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Palaeoecological study of Rockland Broad

Final report to the Broads Authority

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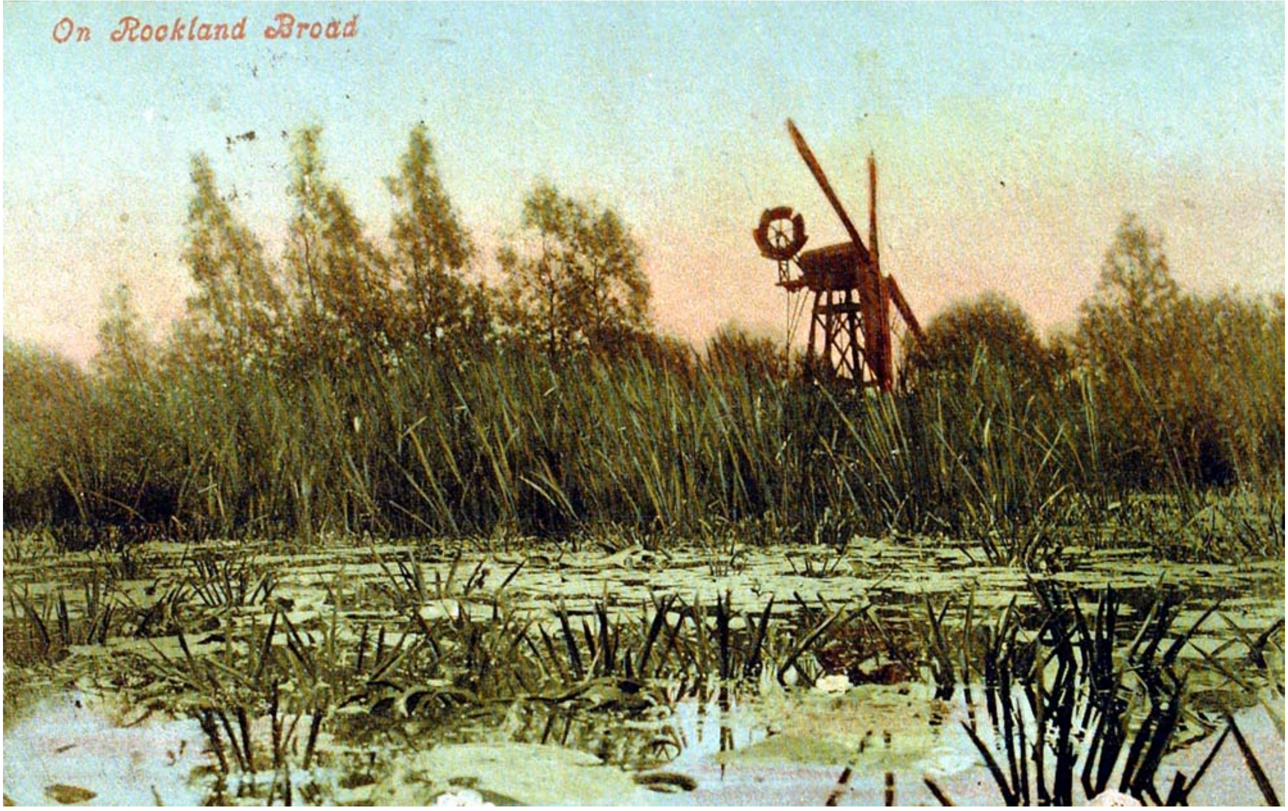

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Cover photo: From Postcard of Rockland Broad sent from Great Yarmouth in 1905.

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Introduction and project objectives

Study Rationale

The decline in ecological quality and conservation value of European fresh waters is an all too common phenomenon. In lowland Britain the main anthropogenic impact on aquatic systems is that associated with elevated nutrient loading. The Broads are internationally important wetlands spanning a number of river basins in East Anglia. The Broads have suffered, along with other wetlands, and it is chiefly eutrophication that has had a deleterious effect on the system (Mason & Bryant 1975, Moss 1977) with a resultant decline in their ecological quality and conservation value. One of the changes in the ecological structure and functioning of shallow lakes in response to enrichment is an alteration in their macrophyte flora (Ris & Sand-Jensen 2001) and in extreme cases there may be the complete loss of submerged plants (Scheffer et al. 1993). The loss of the diversity of the macrophyte flora in the Broads is perhaps the main factor in the decline in their conservation value.

Study Aims

The study had three main aims:

1. To establish a coherent chronology for the core ROCK1 from Rockland Broad.

2. To determine the former macrophyte communities of Rockland Broad and to assess the degree and timing of any shifts in the past macrophyte flora.

3. To assess the changes in the ecological functioning of the Broad associated with changes in the macrophyte flora.

Methods

Coring and Lithostratigraphic Analyses

A sediment core was collected on the 11/11/2002 from the South East corner of Rockland Broad using the 'Big Ben' corer, a custom designed and built wide diameter (150 mm internal diameter) piston corer (Goldsmith et al. unpublished). The core was extruded at 1 cm intervals in the field and the main characteristics of the sediment and any stratigraphic changes were noted.

The percentage dry weight (DW) for each sample was calculated by weighing approximately 1g of wet sediment in a pre-weighed crucible, from each pre-homogenised sediment layer, drying the sediment at 105 ^{o}C for at least 16 hours, then reweighing the crucible. Approximate organic matter content was then determined as a percentage loss on ignition (LOI) by placing the crucible containing the dried sediment in a muffle furnace at 550 ^{o}C for two hours and then reweighing. Carbonate content was calculated by returning the crucible to the furnace for two hours at 925 ^{o}C and then re-weighing.

Radiometric dating

^{210}Pb (half-life = 22.3 years) is a naturally-produced radionuclide that has been extensively used in the dating of recent sediments. Dating is based on determination of the vertical distribution of ^{210}Pb derived from atmospheric fallout (termed unsupported ^{210}Pb, or ^{210}Pb$_{excess}$), and the known decay rate of ^{210}Pb (see Appleby and Oldfield 1992 for further details of the ^{210}Pb method). ^{137}Cs (half-life

= 30 years) is an artificially produced radionuclide, introduced to the study area by atmospheric fallout from nuclear weapons testing, and nuclear reactor accidents. Global dispersion of ^{137}Cs began in AD 1954, with marked maxima in the deposition of ^{137}Cs occurring in AD 1958, AD 1963 (from nuclear weapons testing) and AD 1986 (from the Chernobyl accident). For the latter, the majority of the fallout of ^{137}Cs occurred in the north and west of the UK, with the south and east receiving comparatively little fallout (e.g. Cambray et al. 1987, Watt Committee on Energy 1991). In favourable conditions, periods of peak fallout/discharge provide subsurface activity maxima in accumulating sediments which can be used to derive rates of sediment accumulation (e.g. Ritchie et al. 1990; Cundy & Croudace 1996).

Sediment samples from Rockland Broad core ROCK1 were analysed for ^{210}Pb, ^{226}Ra, and ^{137}Cs by direct gamma assay in the Liverpool University Environmental Radioactivity Laboratory, using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby et al. 1986). ^{210}Pb was determined via its gamma emissions at 46.5keV, and ^{226}Ra by the 295keV and 352keV γ-rays emitted by its daughter isotope ^{214}Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. ^{137}Cs was measured by its emissions at 662keV. The absolute efficiencies of the detectors were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self-absorption of low energy γ-rays within the sample (Appleby et al. 1992).

Spheroidal carbonaceous particle (SCP) analysis

Given the error contained in the Pb210 chronology of ROCK1, sub-samples were analysed for spheroidal carbonaceous particles (SCPs) following the method described in Rose (1994). Dried sediment was subjected to sequential chemical attack by mineral acids to remove unwanted fractions leaving carbonaceous material and a few persistent minerals. SCPs are composed mostly of elemental carbon and are chemically robust. The use of concentrated nitric acid (to remove organic material), hydrofluoric acid (siliceous material) and hydrochloric acid (carbonates and bicarbonates) therefore does them no damage. A known fraction of the resulting suspension was evaporated onto a coverslip and mounted onto a microscope slide. The number of SCP on the coverslip were counted using a light microscope at x400 magnification and the sediment concentration calculated in units of 'number of particles per gram dry mass of sediment' (gDM^{-1}). The detection limit for the technique is c. 100 gDM^{-1} and concentrations have an accuracy of c. ± 45 gDM^{-1}.

