



# UCL



## **Hoveton Great Broad Macrophyte Study: Using the sediment record to inform lake restoration**

ECRC Research Report Number 160

Goldsmith, B., Lambert, S., Henderson, G., Sayer, C.D., Goodrich, S.  
Shilland, J. and Matyskova, V

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# 1. Introduction

## 1.1. Background

Hoveton Great Broad and Hudson's Bay form part of the Bure Marshes SSSI which itself is a component of the Broadland SPA and The Broads SAC. They also form part of the Bure Marshes National Nature Reserve (NNR). Currently both Broads are in 'unfavourable' condition with respect to Habitats Directive targets and fail to reach 'good' ecological status under WFD classifications.

With recent improvements in the water quality within the River Bure, the focus has now shifted to internal nutrient release as the main reason for the poor condition of these waterbodies. Natural England is therefore developing a restoration plan in partnership with the EA, to restore the broads by removing a significant proportion of the nutrient-rich upper sediments from both sites in association with bio-manipulation of the fish community. In so doing, it is hoped that internal nutrient loads will fall and clear water conditions return. Clear water conditions will be facilitated if submerged aquatic plants are re-established in the sites at low fish density.

While the primary reason for sediment removal is to reduce internal nutrient loadings, it may have the added benefit of exposing a viable seed and propagate bank which will facilitate the return of aquatic macrophytes to the two boards after de-silting. There is therefore considerable value in understanding how and where the viability of aquatic plant propagules vary spatially within the two boards and also with sediment depth, i.e. temporally. Additionally, sediment analysis can be used to determine the extent and composition of the past macrophyte communities that populated the sites prior to eutrophication and thus provide accurate baselines for use as restoration targets. It is proposed that this information can be used to inform the de-silting procedure by providing the optimal depth(s) of sediment to remove in order to maximise both nutrient removal and propagule viability.

## 1.2. Aim of the Report

- To determine pre-eutrophication aquatic plant communities in Hoveton Great Broad and Hudson's Bay
- To determine seed and oospore viability in the sediments of the of the two broads
- To provide evidence to inform future restoration work

## 2. Methods

### 2.1. Sediment core collection

Sediment cores were taken at 32 separate locations from the two broads in February 2014; 25 from Hoveton Great Broad and 7 from Hudson's Bay (Figure 1). Cores were collected using a piston corer (adapted Livingstone type) with an internal diameter of 70 mm with most cores being approximately 1.0 m in length. The core locations were chosen in such a way as to provide the best geographical coverage of the two broads. Each location was recorded with GPS (Table 1).

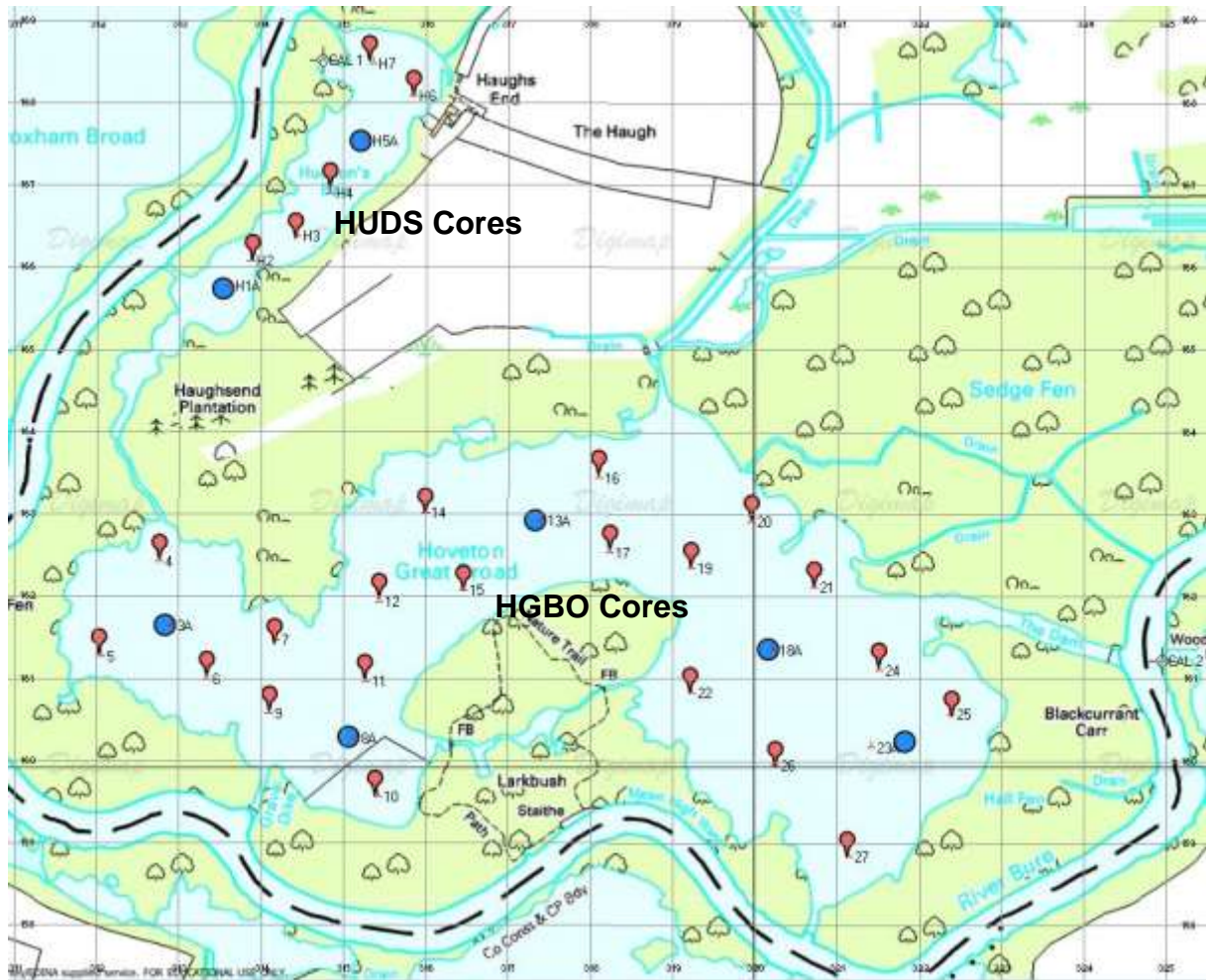


Figure 1 Coring locations at Hoveton Great Broad and Hudson's Bay.

