	103.44	10.55	89.66	2.79	13.78	10.91	33.3	18.9
2.5	1.396	96.14	10.1	92.92	2.73	3.22	10.46	117	98.2
5.5	3.5031	81.29	8.89	80.21	2.41	1.08	9.21	158.3	211
10.5	6.6304	108.26	10.27	91.78	2.81	16.48	10.65	335	348
15.5	9.9265	103.49	9.05	84.49	2.33	19	9.35	918.8	484.7
17.5	11.2631	126.5	12.18	93.98	2.87	32.52	12.51	1255	515.1
20.5	13.5166	84.2	5.9	86.93	1.55	-2.73	6.1	1590.7	560.2
22.5	15.0625	98.48	9.45	89.65	2.69	8.83	9.83	1637.8	573
25.5	17.801	83.79	5.53	80.84	1.46	2.95	5.72	1784.7	610.7
27	19.1377	93.36	11.61	80.25	3.28	13.11	12.06	1875.8	622.1
29.5	21.3157	76.94	8	77.06	2.12	-0.12	8.28	2017.2	658.5

Table 3 Artificial fallout radionuclide concentrations in core VASTG

Depth	Cs-137		Am-241	
cm	Bq Kg^{-1}	±	Bq Kg^{-1}	±
0.5	11.36	1.36	0	0
2.5	7.94	1.27	0	0
5.5	8.01	1.11	0	0
10.5	7.08	1.24	0	0
15.5	6.42	0.97	0	0
17.5	11.35	1.35	0	0
20.5	13.93	0.84	0	0
22.5	24.26	1.61	0	0
25.5	20.29	0.82	0	0
27	31.8	2.17	0	0
29.5	23.66	1.27	0	0

Table 4 ^{210}Pb chronology of core VASTG

Depth	Drymass	Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2013	0				
0.5	0.2437	2012	1	2	0.698	1.25	78.9
2.5	1.396	2011	2	2	3.259	5	326.6
5.5	3.5031	2011	2	4	1.745	2.67	779.6
10.5	6.6304	2008	5	4	0.459	0.71	70.3
15.5	9.9265	1997	16	5	0.232	0.35	62.1
17.5	11.2631	1988	25	5	0.256	0.36	62
20.5	13.5166	1983	30	6	0.543	0.71	131.2
22.5	15.0625	1981	32	6	0.428	0.5	171.4
25.5	17.801	1973	40	8	0.226	0.25	313.9
27	19.1377	1963	50	10	0.134	0.15	388

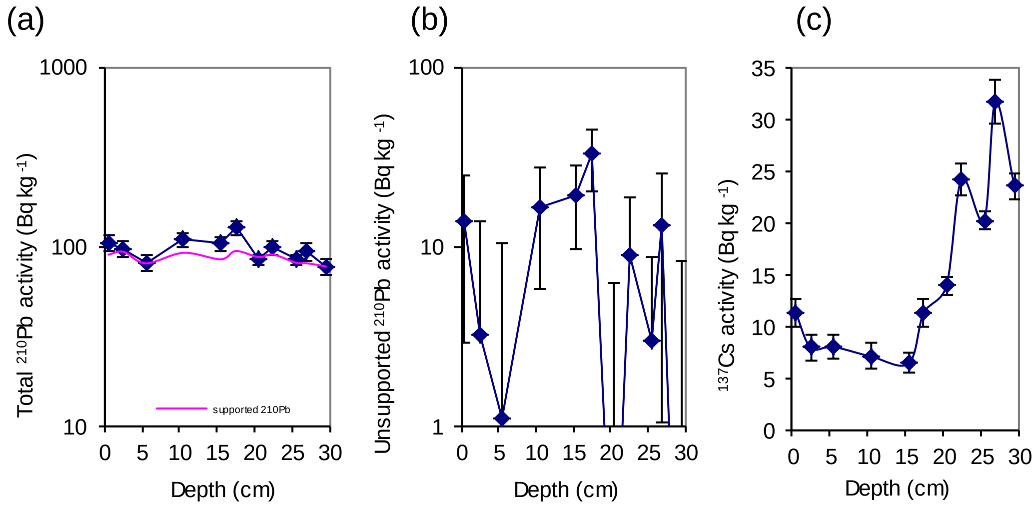


Figure 4 Fallout radionuclide concentrations in core VASTG showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb and (c) ^{137}Cs concentrations versus depth.

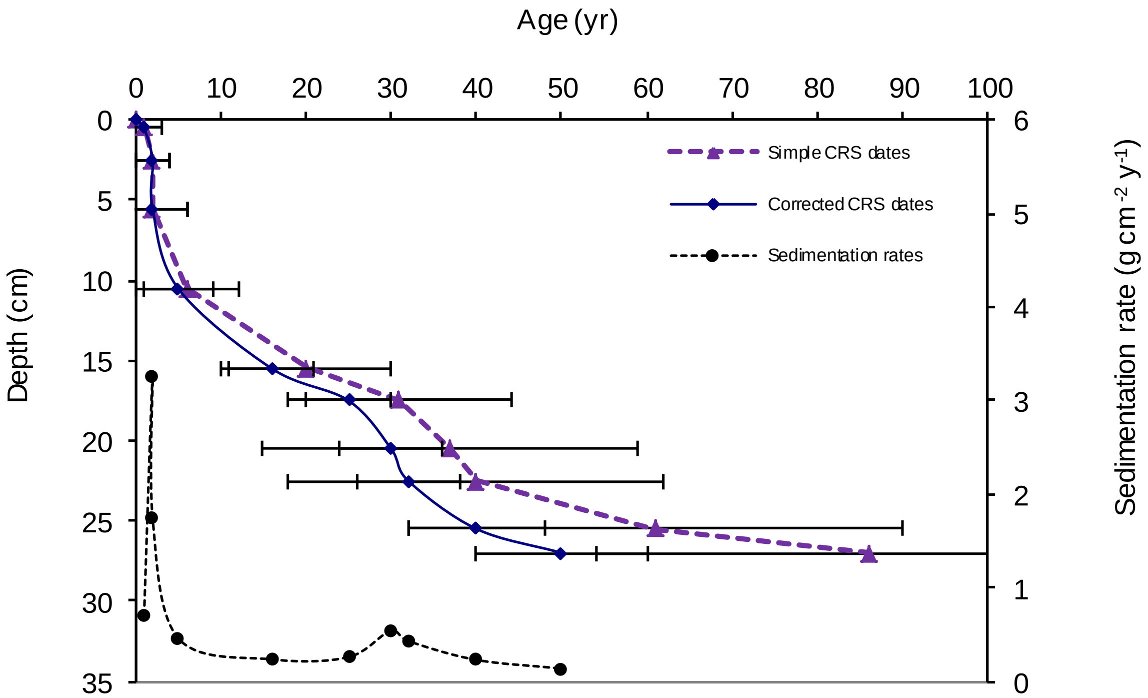


Figure 5 Radiometric chronology of core VASTG, showing the CRS model ^{210}Pb dates and sedimentation rates.