Macrofossil analysis

In the absence of reliable historical information on past aquatic macrophyte communities, analysis of sedimentary macro-remains of plants (the seeds, fruits and remains of stems, leaves and rhizomes) may provide a means of determining changes in the aquatic flora of a site (Birks 1980). Recent work has indicated that plant macrofossils provide a reliable means for tracking shifts in the dominant components of the submerged aquatic flora in shallow lakes (Davidson et al. 2005a).
In this study 15 levels from ROCK1 were examined for macrofossils. Samples will be sieved at 350 and 125 microns, the exact sample volume being measured by water displacement. The entire residue on the 350 micron sieve will be examined under a stereo-microscope at magnifications of X10-40 and plant and animal macrofossils were enumerated. A quantitative sub-sample, approximately one tenth of the sample, from the 125 micron sieve smaller remains, such as leaf spines will be analysed. All material will be identified by comparison to reference material.

Cladoceran analysis

The remains of cladocerans have been shown to reflect past changes in macrophyte abundance and fish community (Jeppesen et al. 2001). Thus, they may provide invaluable information on the mechanisms and causes of any observed change in the macrophyte flora at the site.

Cladocera remains were analysed using an adaptation (Davidson et al. 2007) of standard techniques (Frey 1986; Korhola & Rautio 2000). Ephippial remains were separated and counted along with macrofossil remains using a binocular microscope, thus the counts of ephippia were based on the analysis of at least 30 cm^3 of sediment. Chitinous remains: head shields; carapaces and post abdomens along with small ephippia were counted using a light microscope at x 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 were tabulated separately and the count for each species was the number of the most numerous remain. The occurrences of the various taxa represented by chitinous remains are expressed as percentages or relative abundances. The remains of species best represented by ephippial remains are expressed as numbers per 100 cm^3.

Diatom analysis

Diatoms (*Bacillariophyceae*: unicellular, siliceous algae) have previously been analysed in ROCK1 and the data are added here. Rockland Broad is likely to have experienced significant changes in salinity over the last two centuries. Diatoms are particularly good indicators of past limnological conditions, in particular salinity (Juggins 1992).

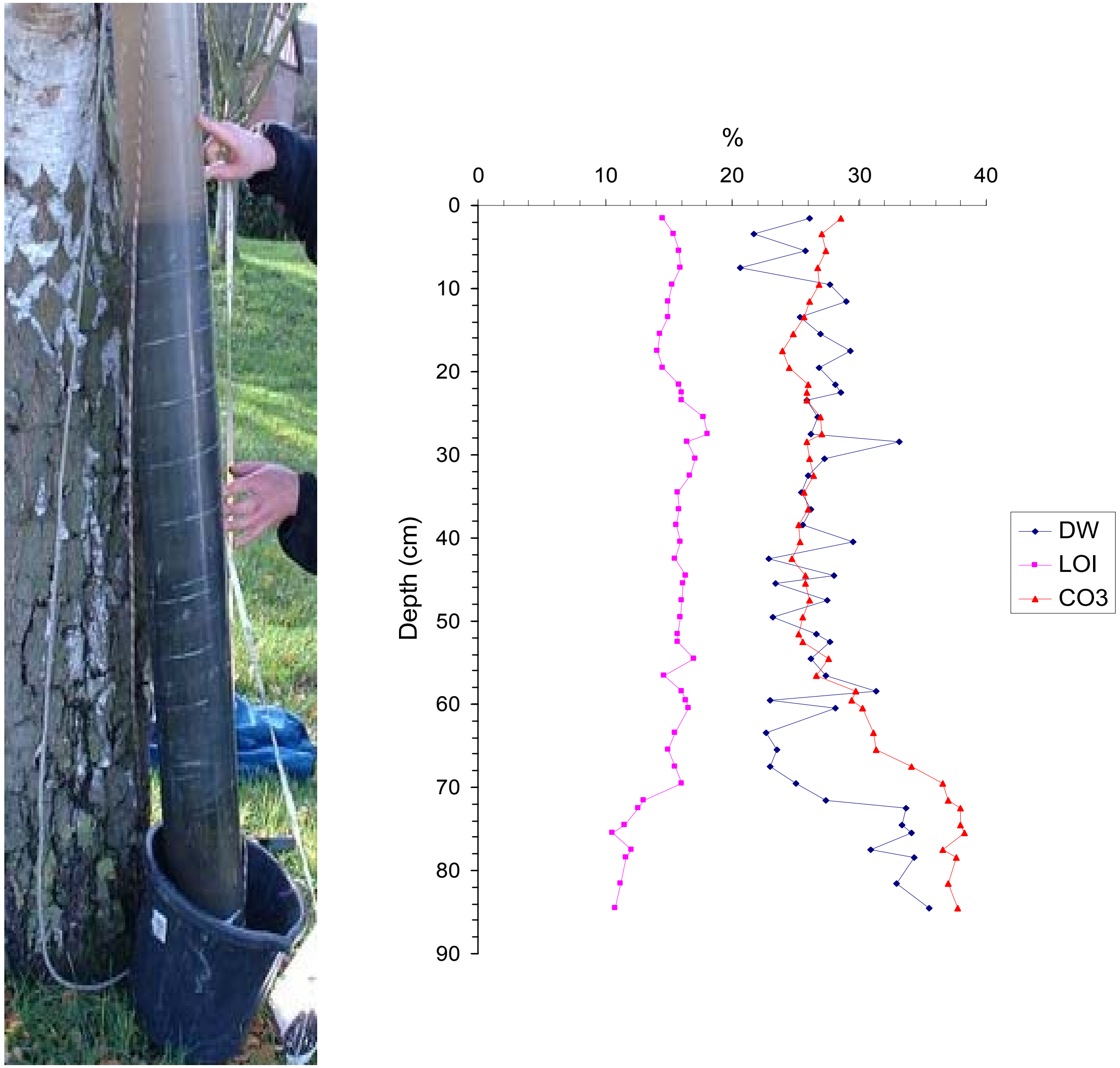
Core samples were prepared for diatom analysis using standard techniques (Battarbee 1986). At least 300 valves were counted from each sample using a Leitz research microscope with a 100 x oil immersion objective and phase contrast. Principal floras used in identification were Krammer & Lange-Bertalot (1986; 1988; 1991a, b). All slides are archived at the ECRC. The data were expressed as percentage relative abundance. Information on the life-form and salinity preference of each taxon, from both the literature and personal observations, was employed to classify each of the common species as either predominantly epiphytic (associated with plant substrates), benthic (associated with sediment substrates) or planktonic (living in the open water). The relative abundance of each life-form group was calculated for each sample.

Results

Site and core description

Rockland Broad (TG332051) is a relatively small (26 ha), shallow (1m average depth) lake which lies in the river Yare system. An 85 cm core (ROCK1) was taken from the South-east corner (TG 335 050) of Rockland Broad at 1m water depth on the 11th of November 2002. There were a number of notable stratigraphic features (Fig. 1). The base of the sequence to around 60cm was a light brown slightly marl-like sediment with abundant mollusc remains visible. This was also reflected in the higher levels of carbonate and slightly lower LOI values below 60cm. At 60cm there was a change in sediment type to a darker brown more organic sediment with lower carbonate values. This may represent an increase in the productivity at the site perhaps reflecting the early effects of eutrophication. From 30cm to the surface of the core there was a further change as the sediment became slightly lighter in colour. There were no significant changes in dry weight or carbonate levels, there was, however, a slight reduction in organic matter.

Figure 1 Sediment core stratigraphy of ROCK1



Depth (cm)	Sediment colour
0-30	Light brown
30-60	Dark brown
60-85	Very light brown with abundant mollusc remains

Core dating

Radiometric dating

The results of the radiometric analyses are given in Table 1 and shown graphically in Figure 2.

Lead-210 Activity

Total ^{210}Pb activity significantly exceeding that of the supporting ^{226}Ra was detected only in the top 20 cm of the core (Figure 2a). Unsupported ^{210}Pb activities in this section of the core were extremely low (Figure 2b), with a maximum value of just 26 Bq kg^{-1}. The ^{210}Pb dating horizon for this core is thus likely to be no more than around two half-lives (between 40-50 years). The ^{210}Pb inventory of the core (1332 Bq m^{-2}) corresponds to a mean ^{210}Pb flux of just 30 Bq m^{-2} y^{-1}. Although significantly lower than the estimated atmospheric flux, this is nonetheless typical of other Norfolk Broads sites.