A single core from each location was extruded on site at 10 cm intervals to provide large volumes of sediment for the germination experiments. At seven location (those in blue in Figure 1), a second core was taken and extruded at 1 cm intervals to provide sediment for detailed analysis of organic and carbonate content and geochemistry. These cores (referred to as the master cores) were also sub-sampled for macrofossil analysis (see below).

Core Code	Location	Extrusion interval	Germination sections (cm)											
			10	20	30	40	50	60	70	80	90	100		
HGBO3	TG3128316162	10 cm												
HGBO3a	TG3128316164	1 cm	LOI, CO <sub>3</sub> , XRF & Macrofossils											
HGBO4	TG3127616242	10 cm												
HGBO5	TG3120516127	10 cm												
HGBO6	TG3133416100	10 cm												
HGBO7	TG3141516150	10 cm												
HGBO8	TG3150716027	10 cm												
HGBO8a	TG3150716032	1 cm	LOI, CO <sub>3</sub> , XRF & Macrofossils											
HGBO9	TG3140916058	10 cm												
HGBO10	TG3154215957	10 cm												
HGBO11	TG3152716097	10 cm												
HGBO12	TG3154316194	10 cm												
HGBO13	TG3173216289	10 cm												
HGBO13a	TG3173216292	1 cm	LOI, CO <sub>3</sub> , XRF & Macrofossils											
HGBO14	TG3160016302	10 cm												
HGBO15	TG3164616208	10 cm												
HGBO16	TG3181016344	10 cm												
HGBO17	TG3182316253	10 cm												
HGBO18	TG3201816135	10 cm												
HGBO18a	TG3201816138	1 cm	LOI, CO <sub>3</sub> , XRF & Macrofossils											
HGBO19	TG3192316234	10 cm												
HGBO20	TG3199516291	10 cm												
HGBO21	TG3207216211	10 cm												
HGBO22	TG3192316083	10 cm												
HGBO23	TG3214816018	10 cm												
HGBO23a	TG3214916012	1 cm	LOI, CO <sub>3</sub> , XRF & Macrofossils											
HGBO24	TG3215116110	10 cm												
HGBO25	TG3223816057	10 cm												
HGBO26	TG3202415995	10 cm												
HGBO27	TG3211415883	10 cm												
HUDS1	TG3135416570	10 cm												
HUDS1a	TG3135216573	1 cm	LOI, CO <sub>3</sub> , XRF & Macrofossils											
HUDS2	TG3138716608	10 cm												
HUDS3	TG3144316638	10 cm												
HUDS4	TG3148416690	10 cm												
HUDS5	TG3151816751	10 cm												
HUDS5a	TG3151816755	1 cm	LOI, CO <sub>3</sub> , XRF & Macrofossils											
HUDS6	TG3158516809	10 cm												
HUDS7	TG3153616848	10 cm												

Table 1 Details of the sediment cores taken from Hoveton Great Broad and Hudson's Bay February 4<sup>th</sup> & 5<sup>th</sup> 2014..



## 2.2. Laboratory Analysis

### Organic Content and Carbonate

In an effort to understand the variation in sediment structure across the coring sites and down-core, and also to help cross-correlate the cores, 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<sub>3</sub>) content were undertaken using standard techniques (Dean, 1974; Heiri et al., 2001).

For each 1 cm slice from the seven master-cores, approximately 1.0 g of wet sediment was weighed ( $\pm 0.0001$  g) into a crucible and dried at 105 °C for 12 hours and then re-weighed to give the percentage dry weight (%DW). The same sample was then placed in a furnace at 550 °C for 2 hours to burn off the organic material and re-weighed to give the percentage organic material (loss on ignition %LOI). The sample was then placed back in the furnace for a further 2 hours at 950 °C and re-weighed to calculate percentage carbonate (%CO<sub>3</sub>).

### Sediment Geochemistry - XRF

In order to make further comparisons between cores and also examine total phosphorus profiles within the cores X-ray fluorescence (XRF) was used on the seven master cores. The units for phosphorus are slightly complicated in that they are estimates of concentration in mg per gram of sediment (mg g<sup>-1</sup>) expressed as diphosphorus trioxide (P<sub>2</sub>O<sub>3</sub>). The method provides no information of the different fractions of P present (e.g. absorbed, adsorbed and possibly co-precipitated in the carbonate structure). Thus, no information on bioavailability or mobility of P is provided, but it does provide an estimate of the direction and magnitude of P loading over time.

In addition to phosphorus, XRF analysis produces a suite of other chemical constituents which can be used both to help cross-correlate cores and also identify other pollutants in the sediments, e.g. copper and heavy metals.

The remaining sediment from the seven master-cores has been dried and archived at UCL for potential future research work.

### Macrofossil analysis

With the focus being on potential sediment dredging a pragmatic approach was taken to the analysis of plant macrofossil remains. It was assumed that dredging would remove somewhere between 30-80 cm of sediment and therefore samples were only analysed from this zone.

Five sediment samples were analysed from each of the seven master cores (35 samples in total) with sediment bulk increased by amalgamating approximately half the material from 3 separate 1 cm slices from each 10 cm section. Methods followed Birks (2001). A measured volume of sediment (~50-80 cm<sup>3</sup>, the exact volume being assessed using water displacement) was analysed for each level. Samples were sieved at 350 and 125 microns and the residues from each transferred 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) 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 to the highest taxonomic level possible by comparison with herbarium documented reference material. The data are presented as numbers of remains per 100 cm<sup>3</sup> of wet sediment and illustrated in a series of summary stratigraphic plots showing change in abundance of the major taxa through time.

### 2.3. Contemporary Macrophyte Survey

Surveys of the current aquatic macrophytes in the two broads were carried out in July 2014 using JNCC Common Standard methodology (JNCC 2005).

The surveys consisted of four components; a strandline survey, emergent and marginal survey, shoreline “wader” survey and boat survey. These were carried out at each site on four discrete 100m sections of shoreline which were considered representative of the board and gave good geographical coverage. Where possible, surveying was performed using a bathyscope, but a double-headed rake was used in deeper water and where poor water clarity restricted visibility. The locations of all survey sections and boat transects were recorded using a Global Positioning System (GPS), backed up with digital photographs where necessary.