Table 5 ^{210}Pb concentrations in core VASTR

Depth			Pb-210			
	Total		Supported		Unsupp	
cm	Bq Kg^{-1}	±	Bq Kg^{-1}	±	Bq Kg^{-1}	±
0.5	65.7	8.8	90.92	2.99	-25.22	9.29
5.5	86.5	9.69	88.3	3.28	-1.8	10.22
10.5	90.76	9.39	81.03	3.09	9.74	9.88
12.5	101.62	9.63	90.14	2.99	11.48	10.08
15.5	105.29	9.34	82.74	2.85	22.55	9.77
17.5	97.06	10.06	96.07	3.2	0.99	10.56
20.5	86.54	5.21	82.73	1.73	3.81	5.49
23.5	106.18	14.37	129.94	5.1	-23.75	15.25
25.5	74.62	6.55	82.39	2.17	-7.77	6.9
30.5	81.86	7.77	77.73	2.5	4.14	8.16
35.5	76.09	9.4	73.39	3.05	2.7	9.88
40.5	82.8	9.5	70.06	2.96	12.74	9.95
45.5	64.27	8.13	69.41	2.56	-5.13	8.52

Table 6 Artificial fallout radionuclide concentrations in core VASTR

Depth	Cs-137		Am-241	
cm	Bq Kg^{-1}	±	Bq Kg^{-1}	±
0.5	10.29	1.42	0	0
5.5	9.01	1.56	0	0
10.5	8.31	1.36	0	0
12.5	11.61	1.53	0	0
15.5	11.98	1.47	0	0
17.5	8.89	1.43	0	0
20.5	6.7	0.76	0	0
23.5	9.98	2.28	0	0
25.5	10.36	1.05	0	0
30.5	11.05	1.23	0	0
35.5	16.48	1.81	0	0
40.5	2.79	1.3	0	0
45.5	2.7	1.03	0	0

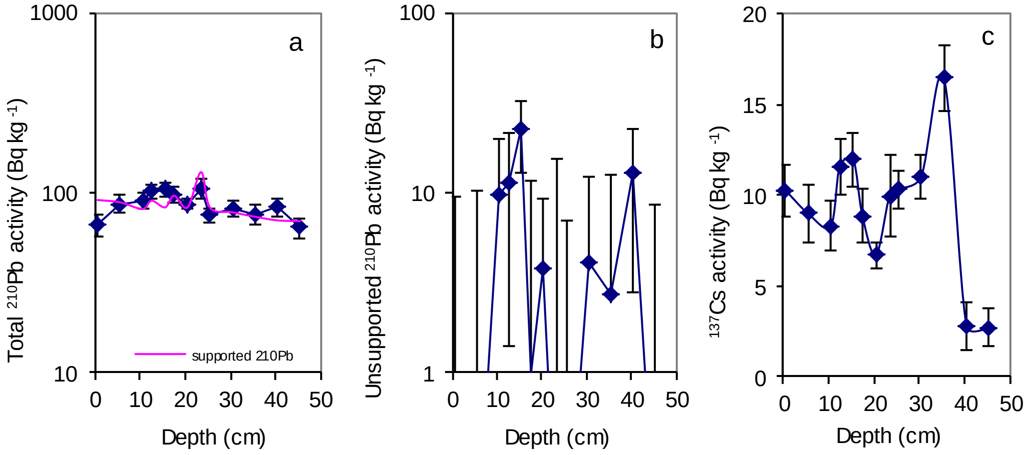


Figure 6 Fallout radionuclide concentrations in core VASTR, showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb and (c) ^{137}Cs concentrations versus depth.

3.3 Diatom analysis

Diatoms were abundant throughout the upper 480 cm of the core and were generally well preserved in most samples.

The quality of diatom samples varied throughout the core with eight of the twenty being either too mineral or with partial diatom dissolution making accurate species identification and enumeration impossible. Mineral material was a major problem within the zones in the 50-125 cm and 250-300 cm sections, with even very dilute samples proving impossible to count accurately. Below 480 cm, the samples showed evidence of dissolution and only very few heavily silicified species (mainly marine) were seen and therefore these samples could not be analysed accurately. The samples analysed are listed in Table 7.

A total of 158 diatom taxa were observed in the 12 samples from the core (Appendix 1) with between 30 and 44 taxa per sample. Between 86 to 96% of the diatom taxa in the fossil samples from the core were present in the Northwest European training set of relatively small, shallow lakes but only approximately 80% were present in the large lakes training set with values dropping to 56% for the 40 cm sample. Caution must therefore be exercised when interpreting the results of the latter.

Table 7 Summary of diatom analysis from the Lake Vastadtjern sediment core

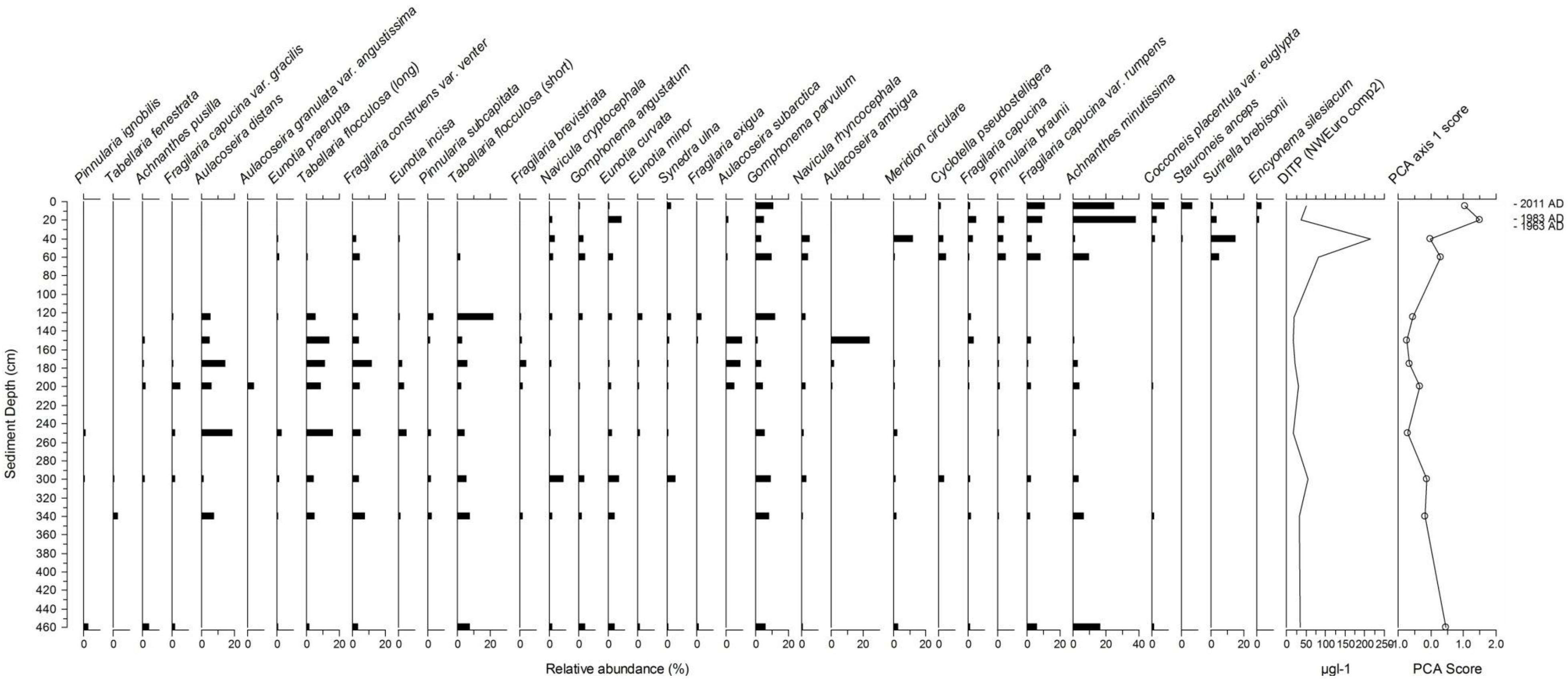
Depth (cm)	Counted?	Slide quality
5	Yes	Good
20	Yes	Good
40	Yes	Good
60	Yes	Good
80	No	Very high mineral content – diatoms present
100	No	Very high mineral content – diatoms present
125	Yes	High mineral content, but analysed
150	Yes	Good
175	Yes	Good
200	Yes	High mineral content, but analysed
225	No	High silt content – diatoms present
250	Yes	High mineral content, but analysed
300	Yes	High mineral content, but analysed
340	Yes	High mineral content, but analysed
390	No	Very high mineral content – diatoms present
450	No	Very high mineral content – diatoms present
480	Yes	High mineral content, but analysed
510	No	Dissolution problems – Marine diatoms present
540	No	Dissolution problems – Marine diatoms present
570	No	High mineral content – no diatoms present