Artificial Fallout Radionuclides

^{137}Cs activity versus depth record (Figure 2c) has a relatively well-resolved peak between 25-42 cm that presumably includes a record of the 1963 fallout maximum from the atmospheric testing of nuclear weapons.

Core Chronology

Figure 3 shows a best estimate of the 1963 depth determined from the ^{137}Cs stratigraphy, together with ^{210}Pb dates calculated using the ^{137}Cs date as a reference point (Appleby 2001). Since the ^{210}Pb record was evidently incomplete, it could not be used on its own to calculate a sediment chronology. Various estimates of the sedimentation rate based on the available data suggest a mean value of 0.20 ± 0.03 g cm^{-2} y^{-1} (0.64 cm y^{-1}). Table 2 gives sediment dates calculated using this value. The incomplete nature of the Pb^{210} record makes the determination of any changes in the accumulation rate of sediments at Rockland Broad very difficult. The analysis of SCPs from ROCK1 may help to provide more detailed information on the nature of these changes at the site.

Figure 2 Fallout radionuclides in the Rockland Broad core ROCK1 showing (a) total and supported ^{210}Pb, (b) unsupported ^{210}Pb, (c) ^{137}Cs concentrations versus depth.

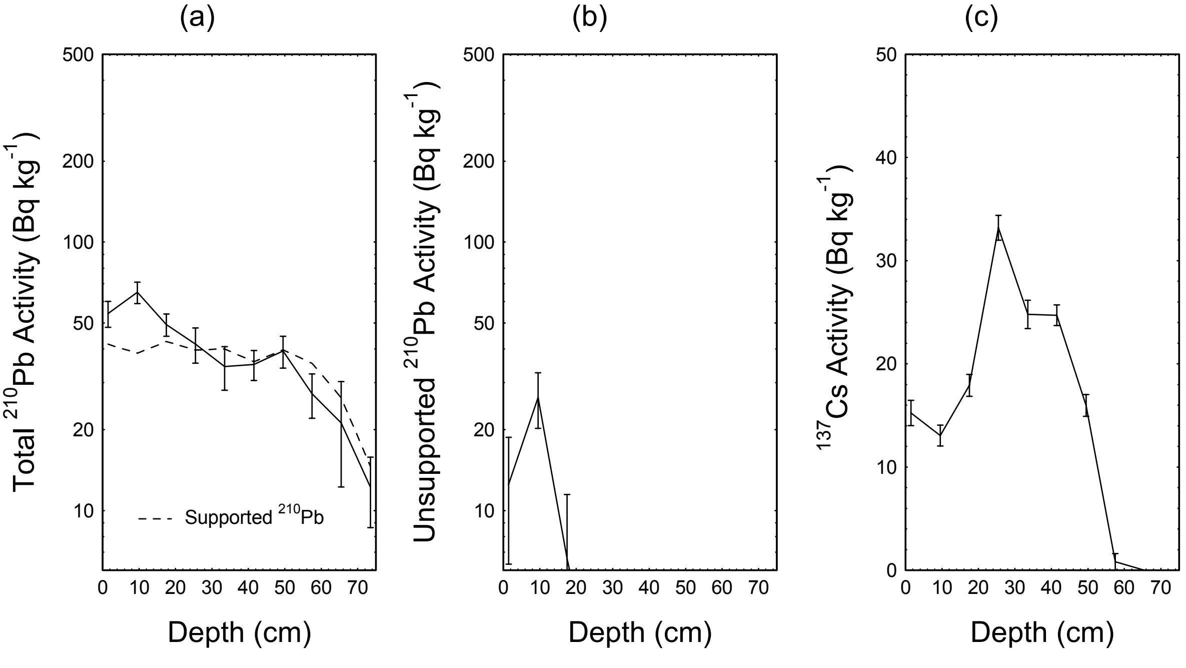


Figure 3 Radiometric chronology of Rockland Broad core ROCK1 showing the raw ^{210}Pb dates, the approximate 1963 depth determined from the ^{137}Cs record, and the corrected radiometric dates and sedimentation rates.

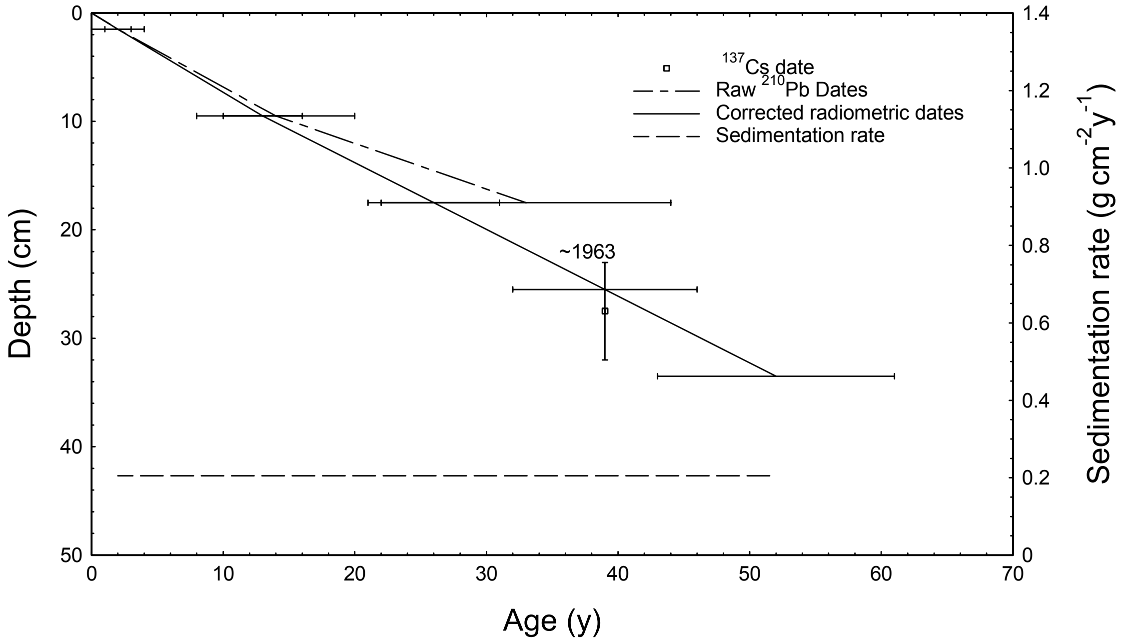


Table 1. Fallout radionuclide concentrations in Rockland Broad core ROCK1

Depth		^{210}Pb						^{137}Cs	
		Total		Unsupported		Supported			
cm	g cm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
1.5	0.5	54.2	6.0	12.5	6.2	41.6	1.6	15.2	1.2
9.5	2.7	65.0	6.0	26.4	6.2	38.6	1.5	13.1	1.0
17.5	5.4	49.3	4.7	6.6	4.9	42.6	1.2	17.9	1.1
25.5	8.0	41.6	6.2	2.0	6.4	39.6	1.4	33.2	1.2
33.5	10.7	34.4	6.3	-5.6	6.6	40.0	1.8	24.8	1.4
41.5	13.2	35.0	4.5	-0.9	4.6	35.8	1.2	24.7	1.0
49.5	15.6	39.3	5.3	-0.4	5.6	39.7	1.5	16.0	1.1
57.5	18.2	27.2	5.1	-8.2	5.3	35.4	1.4	0.8	0.8
65.5	20.8	21.2	9.0	-5.1	9.1	26.3	1.7	0.0	0.0
73.5	23.3	12.2	3.6	-2.3	3.7	14.6	0.9	0.0	0.0

Table 2. ^{210}Pb chronology of Rockland Broad core ROCK1

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.0	2002	0	0			
1.5	0.5	2000	2	1	0.20	0.72	15.7
9.5	2.7	1989	13	3	0.20	0.67	15.7
17.5	5.4	1976	26	5	0.20	0.62	15.7
25.5	8.0	1963	39	7	0.20	0.62	15.7
33.5	10.7	1950	52	9	0.20	0.61	15.7

SCP dating

The results of the SCP analyses are presented in Table 3 and the SCP concentration profile shown in Figure 4. The SCP profile for ROCK 1 clearly displays the characteristic features seen in lake sediment cores throughout Europe (Rose et al.1999). The first presence of SCPs occurs at 68 - 69 cm and concentrations increase steadily until 40 - 45 cm when concentrations increased rapidly to a peak of over 7500 gDM^{-1} at 26 - 27 cm. From this point, SCP concentrations declined markedly to the sediment surface. Dates may be ascribed to SCP profiles in two ways. First, using the three features of the SCP concentration profiles: the start of the record, the rapid increase in concentration and the concentration peak (Rose et al. 1995). Second, by ascribing dates is by using the SCP cumulative percentage inventory profile with the depth of the concentration peak set at 100% (Rose & Appleby, 2005).