The survey sections are assumed to be collectively representative of the site. However, to enable comparison with historic survey data, estimates of species abundance for each set of survey points at a site have been made from the total number of occurrences, and these data have been converted to a DAFOR scale. For submerged and floating-leaved species the category was estimated from the total number of occurrences of each species in the wader and boat surveys as a proportion of the total number of vegetated survey points at the site, where an occurrence at >50% of points = D, 25-50% = A, 10-24% = F, 5 - 9% = O and <5% = R. All field data were recorded onto standard forms printed onto waterproof paper and transferred onto a Microsoft Access database.

### 2.4. Germination experiments

Macrophyte viability studies were undertaken by Veronika Matyskova as part of her MSc. project (Birkbeck) with supervision provided by Stephen Lambert)

Germinations experiments were conducted in 12 litre aquaria over a 6 month period between March – October 2014. The 10 cm sections of sediment core taken from 30 cm to 80 cm depth (five sections from each core), were individually homogenised and spread in the base of a clean, pre-labelled plastic aquarium (Figure 2a). In addition, the upper three 10 cm sections (0-30 cm) and basal section (c. 90-100 cm) from each of the 7 master core locations (see Figure 1) were also placed into aquaria. Each aquarium was filled with 10 litres of river water taken from the River Bure close to the entrance to Hoveton Great Broad at the Woodbastwick slipway, thus providing conditions similar to that of the broad.

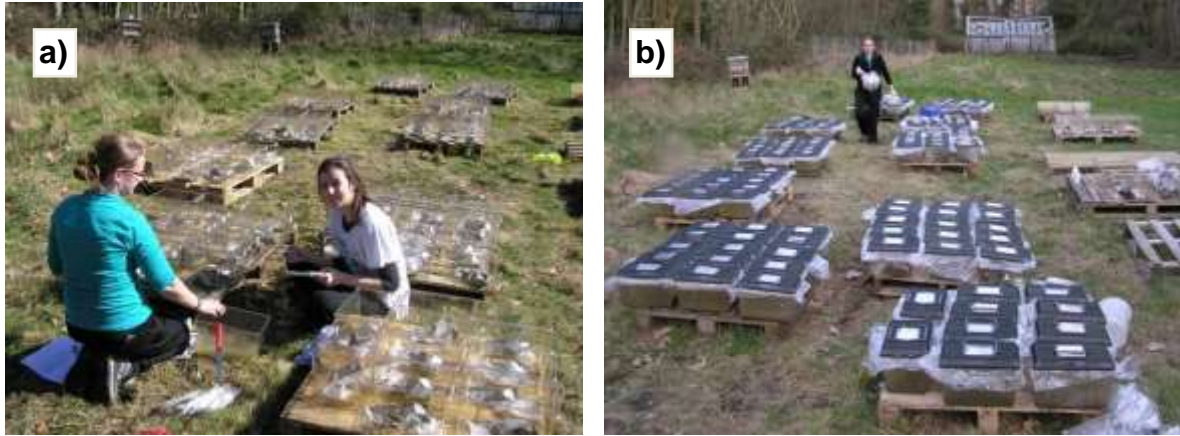


Figure 2 Setting up the aquaria for germination experiments at Woodbastwick, March 2014

Each aquarium was labelled and covered with Cling-Film™ to minimise the loss by evaporation and to prevent rainwater ingress. The aquaria were further protected with fitted lids which included a clear plastic cover and then set out in an organised fashion on wooden pallets (15 aquaria to a pallet) on flat open land owned by Natural England at Woodbastwick, Norfolk (Figure 2b). The 184 aquaria were then left for six months (in the first instance) and observations made of the numbers and species (or type) of germinations.

### 3. Results

#### 3.1. Core descriptions and geo-chemistry

##### Hoveton Great Broad

The five master cores ranged from 80 to 100 cm in length. In general, cores were similar in their stratigraphic appearance, with the upper sections of the cores being relatively uniform with fine grey/brown organic sediments, mostly without any larger remains visible. There was a visible horizon in all the cores between 80 – 100 cm, tending towards lighter, grey sediments, often with visible mollusc remains. None of the master cores, which were taken from open water areas, had peat at the base, whereas in shallower, littoral location peat was common below 70-90 cm. The core taken by Hoare (2007) in 2004 had lake sediments to approximately 140 cm, below which was peat.

Organic content of the sediments (% LOI) was high at the surface in all cores, with a distinct secondary peak also seen between 27 cm (HGB23a) to 52 cm (HGB8a) in all the cores (Figure 3). The dotted line in Figure 3 is a tentative attempt to suggest a point of correlation. Data are also presented from core HGB01 collected in 2004 (Hoare 2007). The 2004 core was collected from a littoral area between HGB08 and 13. Allowing for the fact that the recent cores will have accumulated additional sediments, there is a slight increase in LOI at 27cm, which possibly correlates with the recent cores, but the link is weak.