There were some marked changes in the assemblage during the period represented by the core (Fig. 7). The uppermost 20 cm was dominated by *Achnanthes minutissima* (*Achnanthidium minussimum*) alongside a number of other benthic taxa (e.g. *Fragilaria* spp, *Pinnularia* spp., *Cocconeis placentula* and *Gomphonema parvulum*). Below this there was a peak of *Surirella brebisonii* at around 40 cm and a decline in *A. minutissima*. The zone below this was very high in mineral content to about 125 cm and diatom counts were not possible. Below 125 cm to a depth of 480 cm, the assemblage appeared to be relatively stable in terms of the common taxa. Benthic *Fragilaria* spp. species were still common, but the samples were mostly dominated by *Aulacoseira* spp. with *Tabellaria flocculosa* also present at relatively high abundance.

The sample quality between 340 and 480 cm was very poor and diatom analysis not possible. A count was made of the 480 cm level, which was similar to the upper levels (with higher PCA axis 1 scores). Below 480 cm the samples were again of very poor quality with high mineral content and low diatom concentration (relative to mineral content). What diatom valves were present were of brackish / marine origin with *Grammatophora cf. oceanica, Bacillaria* sp., *Pleurosigma* sp., *Rhaphoneis* sp., and *Cocconeis* sp. noted.

The 570 cm sample was dominated by mineral material and no diatoms were seen in the sample.

Figure 7 Summary stratigraphy for selected diatom taxa for Lake Vastadtjern



The species assemblages were best represented by the NW European shallow lakes training set with between 86 to 96% of the diatom taxa in the fossil samples from the core present. Using this model the second component WA-PLS model provides the most robust internally validated (jack-knifed) root mean square root error statistic (r^2) of 0.81. This model places the recent TP concentrations of the lake to be in the region of 40-50 µgl^{-1}, with levels peaking in the 40 cm level at 214 before falling to between 17 – 55 in the lower part of the core below approximately 100 cm.

With respect to the timing of the changes it would appear that the peak in trophic status was before 1963 which is identified as being at approximately 27 cm in the gravity core. The dating is unreliable before this point, but a crude extrapolation of the dates would suggest the increase to have been within the last 150 years.

3.4 Macrofossil and Cladocera ephippia analysis

The results of the macrofossil analysis are presented in Figure 9. In the lower section of the core (below 350 cm) the overall diversity and abundance of macrofossils was low and was dominated by Nymphaeaceae trichosclereids with some *Nymphaea alba* seed fragments. Small numbers of *Callitriche* cf. *stagnalis* seeds were also found (454 cm).

The section above 350 cm saw a large rise in moss leaves and *Juncus* spp. seeds. Nymphaeaceae trichosclereids remain abundant in this section but at lower abundances than in the lowermost section of the core. *Nymphaea alba* seed fragments are also present throughout this section and reach peak abundances at 180 cm. A small number of *Isoetes lacustis* megaspores were also found at 360 cm.

Between 150 and 20 cm the number of Nymphaeaceae remains (seeds and trichosclereids) reduced substantially. The numbers of broad leaved *Potamogeton* remains increased (see Fig. 8) as did *Potamogeton natans* seeds between 50 and 20 cm. *Potamogeton* remains decreased above 20 cm but *Potamogeton* broad leaved fragments remained present throughout the top section of VASTG. Nymphaeaceae trichosclereids increased again at 10 cm and remained present throughout the top section of VASTG but in lower numbers than were seen in the lower core samples. *Lemna* leaves were present in the uppermost sample of VASTG.

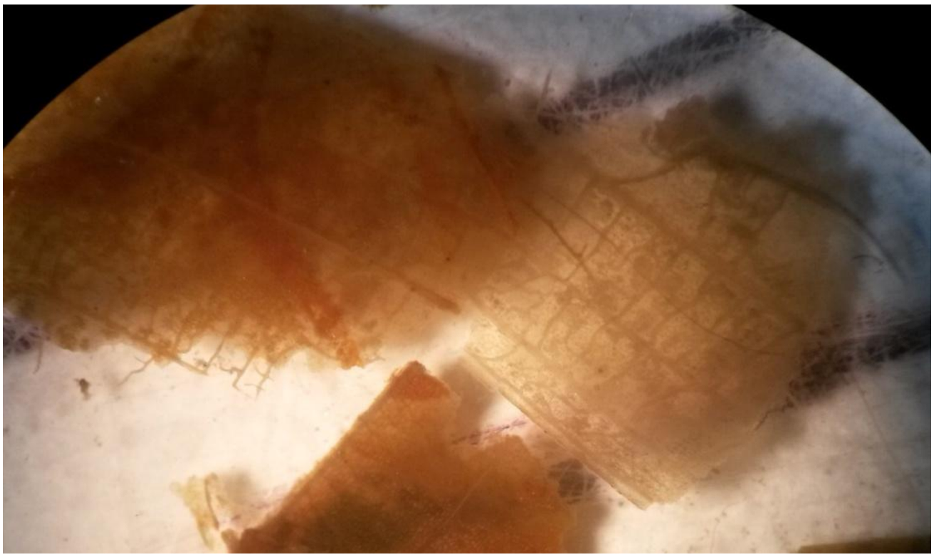


Figure 8 Broad leaved *Potamogeton* remains at 21cm (VASTG).