Considering the first of these approaches, for this area of the UK, the three features usually date to 1850 ± 25, 1950 ± 10 and 1970 ± 5 respectively. When these dates were applied to the ROCK1 core it was immediately obvious that if they were correct then either the profile was curtailed at the lower end or there had been a major increase in sediment accumulation rate post-1950. Two factors suggest that the profile is curtailed. First, the concentration peak and the rapid increase suggest a consistent accumulation rate over c. 50 years, thus, any change in accumulation rate would have to be both a major step-change and sustained. Furthermore, the concentrations below this section are low and consistent with a rapid accumulation rate, whereas a reduced rate lower in the core would be expected to result in increased concentrations. Second, a rapid accumulation rate results in lowering the SCP concentrations to around the limit of detection. Hence the perceived start of the SCP record is simply where the deposition of SCPs exceeds the detection limit of the technique for the first time. The shape of the profile is consistent with this hypothesis. If the accumulation rate estimated from the upper two features is extrapolated then the start of the SCP record might be expected to be at c. 120cm in ROCK1 although it is not possible to tell from these data whether this is correct or not.

Table 3. ROCK 1: SCP concentrations

Sediment depth (cm)	SCP concentration (gDM^{-1})	± 90% Confidence limit (gDM^{-1})
1 – 2	2258	989
6 – 7	3690	1278
10 – 11	4065	1505
16 – 17	5934	1554
21 – 22	6324	1193
26 – 27	7593	1861
32 – 33	4126	1528
38 – 39	2258	990
44 – 45	1117	775
50 – 51	1064	737
56 – 57	565	554
62 – 63	914	517
68 – 69	260	256
74 – 75	0	0
80 – 81	0	0
85 – 86	0	0

The second method of ascribing dates is via the cumulative percentage approach. Again, this can be applied to the ROCK1 core but results in a profile showing a major change in sediment accumulation rate between ‘1920’ and ‘1965’. While this might be true, SCP inventories will also be affected by a curtailed profile (i.e. too few SCPs at lower depths will move some of the dates to more modern times producing a profile similar to that observed here). Therefore, if we assume that the profile is curtailed due to the dilution by a rapid sediment accumulation rate, then we cannot apply the cumulative approach to SCP dating.

Figure 4 ROCK1 SCP concentration profile.

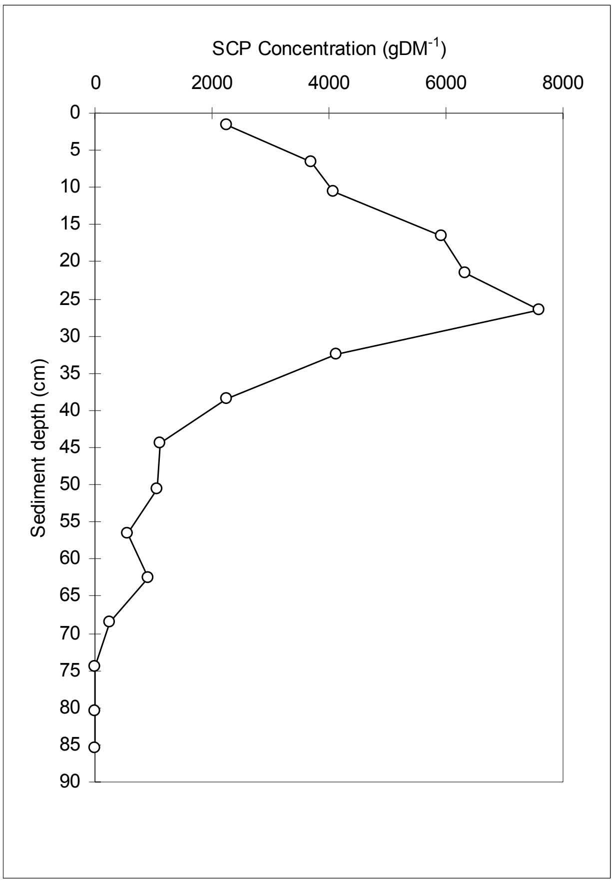
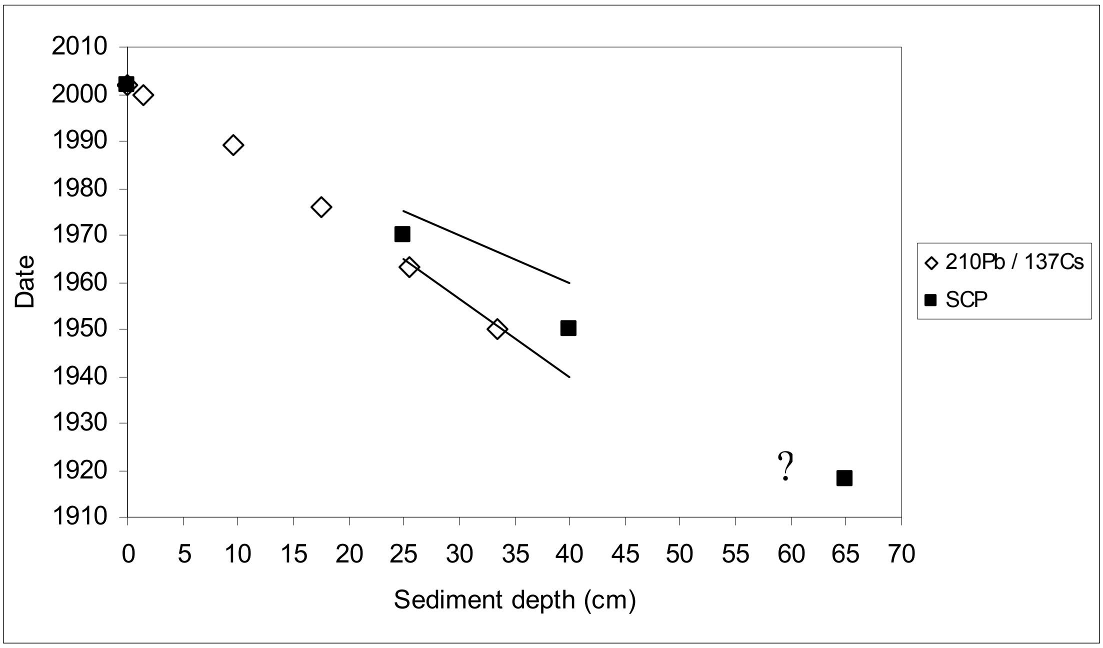


Figure 5 Depth / dates for ROCK1 from both radiometric and SCP data. (Lines indicate errors on SCP data)



A comparison of the SCP dating with the radiometric results is shown in Figure 5. The radiometric data to 1950 provide a linear depth / date profile with a mean sedimentation rate of 0.64 cm yr^{-1}. By comparison the SCP data also suggest a linear profile over this period, but with a slightly higher sedimentation rate of 0.77 cm yr^{-1}. The errors on the SCP dates (shown as lines on Figure 2) show that the lower boundary is very similar to the radiometric estimates. While there is no reliable evidence to extrapolate the SCP dates beyond the 'rapid increase' feature (1950), there is also an argument that says that the SCP profile appears consistent with the expected trend in concentrations down to where it falls below the limit of detection. This being the case then extrapolating the mean accumulation rate to this depth suggests that the first presence of SCPs at 65cm could be ascribed to c. 1920. It should be stressed that this date is highly speculative and is thus labelled with a large '?' on Figure 5.

Summary

The SCP concentration profile from the Rockland Broad core ROCK1 shows the main features of a typical profile from the UK, although it maybe curtailed by the rapid sedimentation rate reducing the SCP concentrations to below the limit of detection. As a result reliable dates are only possible for the upper 40cm of the core. This suggests a mean accumulation rate of 0.77 cm yr^{-1}, slightly faster than that produced by radiometric analysis. While there are no reliable dates prior to 1950 the SCP profile remains typical down to the level where it falls below the limit of detection (65cm). Extrapolating the mean accumulation rate to this depth produces the chronology shown in Table 4 although the uncertainty for the lower dates is high and they should be treated with caution.