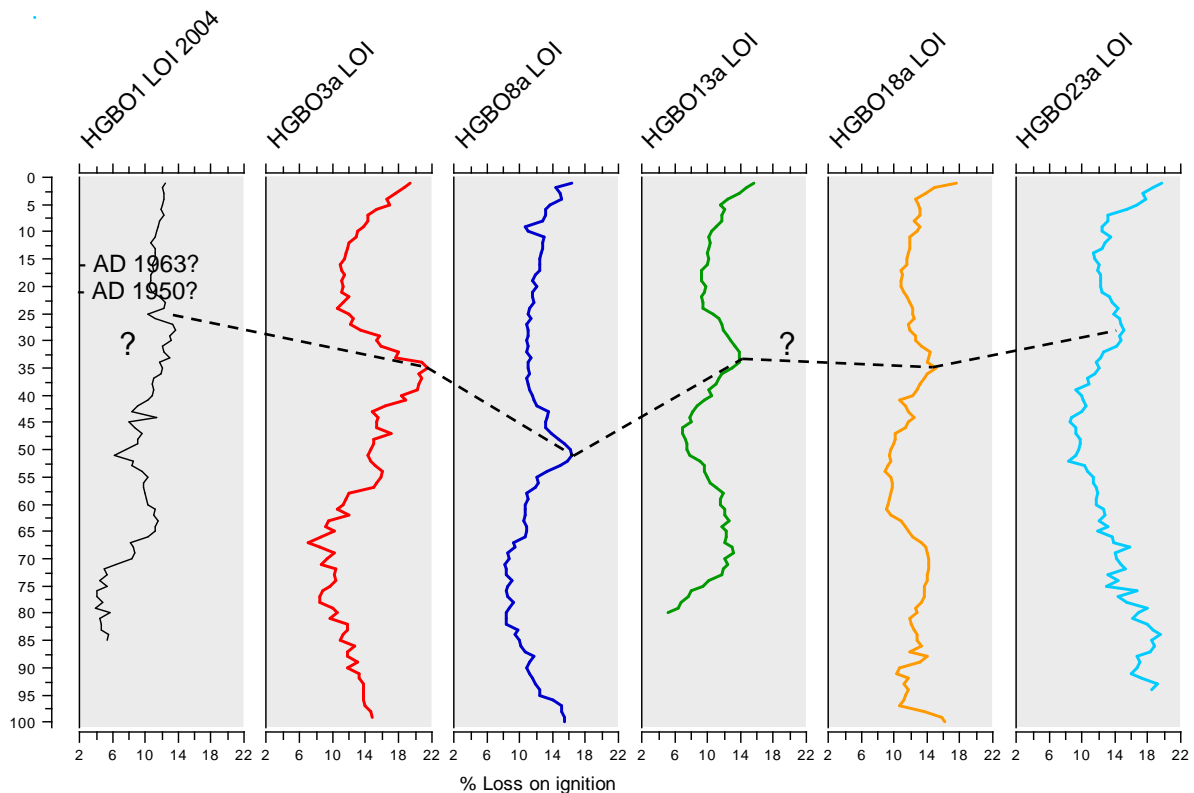


Figure 3 Organic content of the HGB master cores. HGB01 taken in 2004 (Hoare 2007).

Carbonate concentrations were relatively high throughout the cores (25 - 50%) and showed down-core variation in all the cores (Figure 4) with a shallow peak between 10 – 40 cm and another lower down the core. Carbonate is negatively correlated with LOI and therefore between-core correlation is very similar to when using LOI. These data appear to show HGBO3a and HGBO8a, from the western side of the broad, to more rapid accumulation rates than the cores taken from the centre and eastern end.

Radiometric dating applied to HGBO1 (Hoare 2007) was tentative at best due to very low levels of unsupported  $^{210}\text{Pb}$  activity, although it did show a relatively good peak for  $^{137}\text{Cs}$  attributed to 1963 at 16.5 cm. While it may seem tempting to transcribe these dates to peaks in the recent cores, it should be stressed that errors within both the dating and potential matching of the cores means very little confidence is placed in doing this. This is further complicated by irregularities in the concentrations of other elements in the core profile (See below).

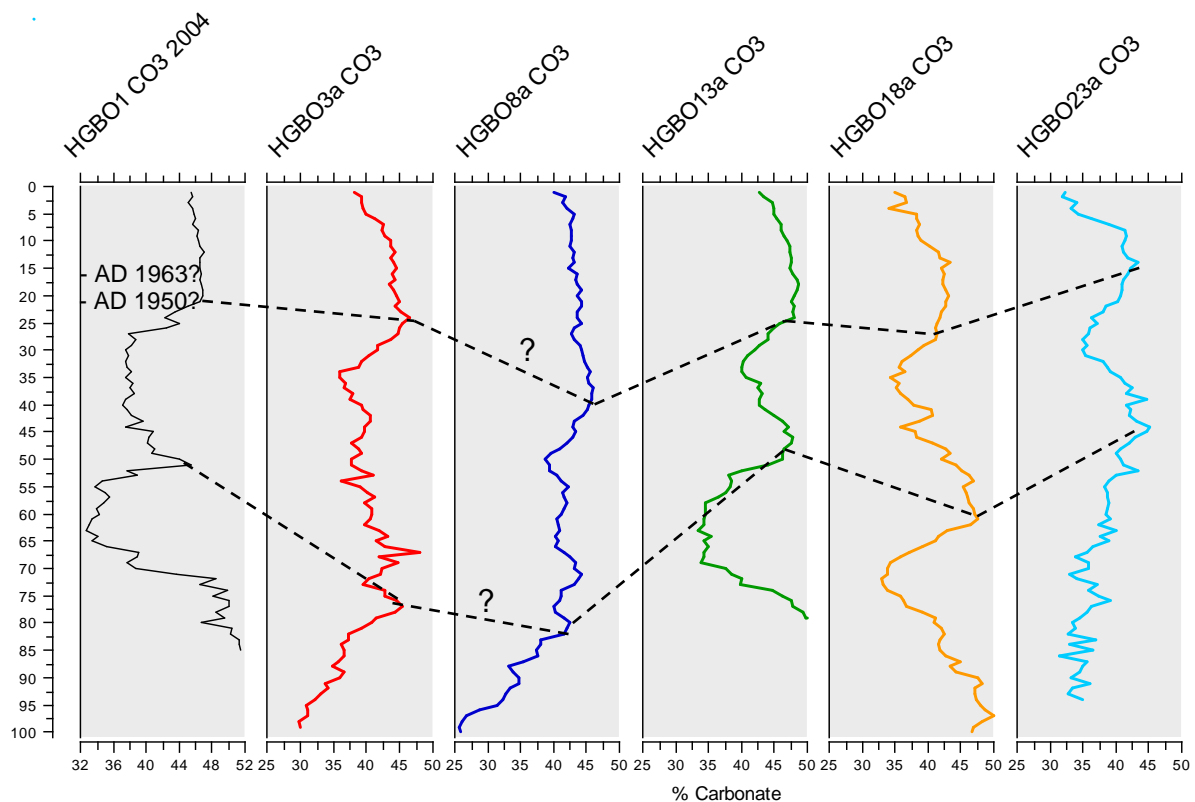


Figure 4 Carbonate content of the HGB master cores. HGBO1 taken in 2004 (Hoare 2007).