The results of the animal, bryozoan and invertebrate remains are presented in Figure 10. The lowermost section of the core (below 350 cm) have very few remains present with only Oribatid mite heads and low numbers of *Plumatella* present throughout the section. In the section above this (360-155 cm) the remains are dominated by bryozoan remains (*Plumatella* and *Cristatella* statoblast halves) and Oribatid mite heads were also consistently present throughout the section. Caddis case remains were only found in samples at 330 and 360 cm. Frontoclypeal apotome remains were observed in two samples in the lower half of the core.

Above 350 cm *Cristatella* halves were absent from the core and *Plumatella* halves decreased at the same point but increased again at 70 cm with a particularly large number being present at 20 cm. Fish scale remains occurred only in samples at 40-70 cm.

The Cladocera ephippia remains are presented in Figure 11. As with the macrofossils and the animal remains the lower section of the core (below 160 cm) was markedly different to the upper section in terms of the abundance levels of the ephippial remains. Below 160 cm the samples were dominated by *Ceriodaphnia* spp. (with a short absence between samples at 500-450 cm), *Daphnia pulex* and *Daphnia hyalina* agg. All of these species declined dramatically above sample 160 cm and remained at very low numbers, or were absent, throughout the rest of the core. *Simocephalus* spp. were present between 360-160 cm, declined in abundance between 130-70 cm and increased again in the upper section of the core with a gradual decline again towards the core top.

3.5 Chitinous Cladocera analysis

The results of the chitinous Cladocera analysis are presented in Figure 12. The lower section of the core (below 110 cm) was dominated by *Bosmina* species and to a lesser extent by *Daphnia longispina*, *Acroperus harpae* and various *Alona* and *Alonella* species. The *Bosmina* species declined substantially above 90 cm and remained low until the uppermost core sample where their abundance increased again.

As the *Bosmina* and *Alona* species declined, *Chydorus sphaericus* increased and dominated the assemblage above 70 cm. In this upper section many species increased in abundance, or appeared for the first time in the core profile, including *Eurycercus* spp*., Graptoleberis testudinaria* and *Pleuroxus truncatus.*

Figure 9 Summary stratigraphy for selected plant macrofossils for Lake Vastadtjern (Note variable scaling on the x axis)

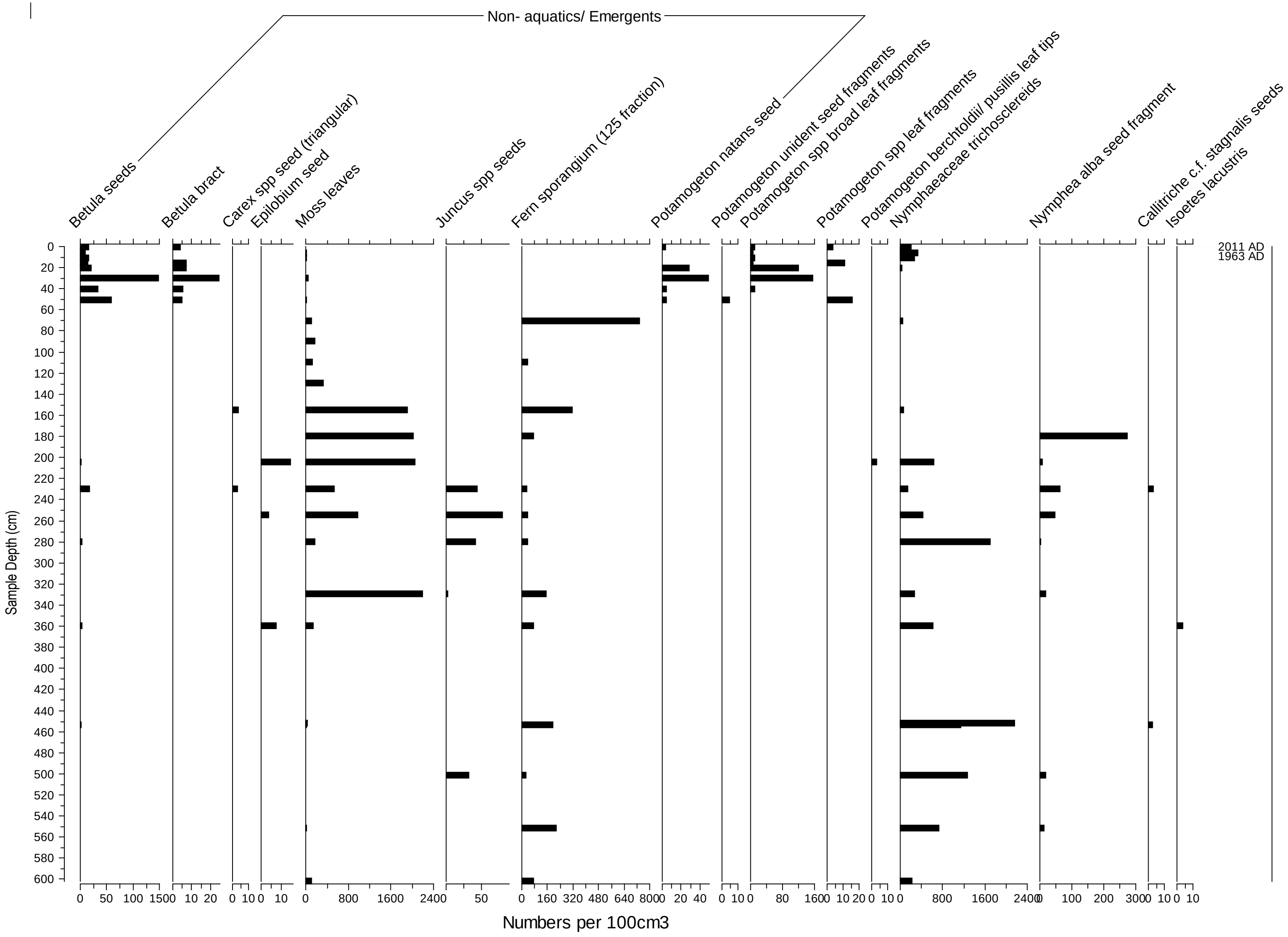


Figure 10 Summary stratigraphy of animal, bryozoan and invertebrate remains for Lake Vastadtjern (Note variable scaling on the x axis)