Table 4. Depths and dates for ROCK1 from SCP analysis. (NB. Data shown in italics are extrapolated and should be treated with caution.)

Depth (cm)	Date	±
0	2002	
10	1989	5
20	1976	5
30	1962	10
40	1949	10
50	*1935*	*15*
60	*1924*	*15*

In the presentation of the palaeo results the results of both dating techniques are given. They correspond relatively well with the SCP dating suggesting a slightly higher accumulation rate than the radiometric dating. The data demonstrate that the sequence here does not cover the entire history of the site, it is likely that the accumulation rate changed significantly after 1940 thus it is difficult to say the time period covered by the core. It, is however, unlikely that the base of the sequence is older than 1800.

Macrofossil results

Plant remains

The abundance and diversity of remains found in ROCK1 (Figure 6) was lower than has been found in other cores from the Norfolk Broads (e.g. Davidson et al. 2005b). The data do, however, indicate that there have been profound changes in the macrophyte flora of the site. The base of the sequence was the most diverse sample with a flora of *Callitriche* spp., *Ceratophyllum* spp. more likely *C. demersum* than the less common *C. submersum*, *Stratiotes aloides*, *Potamogeton friesii*, *Nuphar lutea* and *Ranunculus* sect. *Batrachium*. Above 70 cm there was a change in the macrofossil assemblage with *P. friesii* and *R.* sect *Batrachium* absent, *Callitriche* spp. and *Nymphaeaceae* trichoschlereids numbers decreased sharply and there was a slight increase in *S. aloides*. At 55cm, corresponding to about 1930, *Chara* spp. first appeared in the record, but numbers of oospores are relatively low and probably do not reflect extensive beds of *Chara* (Zhao et al. 2006). *Chara* oospores were present sporadically and in relatively low numbers for the rest of the sequence. Above 55 cm *Callitriche* spp. was very rare and disappeared above 40 cm, a pattern of occurrence repeated by *Ceratophyllum* leaf spines, which were absent above 35 cm. *S. aloides* leaf spines increased briefly between 45 and 35 cm and then disappeared from the record. *Nymphaeaceae* trichoschlereids increased from 40 cm and were present in relatively high numbers to the surface of the core. Above 35 cm there were relatively few macrofossils found in the record with only Lily remains consistently present. At the surface of the core there *Nitella* oospores appear in very low numbers and strands of filamentous algae were present in the top two samples.

Animal remains

In contrast to the plant remains, animal remains were numerous in ROCK1 (Figure 6 & 7), with abundant cladoceran ephippia, bryozoans, fish scales and mollusc shells. The samples at the base of the sequence, below 65 cm were similar, with assemblages including a number of mollusc species, such as, *Valvata piscinalis*, *Valvata cristata* and *Lymneae peregra* along with numerous bryozoans, *Cristatella mucedo*, *Plumatella* spp. and the currently rare *Lophopus crystallinus*. The cocoon of the leech *Piscicola geometra*, which feed on fish, were also present, *P. geometra* requires a substrate, such as submerged plants on which to place its cocoons and is strongly associated with the presence of submerged plants (Odgaard & Rasmussen 2001). There were also high numbers of glochidia, which are remains of mussels, most likely from the swan mussel (*Anodonta cygnea*). The remains of fish found were chiefly scales which are seldom identifiable to species and are ascribed to the lower taxonomic resolution, but still ecologically significant groups of either percid or cyprinid (Jeppesen et al. 2000). Cyprinid remains were present more consistently than those of percids in the lower section of the core. *Daphnia* and *Ceriodaphnia* ephippia were also abundant in the basal section of the core. At 70 cm *Daphnia* and *Ceriodaphnia* remains started to fall and concurrently *Simocephalus* ephippia increased in numbers.

There was a shift in assemblage between around 60 cm with a decline in the abundance and species richness of molluscs with their remains almost completely absent between 60 and 35 cm. Between 60 and 40 cm, corresponding to 1924 and 1949 respectively, the numbers of remains of all animal (excluding cladocerans), with perhaps the exception of the bryozoan, *Plumatella* spp., declined. The other bryozoan species *C. mucedo* declined sharply to very low numbers and *L. crystallinus* disappeared completely. *P. geometra* cocoons remains were also absent from the record above 60 cm, ostracods were still present at this time but their abundance was low. The cladoceran species *Simocephalus* numbers were at their peak at 60 cm but then fell sharply to 45 cm at this time *Ceriodaphnia* ephippia increased gradually and *Daphnia* ephippia numbers declined and disappeared from the record, albeit for only two samples.

Above 35 cm, which corresponds to around 1950, molluscs re-appeared, but not in their former diversity or abundance. Glochidia were also abundant post 1950 as were ostracod shells, in addition *P. geometra* returned in the top two samples. *L. crystallinus* reappeared briefly in the record at 35 cm but was not found after that time, the other two bryozoan groups continued to be present in the record but in lower numbers. Post-1950 (35 cm) *Simocephalus* spp. numbers dramatically declined and often absent and when present their numbers were low. *D. hyalina* agg. ephippia increased slightly in number post 1950 but decreased again post 1980 (15 cm) to relatively low numbers. This pattern is reflected by the shifts in *Ceriodaphnia* spp. ephippia which increased from 1950 and thereafter gradually declined.

Figure 6 Summary stratigraphy for selected plant macrofossils and cladoceran ephippia for ROCK1