Analysis of other stable elements in the cores using XRF, does show some similarity of patterns between the five cores, but there are also anomalies in these profiles that prevents strong correlations being made. There is relatively good down-core agreement between the lead profiles for example, with all five cores peaking at between 20 to 50 cm. Below this, there is evidence of a second peak in cores HGBO8a, 13a and 18a, but this is less distinct in HGBO3a and 23a (Figure 5) suggesting poor correlation between the lower portions of the cores.

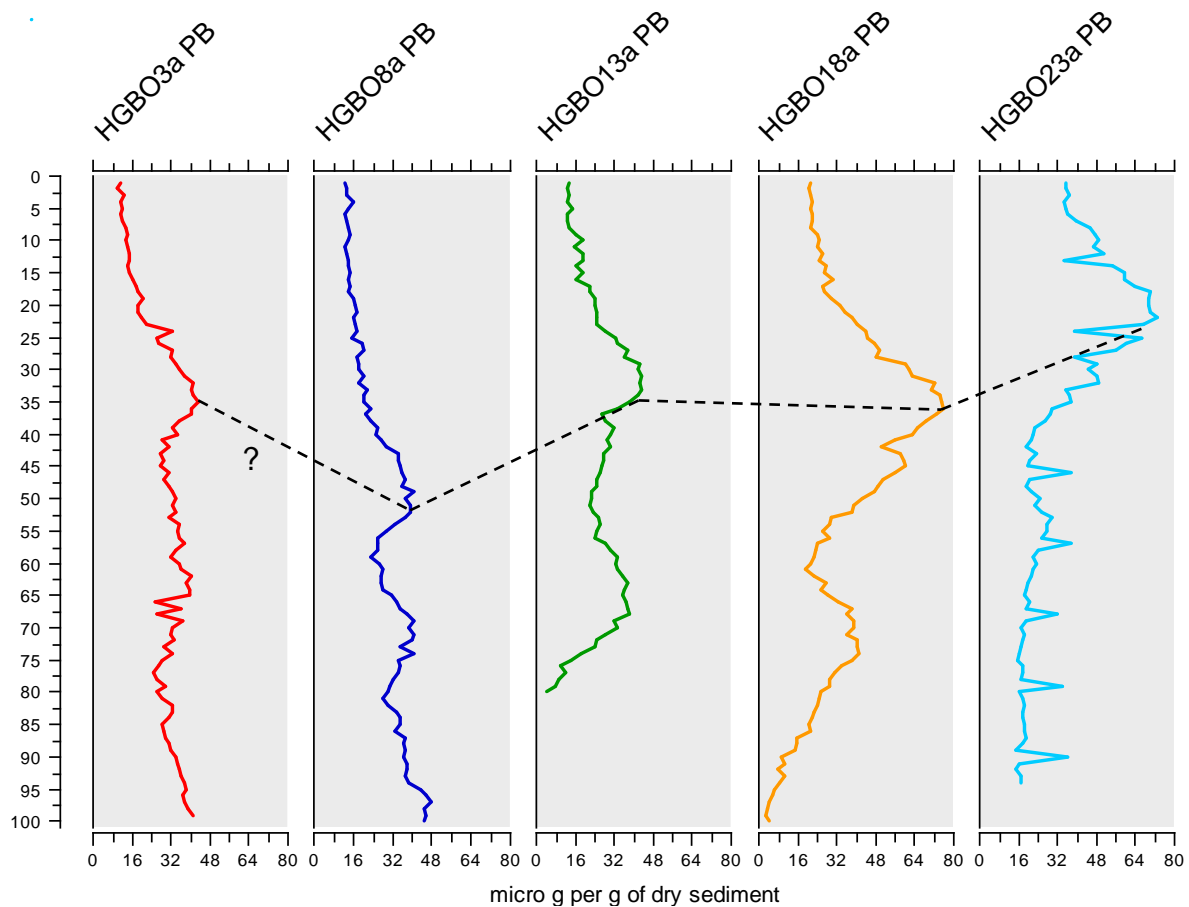


Figure 5 Lead (Pb) content of the HGB master cores.

The geochemical profiles for Al, Si, and Ti are normally relative stable with depth and therefore allow for confidence in core correlations to be assessed. As seen in the figures below, there is good agreement between some of the cores, but it is hard to say with any confidence that all five cores can be matched. HGBO3a and 8a are in good agreement and with only a down-core increase in Al, Si and Ti and no peak, suggest either different sediment sources, or that they have higher accumulation rates than the other cores and the increase at the core base is a truncated peak. This does not however agree with the LOI and carbonate profiles.

Cores 13a, 18a and 23a do show some agreement, with all three having a double peak in the profiles of Al, Si and Ti, albeit less clear and rather noisy in 23a.

Core 8a shows general agreement with the other cores despite the coring area having suffered disturbance from the removal of stakes and wire netting.