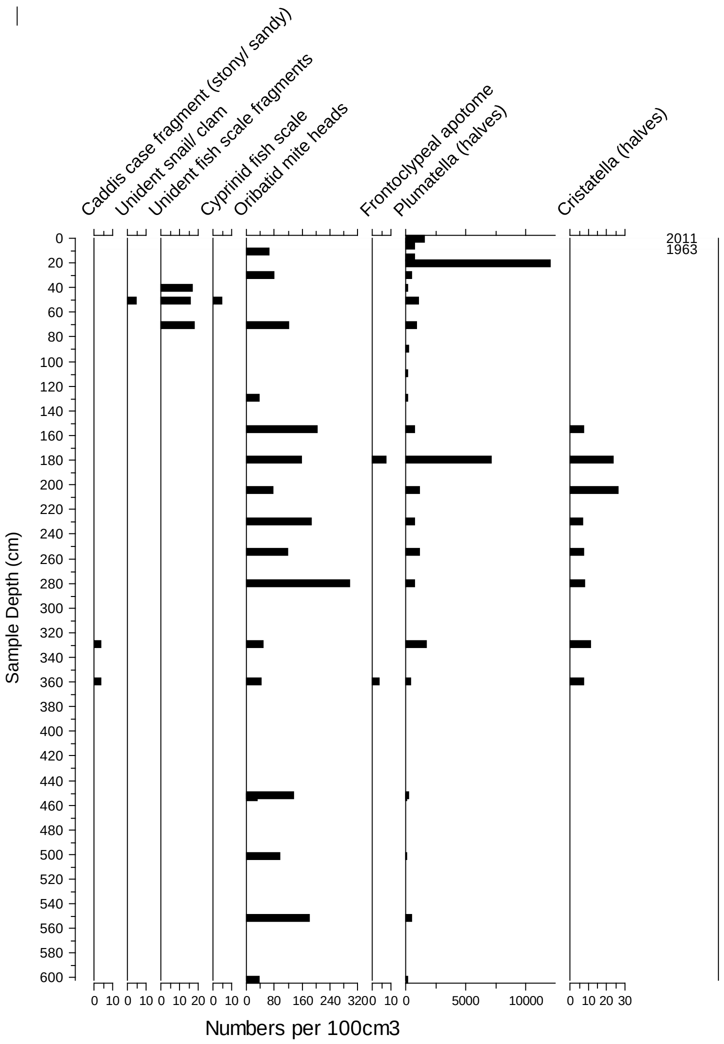


Figure 11 Summary stratigraphy of Cladocera ephippia for Lake Vastadtjern (Note variable scaling on the x axis)

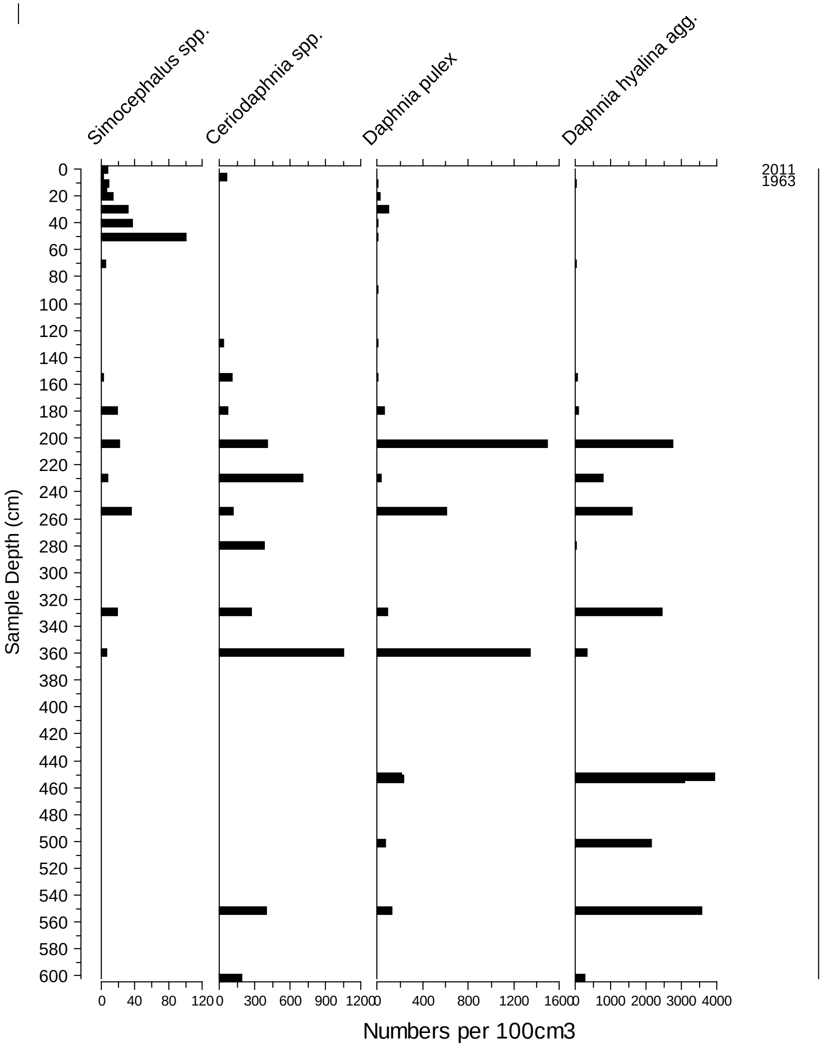
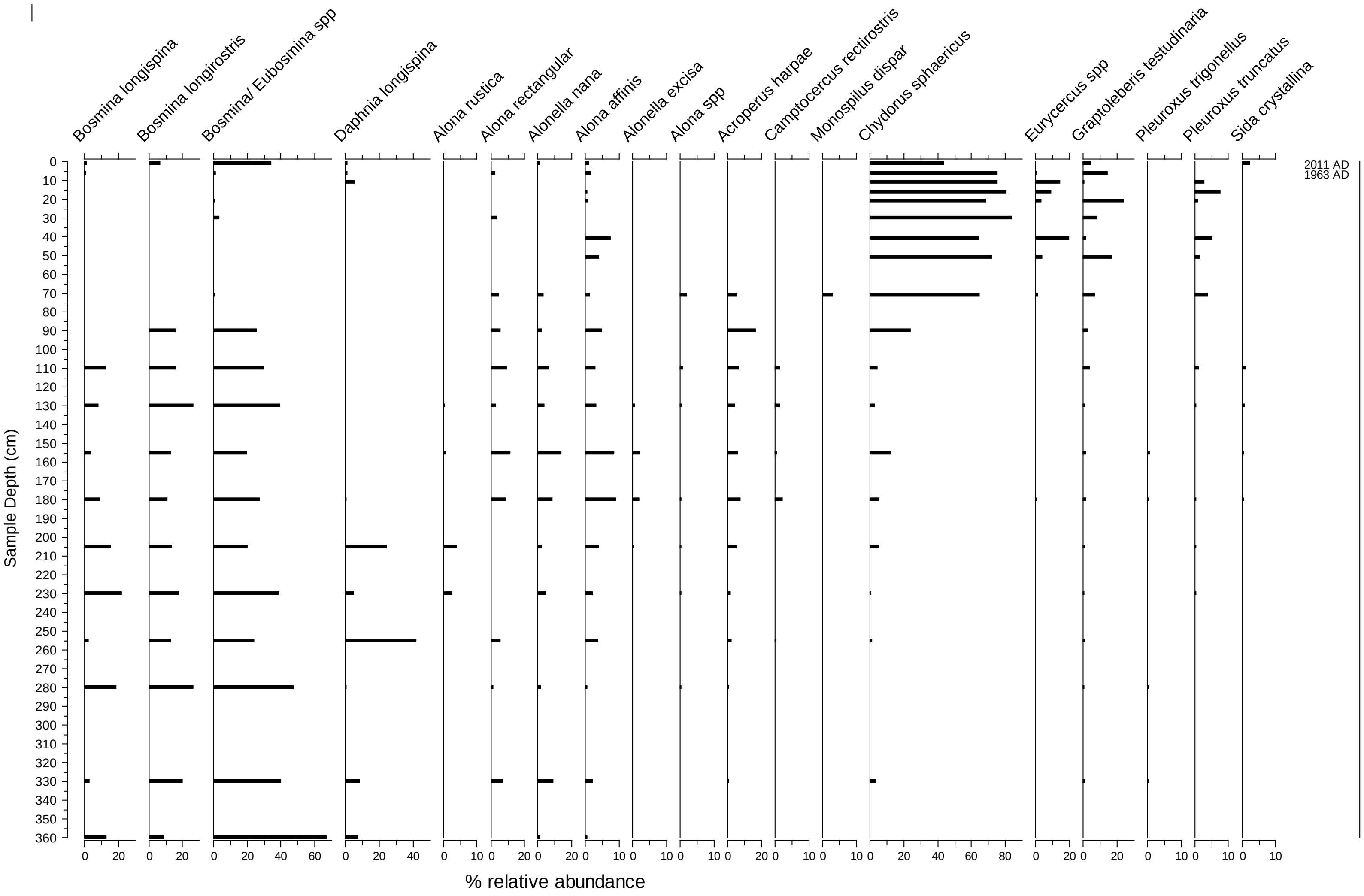