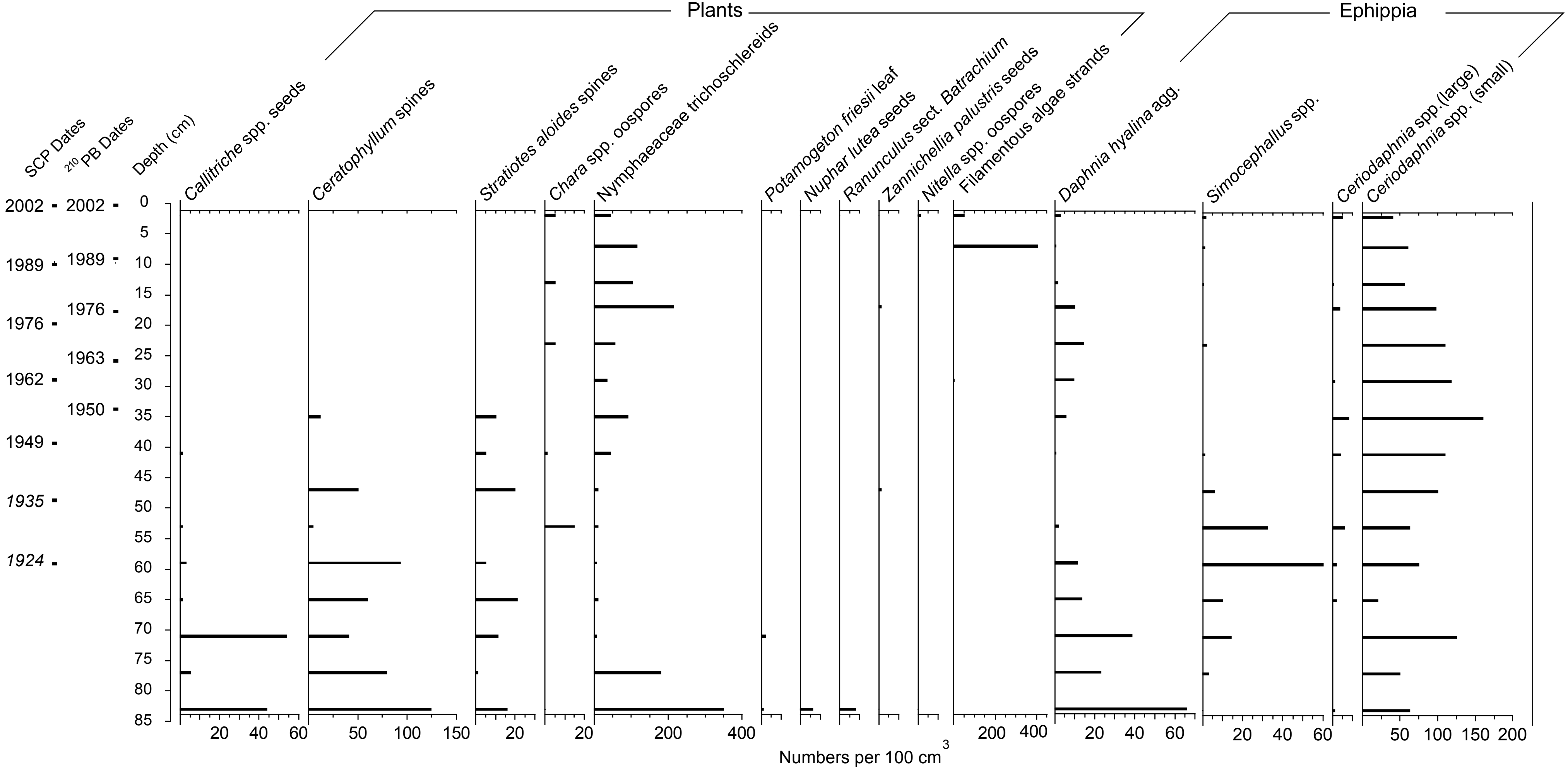
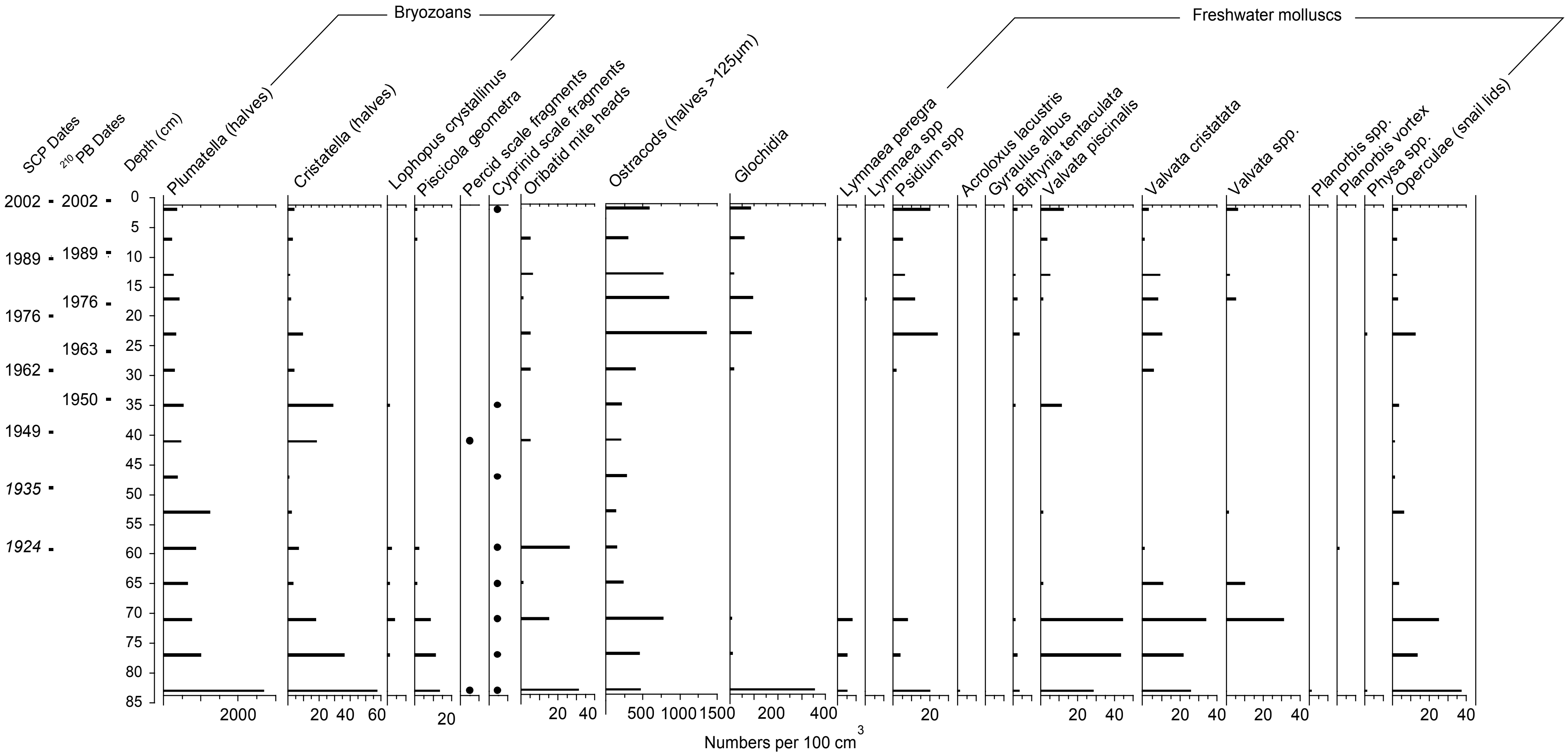


Figure 7 Summary stratigraphy for selected animal macrofossils for ROCK1



Microfossil results

Cladoceran remains

There were a number of shifts in the cladoceran assemblage over the period covered by the core (Figure 8). Slightly distinct from the macrofossil remains the assemblages were relatively homogenous between the base and 55 cm. This period was characterised by the presence of a number of plant associated species, *Graptoleberis testudinaria*, *Eurycercus lamellatus* and *Acroperus harpae* (Quade 1969). *Chydorus sphaericus* was also abundant in the basal samples, this species is relatively plastic in its response to fish and plant abundances, being both semi-planktonic and plant associated (Alonso 1989), in shallow lakes, however, it is often dominant with where submerged plants are abundant (Davidson et al. in press). Above 55cm there was a very sharp decline in *C. sphaericus* and the relative abundance of all other plant-associated taxa fell. There was a general shift to the more generalist *Alona* taxa, in particular *A. rectangula* had a spike in abundance between 45 and 30 cm. From 35 cm to the surface the assemblages were similar with a number of the plant-associated species returning, with the exception of *A. harpae*. It is noteworthy that the number of *C. sphaericus* did not return to their former relative abundance but that the planktonic species *B. longirostris* did.

Diatom remains

The summary stratigraphy of diatoms from ROCK1, split into functional groups (Figure 9), indicate that there have been profound changes in the chemistry and biology of the site. The profile suggests there have been changes in the tidal influence, with saline incursions a historical feature of the lower Yare valley. In the basal section of the core, epiphytic and benthic, freshwater-brackish species dominated. At 65 cm the proportion of brackish-fresh and brackish species increased and that of more freshwater taxa fell slightly. Numbers of fragments of marine species were relatively abundant at this time and continued to be so until around 50 cm. This period of apparent marine influence saw little, or no, change in the habitat preference of the diatom taxa present, with epiphytic and benthic taxa dominant up to 50 cm. Above 50 cm there was a shift away from more freshwater taxa with an increase in both brackish and brackish-fresh taxa up to around 30 cm. Concomitant with these changes in salinity preferences there was a shift from epiphytic and benthic to dominance of pelagic taxa. Above 30 cm there was a shift back to the more freshwater species, although the brackish and brackish-fresh taxa persisted and there was a decline in the proportion of pelagic taxa and an increase in those species classified as epiphytic.