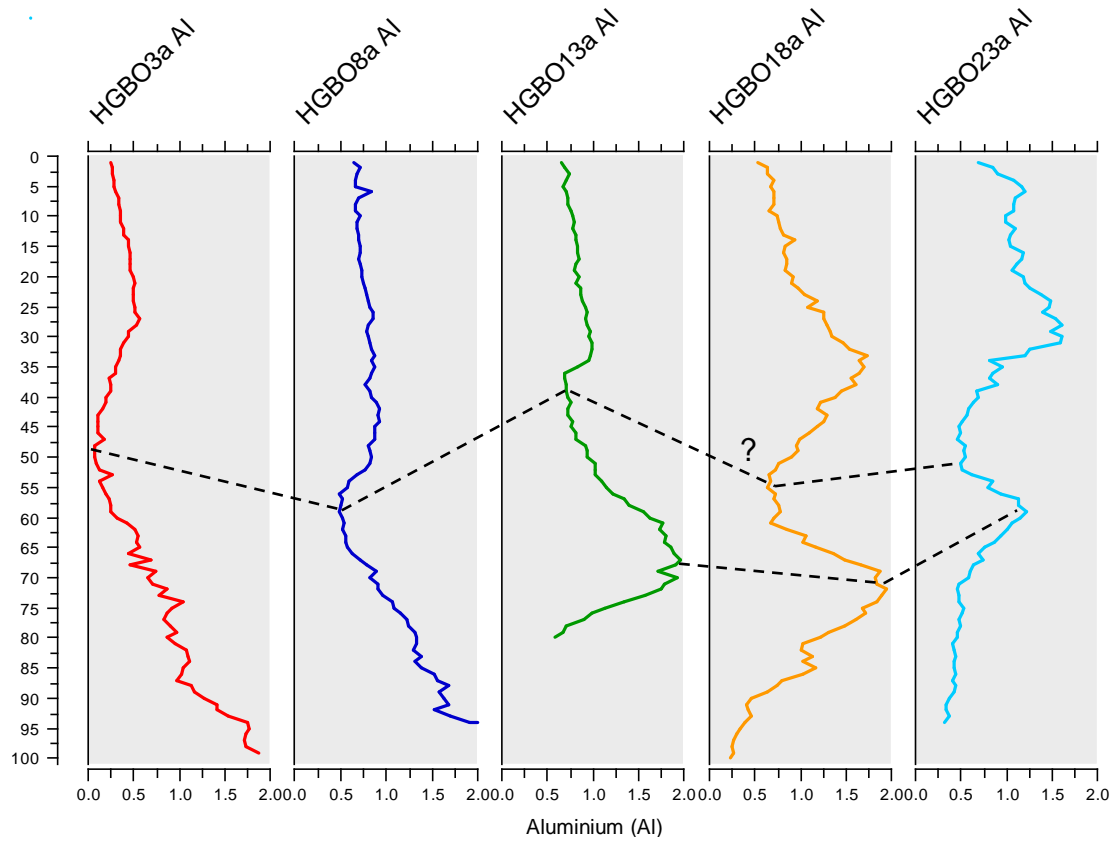


Figure 6 Aluminium (Al) content of the HGB master cores.

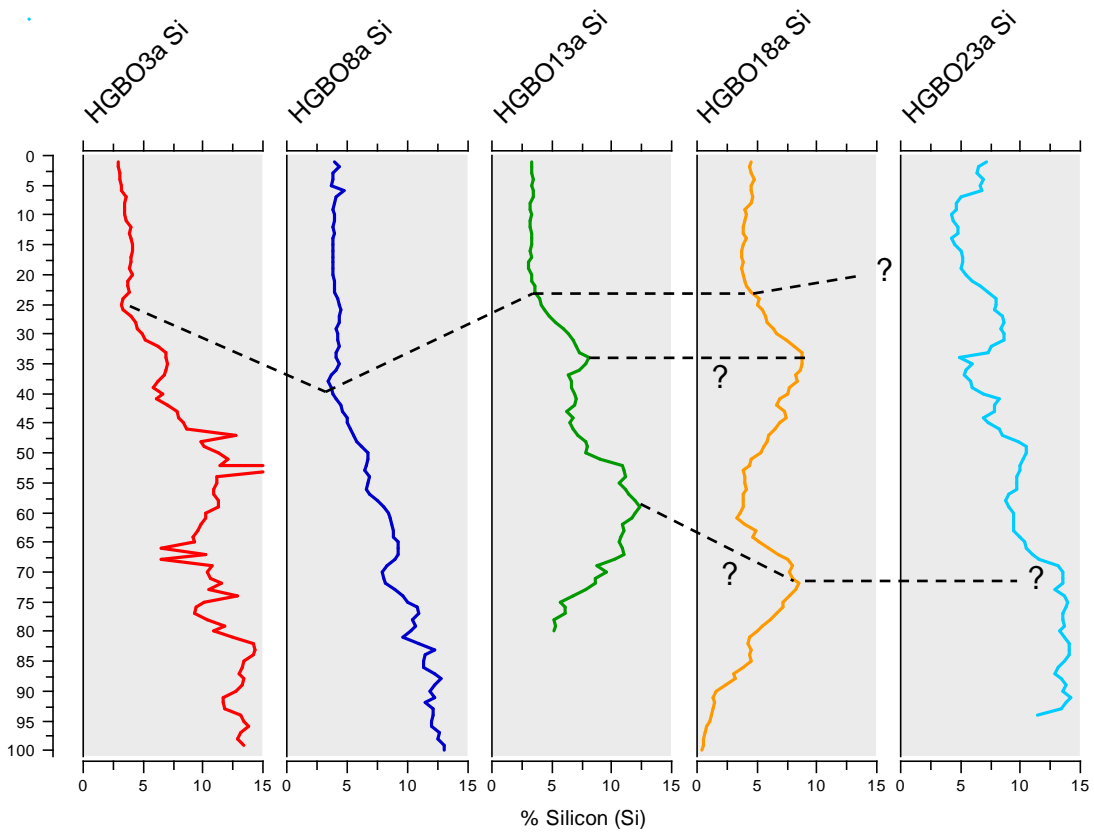


Figure 7 Silicon (Si) content of the HGB master cores.