Figure 12 Summary stratigraphy for selected sub-fossil cladoceran remains (>2% relative abundance) in Lake Vastadtjern



4. Discussion

4.1 Diatoms

The interpretation of the diatom data is somewhat limited by the relatively small number of samples for a long core and additionally by gaps in the record due to the poor quality samples. Nonetheless, the results suggest that the site has experienced three major changes in environmental conditions.

Early history: Below approximately 500 cm in the core the sediments were very mineral and diatom concentrations very low. What diatoms were present were heavily silicified species and many showed signs of partial dissolution. Under these conditions it is very likely that smaller and less heavily silicified taxa will have dissolved completely. Although samples were not analysed in full, what species were recorded were almost all characteristic of brackish and marine environments and therefore indicative of a period when the site was saline. The deepest sediments (570 cm) had no diatoms. It is unclear from this study if this is due to complete dissolution or if the core material was not of aquatic origin.

Middle history: From approximately 500 cm to 125 cm the diatom flora is relatively similar suggesting conditions at the site to have been stable. The lowest sample (480 cm) has slightly higher numbers of *Achnanthidium minutissimum,* and no *Aulacoseira* spp, and possibly therefore represents a transitional phase when the lake was fresh, but without any significant inputs from the catchment. The presence of *Aulacoseira* spp in the mid section of the core is typical of slight eutrophication (c.f. Meriläinen *et al*., 2000; Anderson *et al*., 2006) which in the Lake Vastadtjern area is likely to result from the naturally occurring mineral P in the marine clay deposits (Borch *et al.*, 2008). The modelled TP and diatom PCA analysis suggests the site to have been relatively stable with respect to the diatom assemblages.

The diatom inferred TP concentrations show the site to have been moderately enriched throughout this period with TP concentrations typical of a naturally nutrient-rich lake.

Recent history: There were only a limited number of samples analysed above 125 cm, but the diatoms from these suggest there to have been a significant shift in the conditions at the site during this most recent phase. *Aulacoseira* spp. and *Tabellaria flocculosa* disappear almost completely and we see increases in *A. minutissimum, Surirella brebisoni, Cocconeis placentula* and *Fragilaria capucina* agg. This change is consistent with a shift from pelagic productivity to more benthic production and may therefore be a result of higher plant biomass in the site as evidenced from the macrofossil remains (section 4.2 below). Furthermore, it would appear that there was a period of increased nutrient input during this period which has since been alleviated. The DI-TP increased to a maximum of 214 μgl^{-1} at 60 cm before declining again to the current inferred level of 50 μgl^{-1}. The exact timing of this trophic peak is unknown, but was likely to have been after 1850 and before 1963.

The diatom data, therefore, indicate that the lake is naturally mesotrophic, but has experienced enrichment in the last 150 years. These results are consistent with the findings seen from the other biological proxies analysed in the Lake Vastadtjern core.

4.2 Macrofossils

The macrofossil results indicate a distinct shift at c. 160 cm with markedly different assemblages below and above this depth. In particular there are greater numbers of moss leaf remains in the lower core. The moss leaves were not, however, identified to species level and therefore could be from a terrestrial or aquatic source. Nonetheless, the shift in abundance could indicate changes in catchment conditions or lake level change in the past. *Cristatella* remains also show this distinct pattern of decrease above 160 cm and are absent in the upper and lowermost sections of the core, which could indicate habitat shifts occurring in the lake at this time. The plant macrofossil data indicate that Nymphaeaceae, including *Nymphaea alba,* were a dominant component of the aquatic vegetation in the past (below 160 cm). These are floating macrophytes and were likely growing in the lake margins. The only submerged species that was observed in the lower core was *Isoetes lacustris* which was seen in the basal sediments of VASTR (date - Hakon?). This species prefers to inhabit deep lakes and its presence may also indicate lower nutrient levels in the past as it is often found dominating oligotrophic, softwater lakes (Čtvrtlíková et al., 2014). In addition caddis case remains were present only in the bottom of the core which could be related to nutrients or pH.

Aquatic plant remains were sparse in samples from the 150-50 cm section but above 50 cm there was an increase in the broad leaved *Potamogeton* leaf remains, *P. natans* was also observed and Nymphaeaceae remains were present once more. This is in good agreement with the current macrophyte flora of Lake Vastadtjern which supports lilies and broad leaved *Potamogeton* species. However the historical species list provided for the lake does not include any broad leaved *Potamogeton* species with only the fine leaved *Potamogeton berchtoldii* being listed. This increase in the broad leaved *Potamogeton* taxa in the upper section of the core may indicate a rise in nutrient levels in the lake as several studies have observed increases in *Potamogeton* density with an increase in nutrient concentrations (Blindow *et al.,* 1992; Davidson *et al.,* 2005). Fish scale remains increase at the same time as the *Potamogeton* increase. This apparent increase in fish densities may be related to greater cover provided by the macrophytes or could be associated with higher nutrient levels in the lake. The broad leaved *Potamogeton* spp*.* remains decrease again towards the very top of the core as the Nymphaeaceae return.