Figure 8 Summary stratigraphy for chitinous cladoceran remains for ROCK1

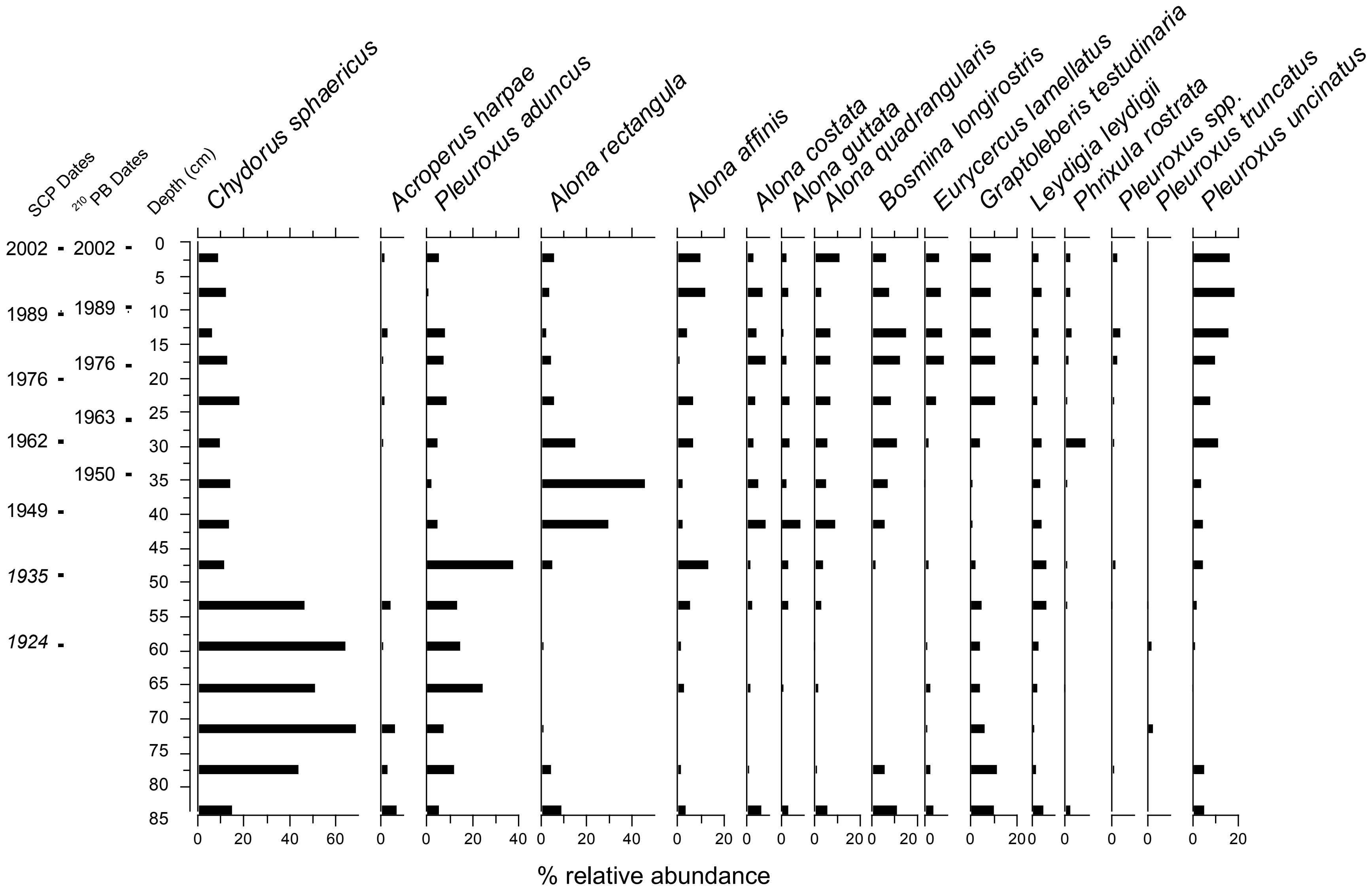
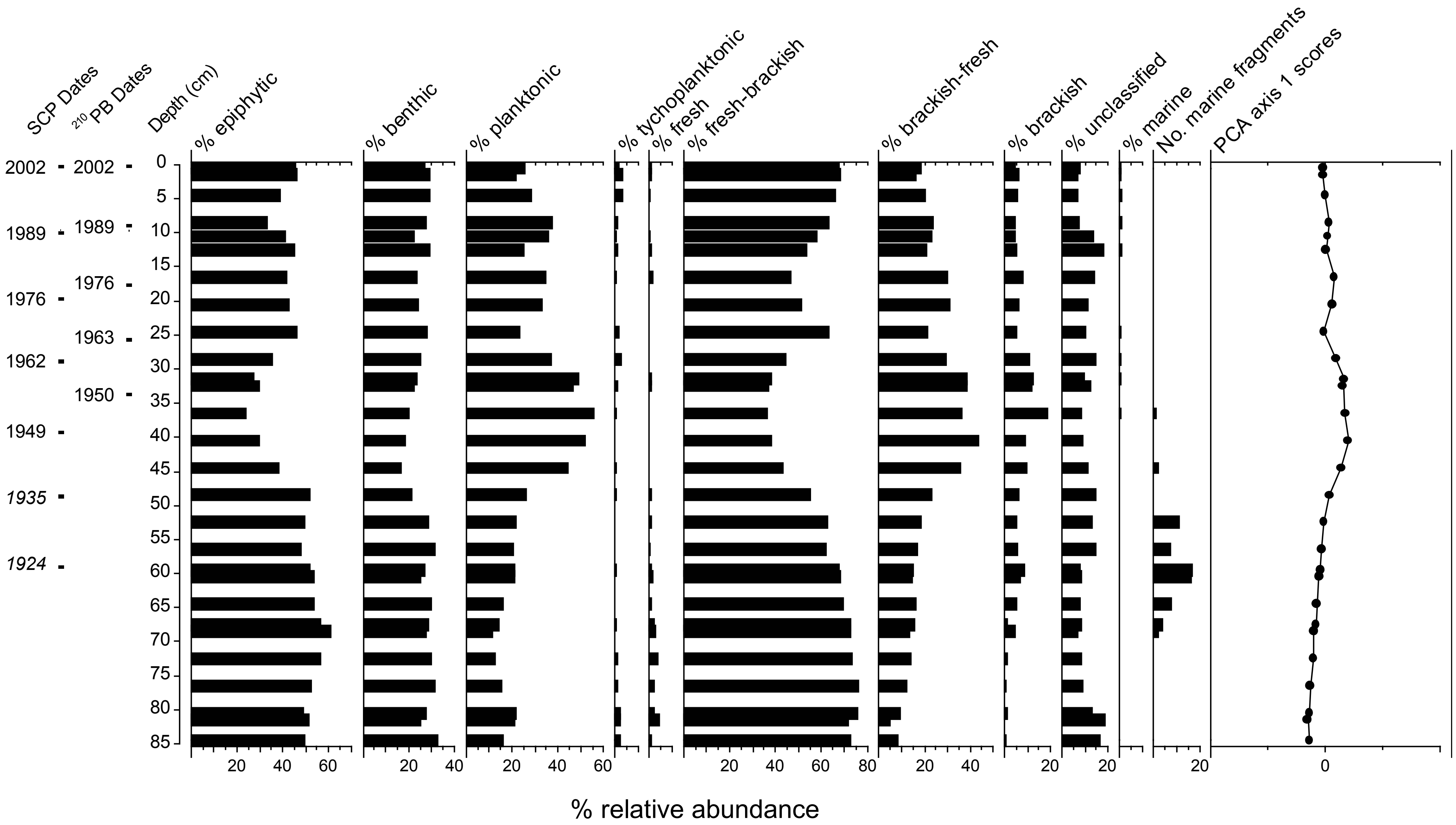


Figure 9 Summary diatom stratigraphy, categorised into functional groups, for ROCK1



Discussion

Interpretation of results

The two methods of determining the chronology of ROCK1, established by both radiometric and SCP techniques, tallied relatively well, although they both became unreliable prior to 1950. It is, therefore, difficult to be certain about the time period covered by the core, as there are likely to have been changes in the accumulation rates, particularly given the changes in biological assemblages that have occurred over the length of the core. A rough estimate for the age of the base of the core is 1800-1850, thus a relatively small proportion, (150-200 years) of the life of the Broad was covered by ROCK1.

The number and diversity of plant remains found in ROCK1 were generally lower than previous work on the Broads and other published data (e.g. Odgaard & Rasmussen 2001; Davidson et al. 2005b; 2008). A number of studies have demonstrated that the analysis of plant macrofossils in sediments is unlikely to reconstruct absolute species diversity as rare species and those which leave fewer remains (e.g. *Potamogeton* species) are likely to be under-represented (Davis 1985; Dieffenbacher-Krall & Halteman 2000). The method has, however, been shown to provide a reliable means with which to track changes in the dominant components of the submerged vegetation of shallow lakes (Davidson et al. 2005a). Thus, despite the fact there were fewer remains of plants in the sediments compared with other studies there were sufficient to provide valuable reliable information on the former submerged flora of Rockland Broad.

In addition to sub-fossils of aquatic vegetation, those left by animals, such as fish, molluscs and cladocerans can shed light on past changes in the ecological structure and function of shallow lakes (Jeppesen et al. 2001). Cocoons of the fish leech *P. geometra* may provide information on plant abundance as they require not only fish, on which they feed, but also plant surfaces to which the cocoons are attached (Odgaard & Rasmussen 2001). Thus, in addition to the direct information provided by the remains of the actual plants, some animal remains provide complementary information on both plant abundance and wider changes in ecological functioning. In addition to the macrofossil analysis, microfossils of cladocerans and diatoms were analysed as part of this and previous studies on ROCK1 and have been integrated into this report. The use of multiple palaeolimnological indicators from a variety of trophic levels applied here is potentially a very powerful technique to explore past environmental change (Sayer et al. 1999). The power, in part, stems from the fact that multiple groups provide insights into, not only, how the site has changed and but also indications of what the causes for these changes were.