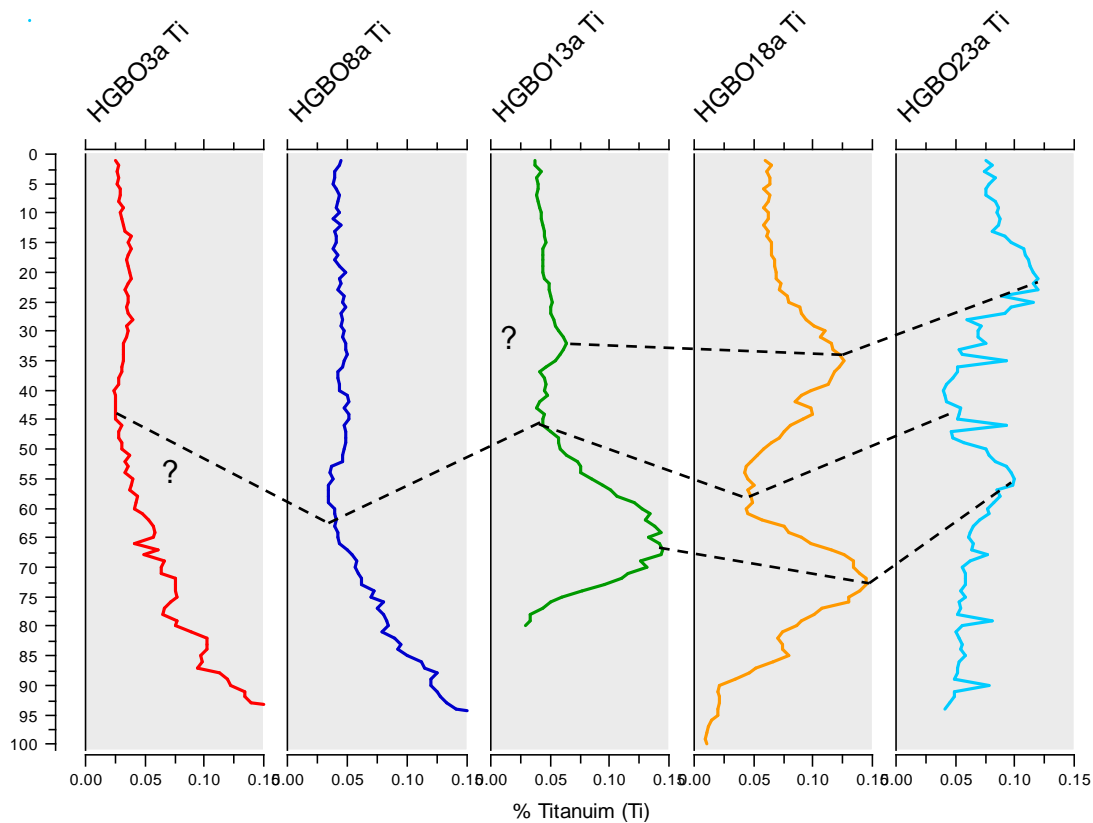


Figure 8 Titanium (Ti) content of the HGB master cores.

There is an increase in P concentrations in all the cores with the values at least doubling between the base sample and upper 5 cm of the cores. The general trend within all the cores is for the P values to follow the same pattern as changes in % LOI, suggesting that P concentrations are in the most part associated with organic matter.

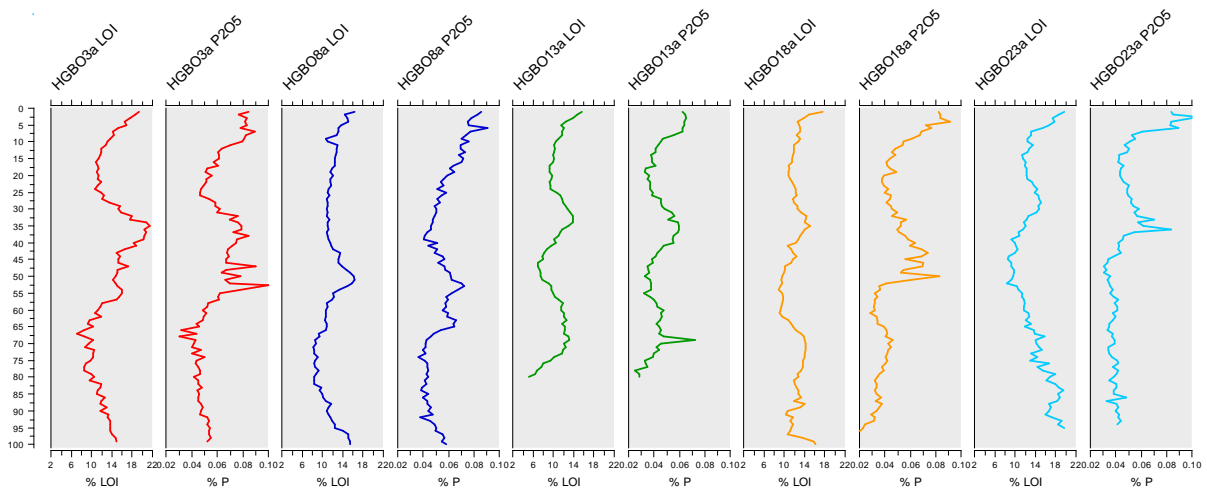


Figure 9 Comparative graphs of sediment P and organic matter

It is interesting to note that all the cores show a peak in the P concentration in the middle part of the record as well as toward the top, suggesting P in the sediments



(but not necessarily in the water) to have fallen during a period loosely attributed to the latter half of the 20<sup>th</sup> century, before rising again towards the present day (Figure 9).

In the uppermost part of HGB013a, 18a and 23a there is some suggestion of a downturn in the values that is not seen in the LOI data. It would be somewhat optimistic to relate these figures to improvements in the water quality of the River Bure in recent years without further investigation.

### Hudson's Bay

The two master cores were both 100 cm in total length, but HUDS5a had a 4 cm gap caused by problem during the extrusion process. The two cores were similar in appearance, with the upper sections of the cores being relatively uniform with fine grey/brown organic sediments, mostly without any larger remains visible. There was a visible horizon at approximately 73 cm in HUDS1a and 60 cm in HUDS5a, below which the sediment was darker grey with visible mollusc remains. The underlying peats were not reached with either core. The organic content and carbonate profiles are similar from both HUDS cores (Figure 10)