In summary the macrofossil data suggest a marked change from dominance by Nymphaeaceae in the lower core to the presence of broad leaved *Potamogeton* spp. in the central section of the core (130-20 cm), followed by a slight increase in Nymphaeaceae again in the uppermost sediments.

4.3 Cladocera ephippia and chitinous remains

Remains of cladocerans have been shown to reflect past changes in macrophyte abundance and fish community (Jeppesen *et al*., 2001) and are therefore a useful indicator of past lake conditions and are particularly useful when analysed in conjunction with macrofossil remains. In the Lake Vastadtjern record there is a distinct shift in the assemblages of both the Cladocera ephippia and the chitinous remains with the upper section of the core differing to the lower in both cases.

Pelagic species dominated the bottom of the core, namely *B. longirostris, D. hyalina* agg., *D. pulex, D. longispina* and *Ceriodaphnia* spp., which may be linked to a lack of fish predation at the time. Indeed fish scale remains increase in the section 40-70 cm suggesting higher fish density and thus predation pressure on the zooplankton and this may explain the decrease seen in pelagic Cladocera taxa at this time. For the chitinous remains, Cladocera species diversity decreased towards the top of the core and the species assemblage shifted markedly at around 70 cm with a large increase in *Chydorus sphaericus* and a reduction in *Bosmina*. *C. sphaericus* is a very tolerant species which can live in a great variety of habitats including on plants and on the benthos as well as in the open water. Therefore, changes in abundance of this taxon in the sediment record can be hard to interpret in terms of habitat shifts. This species is, however, usually more abundant in eutrophic waters (Szeroczyńska, 1998 and Great Lakes Environmental Research taxonomic database). Hence, the large increase seen in the upper core may be related to enrichment. Equally the increase may be associated with lake habitat or water depth changes as it coincides with the shifts in the macrofossil remains. *Alona and Alonella* species and *Acroperus harpae*, which were abundant in the lower core, decreased above 40 cm and remained low in the upper core. This reduction could be related to an increase in nutrients as *Alonella nana, Alonella excisa* and *Acroperus harpae* have all been shown to prefer less productive lakes (Bos & Cumming, 2011). The rise seen in *Eurycerus* spp, and *Graptoleberis testudinaria* in the upper core could also be related to nutrient changes as both of these species are typically associated with higher plant abundances and can tolerate turbid waters and high nutrient concentrations (Bos & Cumming, 2011). These findings are consistent with the diatom inferred TP model, which suggests a significant increase in nutrient status in the site during the period represented by the upper 120 cm.

In the ephippia record *Simocephalus* spp. numbers increased at 50 cm to an abundance of 101 per 100 cm^3. The rise was short-lived, however, with *Simocephalus* ephippia numbers reducing to 37 per 100cm^3 at 40 cm and decreasing steadily towards the top of the core. *Simocephalus* is a plant associated species so its abundance may reflect the presence of *Potamogeton* and Nymphaeaceae evident from the macrofossil record. Plant macrofossil abundance and *Simocephalus* spp. numbers both decrease in the central section of the core (160-70 cm) possibly reflecting a period of lower macrophyte density. Furthermore the lack of *Ceriodaphnia* ephippia in the central part of the core may reflect lower macrophyte abundance at this time (Jeppesen *et al.,* 2001). However, unlike *Simocephalus* spp, the numbers of *Ceriodaphnia* spp. do not increase again in the upper section of the core when plant macrofossil numbers increase once more.

In summary, there were marked changes in the Cladocera remains from a diverse assemblage of pelagic and plant-associated taxa to an assemblage comprising smaller taxa and several species indicative of higher productivity. The causes of the shifts are uncertain but a combination of nutrient increase, alterations in lake habitat (macrophyte coverage) and water depth, and changes in fish predation pressure are all likely drivers.

5. Summary

Based on the multi-proxy palaeoecological study, the reference conditions of Lake Vastadtjern can be described as a macrophyte community dominated by floating-leaved Nymphaeaceae, a diverse Cladocera assemblage comprising *Daphnia* spp., *Bosmina* spp. and several benthic and plant-associated taxa and a diatom community comprising of *Aulacoseira* spp and *Tabellaria flocculosa*. The data indicate that there was a major change in the lake at c. 150 cm depth with a very different flora and fauna above this depth from that of the lower core. There appear to be no ecological shifts associated with the increase in organic matter in the central part of the record (c. 130-190 cm in VASTR). While the exact causes of the ecological shifts cannot be established, there is a suggestion that the changes may at least in part be a result of recent nutrient enrichment.

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Appendix 1 List of all diatom taxa observed in the Vastadtjern cores

CODE	Taxon Name	Total
AC167A	*Achnanthes daonensis*	2
AC169A	*Achnanthes grischuna*	1
AC032A	*Achnanthes hungarica*	8
AC001A	*Achnanthes lanceolata*	25
AC001R	*Achnanthes lanceolata subsp. frequentissima*	12
AC002A	*Achnanthes linearis*	12
AC022A	*Achnanthes marginulata*	6
AC013A	*Achnanthes minutissima var. minutissima*	335
AC035A	*Achnanthes pusilla var. pusilla*	33
AC136A	*Achnanthes subatomoides*	1
AC034A	*Achnanthes suchlandtii*	1
AP001A	*Amphipleura pellucida*	4
AM001A	*Amphora ovalis var. ovalis*	2
AS001A	*Asterionella formosa var. formosa*	1
AU002A	*Aulacoseira ambigua*	83
AU005A	*Aulacoseira distans var. distans*	157
AU003A	*Aulacoseira granulata*	10
AU003B	*Aulacoseira granulata var. angustissima*	13
AU020A	*Aulacoseira subarctica*	81
BR001A	*Brachysira vitrea*	1
CA002A	*Caloneis bacillum var. bacillum*	6
CO067A	*Cocconeis neothumensis*	9
CO001B	*Cocconeis placentula var. euglypta*	55
CO007A	*Cocconeis scutellum var. scutellum*	1
CI002A	*Craticula accomoda*	1
CY003A	*Cyclotella meneghiniana var. meneghiniana*	18
CY002A	*Cyclotella pseudostelligera*	39
CM006A	*Cymbella cistula var. cistula*	1
CM009A	*Cymbella naviculiformis*	8
DT004A	*Diatoma tenue var. tenue*	1
DP9999	*Diploneis sp. (modica?)*	28
EY017A	*Encyonema gracile*	19
EY011A	*Encyonema minutum*	11
EY016A	*Encyonema silesiacum*	18
EU109A	*Eunotia circumborealis*	1
EU049A	*Eunotia curvata var. curvata*	100
EU009A	*Eunotia exigua var. exigua*	10
EU018A	*Eunotia formica*	2
EU107A	*Eunotia implicata*	4
EU047A	*Eunotia incisa*	44
EU110A	*Eunotia minor*	24
EU048A	*Eunotia naegelii*	1
EU040A	*Eunotia paludosa*	11
EU002A	*Eunotia pectinalis var. pectinalis*	12
EU003A	*Eunotia praerupta var. praerupta*	27
EU011A	*Eunotia rhomboidea*	1
EU004A	*Eunotia tenella*	2
EU053A	*Eunotia tridentula*	1
FR003A	*Fragilaria bicapitata*	15