The array of data presented here suggest that below 65 cm, corresponding to pre-1920, Rockland Broad, had a diverse and relatively abundant plant flora, indicated by the direct macrofossil data but perhaps more so by the animal macro-remains with a species rich and abundant mollusc fauna. In addition, other benthic species suggested abundant submerged plant cover, such *P. geometra* and the cladoceran taxa, *G. testudinaria*, *A. harpae* and *E. lamellatus* (Whiteside 1970) which were present in relatively high numbers. The cladoceran data indicated that there was a relatively even balance between benthic and pelagic primary production reflected by relatively abundant benthic species taxa along with relatively numerous pelagic cladocerans, particularly *D. hyalina* and *Ceriodaphnia* spp. In slight disagreement the diatom results indicate the dominance of epiphytic and benthic production. The shift from the dominance from benthic to pelagic primary production has been shown to be one of the results of nutrient enrichment (Vadeboncoeur et al. 2005). Recent developments in palaeolimnology have demonstrated that, in shallow lakes at least, cladoceran assemblages are more sensitive to the initial impacts of nutrient enrichment than diatom assemblages (Davidson et al. in press). Thus, it appears that even at the base of ROCK1 the ecological function and most likely the macrophyte flora were already significantly altered by nutrient enrichment.

The majority of plant macrofossil studies in the Norfolk Broads have indicated that Charophytes formed a major component of the ancestral plant community (Davidson et al. 2005b; Ayers et al. in press; Davidson et al. 2008). There is some variation between the river basins, but in general *Chara* has been dominant to sub-dominant at all sites investigated. The Yare Broads have some of the highest alkalinity values of all the Broads and have typically had a very rich mollusc fauna as a result, conditions which would favour an abundant *Chara* community. The question arises, therefore, of whether: a) Rockland never had a rich charophyte community or b) ROCK1 was not long enough and the period of *Chara* dominance is lower in the sequence or c) The area the core was taken in has never had abundant *Chara* beds. The complete absence of any oospores of *Chara* from the basal sequence is unusual, (although a previous undergraduate study found a very small number of oospores at 75 cm) the data indicate that the site was already impacted at the bottom of the core. It seems likely, therefore, that the more likely answer to the question of why there are no *Chara* oospores in the base of ROCK1 is a mixture of the core not being long enough and perhaps coring location. The cover photo of the report probably dates from around the turn of the 19th & 20th century and shows dominance of *S. aloides* and water lily in the coring location. Further evidence of the site already being impacted, in addition to the large number of *D. hyalina* ephippia, was provided by the mollusc species present, *V. piscinalis* and *Pisidium* spp. are more mud than plant associated (Lodge 1985) and are detrital feeder by preference (Reavell 1980) which accords well with significant phytoplankton production. The presence of truly plant-associated cladocerans and a number of more epiphytic molluscs, such as *L. peregra*, suggest a relatively even balance between benthic and pelagic primary production. Thus, it is likely that despite a eutrophication-induced shift to more planktonic primary production the water clarity remained relatively high and submerged plants persisted in good condition.

The next stage in the history of Rockland Broad, between 65 and 50 cm was characterised by a decline in abundance of all plant remains, although *C. demersum* and *S. aloides* persisted through this period. Mollusc numbers decreased sharply as did numbers of *D. hyalina* agg., whereas numbers of *Simocephalus* substantially increased. The key explanation for this shift is the presence of fragments of marine diatoms in this period of the core. There may have taken the form of a chronic input of salinity or, perhaps more likely, a series of short-lived intrusions with high tides and low flows. Whether or not plant abundance decreased is an interesting question *Simocephalus* is a strongly plant associated species (Alonso 1996), which can tolerate relatively high salinity (Amsinck et al. 2005) which suggests that plants were still abundant. It may be that a few species, more tolerant to elevated salinity, had a relatively high abundance. The postcard image on the front cover of the report showing prolific growths of *S. aloides*, water lily and what appears to be *Lemna minor* may come from this time.

Above 55 to around 30 cm the numbers of marine diatoms fragments fell but the number of brackish-fresh species remained relatively high suggesting a continued but reduced tidal impact. There may be indications of recovery in the macrophyte community with the appearance of *Chara* oospores, albeit in very low number and a slight increase in the number of *S. aloides* spines. At this time up to around 30 cm there was an increase in the relative abundance of planktonic diatoms. The increase in the abundance of the small-bodied benthic cladoceran *Alona rectangula*, a detrital feeding species (Davidson 2006), perhaps suggests that this plankton is not being extensively grazed and this combined with the lack of abundant pelagic cladocerans, suggests relatively turbid water.

Above 30 cm there appears to have been some recovery in the system, with the return of several mollusc species and the increase in *D. hyalina* agg. Notably *A. rectangula* numbers fell and perhaps water clarity increased, as the planktonic proportion of the diatom flora fell. It seems that this apparent increase in water clarity resulted directly from top-down grazing pressure (Carpenter et al. 1985), perhaps indirectly associated with the increase in *Nymphaeaceae* remains (Timms & Moss 1984). There may be some indication of a slight decline in ecological quality above 15 cm with a decline in the abundance of lily remains, *Daphnia* ephippia and a shift in the mollusc assemblage towards the dominance of *Pisidium* spp.. The low numbers of large bodied pelagic cladocerans, suggest grazing pressure is low and turbidity relatively high, however, the chitinous cladoceran remains along with the diatom data suggest that there is still some benthic and epiphytic production.

The application a number of palaeolimnological techniques to the Rockland Broad core has proven very powerful in tracking the past chemical and biological conditions. The use of multiple biological group from different trophic levels and, perhaps crucially, representing both benthic and pelagic habitats, has allowed not only tracking of changes but also a more well founded interpretation of the causes of these changes.

Management recommendations

The data presented here demonstrate that Rockland Broad is a highly impacted system, there is still, however, some evidence of benthic production. One key finding of this study is the impact that saline incursions have had on the site. Prior to the historical period of saline incursions towards the base of the core, around the turn of the 19th and 20th century, the site was in relatively good condition and would have been resilient to major disturbance. Any current saline incursions would find a site of much diminished resilience and may have a profound impact, particularly through excluding large bodied cladocerans. Future climate change and sea level rise may have a profound impact on these sites vulnerable to saline intrusions. The aim should be to re-establish the resilience of the site. Nutrient loads clearly have a profound impact upon the resilience and so key recommendations are to:

- Reduce point and diffuse nutrient inputs to the site to an absolute minimum.
- Promote catchment sensitive farming and land use.
- Continue chemical and biological monitoring of the Broad

In terms of recovery of all the Norfolk Broads, where in general nutrient levels are falling but healthy, species rich communities of submerged are still rare, there is a clear need for further research into the role of sediment phosphorus release, sediment structure, not only re-suspension, but suitability of substrate, both chemical and physical for rooted plants. It may be that water quality is returning to levels where macrophytes could prosper, but aspects of the sediment chemistry and structure precludes their establishment. In addition, and in particular given the current vogue for sediment removal from Broads, it is vital that the integrity of the seed bank is established in order to successfully manage for the return of a biodiverse both in terms of species and genetic diversity.

Further work in the Yare Broads

This study has produced some interesting data on the history of Rockland Broad, the core did not, however, cover the entire history of the site. Therefore, it would be interesting, and of some use to take a longer core to assess the conditions prior to the time period covered by ROCK1. This could be done by coring at the same site and analysing the samples below the higher carbonate period in the core.

There are a number of other interesting sites in the Yare valley, such as Buckenham and Strumpshaw Broads, they have, however, been dredged and thus no sediment record remains. Hassingham Broad has also been dredged, but in this case a number of cores were taken prior to the dredging operation. It would therefore be extremely interesting, and provide useful management information to analyse this core for plant remains. The current study of Rockland demonstrates the power of the multi-proxy approach which should be considered if possible. The interpretation of ROCK1 would have difficult without cladoceran and diatom remains to provide information on changing ecological function in addition to the plant and animal macrofossil remains.

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