CODE	Taxon Name	Total
FR026A	*Fragilaria bidens*	5
FR006A	*Fragilaria brevistriata var. brevistriata*	35
FR009A	*Fragilaria capucina var. capucina*	69
FR009H	*Fragilaria capucina var. gracilis*	42
FR009B	*Fragilaria capucina var. mesolepta*	4
FR009G	*Fragilaria capucina var. rumpens*	145
FR010A	*Fragilaria constricta fo. constricta*	1
FR002A	*Fragilaria construens var. construens*	1
FR002C	*Fragilaria construens var. venter*	145
FR018A	*Fragilaria elliptica*	16
FR064A	*Fragilaria exigua*	19
FR001A	*Fragilaria pinnata var. pinnata*	17
FR007A	*Fragilaria vaucheriae var. vaucheriae*	8
FR005A	*Fragilaria virescens var. virescens*	9
FU002A	*Frustulia rhomboides var. rhomboides*	8
GO006A	*Gomphonema acuminatum var. acuminatum*	11
GO020A	*Gomphonema affine var. affine*	1
GO003A	*Gomphonema angustatum var. angustatum*	60
GO073A	*Gomphonema angustum*	2
GO075A	*Gomphonema anoenum*	3
GO019A	*Gomphonema augur*	3
GO038A	*Gomphonema exiguum*	6
GO004A	*Gomphonema gracile*	4
GO043A	*Gomphonema insigne*	3
GO013A	*Gomphonema parvulum var. parvulum*	212
GO080A	*Gomphonema pumilum*	1
GO023A	*Gomphonema truncatum var. truncatum*	3
HA001A	*Hantzschia amphioxys var. amphioxys*	15
LU003A	*Luticola goeppertiana*	1
MR001A	*Meridion circulare var. circulare*	80
NA066A	*Navicula capitata var. capitata*	5
NA066B	*Navicula capitata var. hungarica*	1
NA046A	*Navicula contenta fo. contenta*	3
NA007A	*Navicula cryptocephala var. cryptocephala*	68
NA056A	*Navicula cuspidata var. cuspidata*	1
NA100A	*Navicula explanata*	1
NA023A	*Navicula gregaria*	7
NA433D	*Navicula ignota var. acceptata*	1
NA433C	*Navicula ignota var. palustris*	2
NA009A	*Navicula lanceolata*	1
NA156A	*Navicula leptostriata*	1
NA142A	*Navicula medioconvexa*	1
NA042A	*Navicula minima var. minima*	30
NA739A	*Navicula monoculata*	1
NA025A	*Navicula mutica var. mutica*	3
NA754A	*Navicula muticopsis*	1
NA047A	*Navicula protracta var. protracta*	3
NA003A	*Navicula radiosa var. radiosa*	15
NA008A	*Navicula rhyncocephala var. rhyncocephala*	59
NA650A	*Navicula stroemii*	2
NA134A	*Navicula subminuscula*	2

CODE	Taxon Name	Total
NA675A	*Navicula tenelloides*	12
NA063A	*Navicula trivialis*	1
NA001A	*Navicula tuscula var. tuscula*	2
NA054A	*Navicula veneta*	1
NE003A	*Neidium affine var. affine*	2
NE036A	*Neidium ampliatum*	1
NE004A	*Neidium bisulcatum var. bisulcatum*	4
NI030A	*Nitzschia acidoclinata*	19
NI080A	*Nitzschia clausii*	1
NI083A	*Nitzschia constricta*	2
NI015A	*Nitzschia dissipata*	2
NI043A	*Nitzschia inconspicua*	4
NI129A	*Nitzschia littoralis var. littoralis*	1
NI009A	*Nitzschia palea var. palea*	15
NI033A	*Nitzschia paleacea*	2
NI005A	*Nitzschia perminuta*	4
NI050A	*Nitzschia perpusilla*	1
NI025A	*Nitzschia recta*	5
NI9999	*Nitzschia sp.*	1
NI195A	*Nitzschia supralitorea*	3
NI048A	*Nitzschia tubicola*	4
OP008A	*Opephora olsenii*	1
PI014A	*Pinnularia appendiculata*	6
PI012A	*Pinnularia borealis*	1
PI170A	*Pinnularia braunii*	56
PI016A	*Pinnularia divergentissima var. divergentissima*	1
PI169A	*Pinnularia ignobilis*	17
PI047A	*Pinnularia intermedia*	2
PI004A	*Pinnularia interrupta*	10
PI011A	*Pinnularia microstauron var. microstauron*	7
PI139A	*Pinnularia obscura*	6
PI168A	*Pinnularia pulchra*	1
PI9999	*Pinnularia sp.*	6
PI022A	*Pinnularia subcapitata var. subcapitata*	32
PI007A	*Pinnularia viridis var. viridis*	2
RE001A	*Reimeria sinuata*	1
SL001A	*Sellaphora pupula var. pupula*	26
SL002A	*Sellaphora seminulum*	14
SA001A	*Stauroneis anceps var. anceps*	34
SA012A	*Stauroneis kriegeri*	10
SA055A	*Stauroneis montana*	2
SA006A	*Stauroneis phoenicenteron var. phoenicenteron*	3
SA003A	*Stauroneis smithii var. smithii*	1
ST001A	*Stephanodiscus hantzschii*	3
ST010A	*Stephanodiscus parvus*	3
SU001A	*Surirella angusta*	19
SU073A	*Surirella brebisonii var. brebisonii*	80
SU016A	*Surirella minuta*	18
SU003A	*Surirella ovalis var. ovalis*	10

CODE	Taxon Name	Total
SY003A	*Synedra acus var. acus*	5
SY003C	*Synedra acus var. angustissima*	10
SY004B	*Synedra parasitica var. subconstricta*	5
SY013A	*Synedra tenera*	19
SY001A	*Synedra ulna var. ulna*	44
TA9998	*Tabellaria [flocculosa (long)]*	186
TA9997	*Tabellaria [flocculosa (short)]*	145
TA002A	*Tabellaria fenestrata*	15
TA004A	*Tabellaria quadriseptata*	3