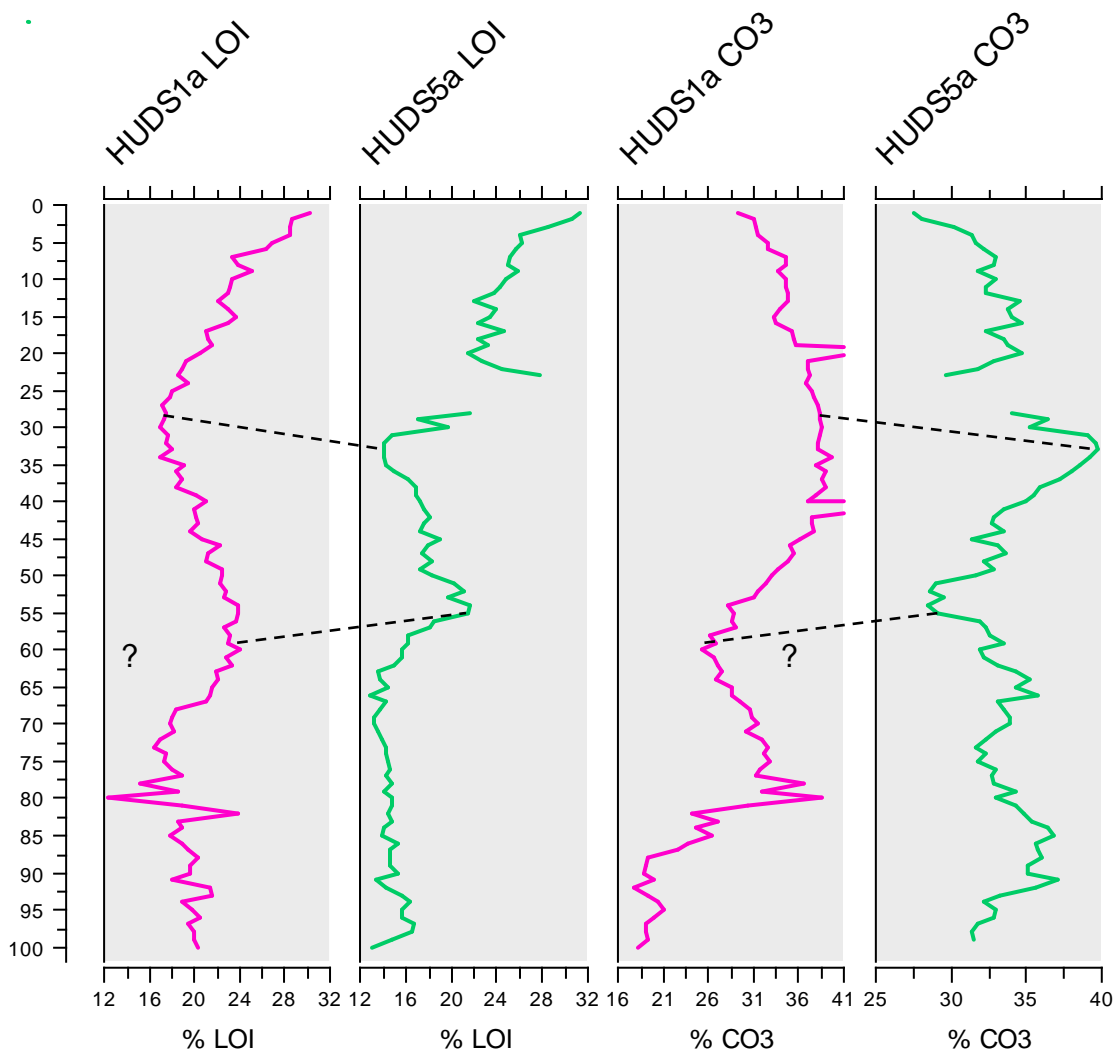


Figure 10 Organic and carbonate content of HUDS master cores

The organic content of the sediments (% LOI) showed a similar pattern to that seen in the HGB cores, with high %LOI at the top and a secondary peak midway down the core. The dotted line in Figure 10 picks out the most obvious features correlating the cores. Carbonate concentrations were relatively high throughout the cores 16 - 40% and showed a strong negative correlation with LOI.

Analysis of other stable elements in the cores using XRF, does show some similarity of patterns between the five cores, but there are also anomalies in these profiles that prevents strong correlations being made. There is agreement of the upper part of the lead and Silicon profiles, but the lower section of the cores are less easily matched (Figure 11). between the lead profiles for example, with all five cores peaking at between 20 to 50 cm. Below this, there is evidence of a second peak in cores HGBO8a, 13a and 18a, but this is less distinct in HGBO3a and 23a (Figure 5) suggesting poor correlation between the lower portions of the cores.

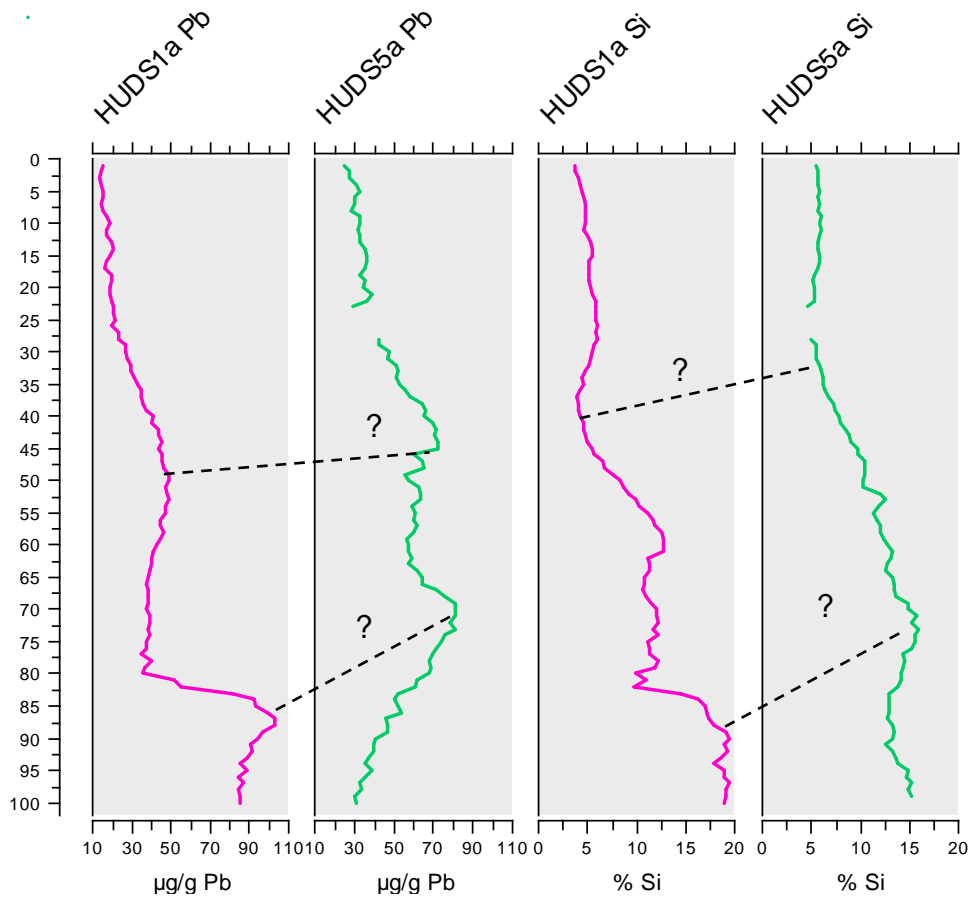


Figure 11 Lead (Pb) and Silicon (Si) content of the HUDS master cores.

Similarly, the profiles for titanium and aluminium are relatively stable in the upper 75 cm of the cores, but the increases in metal concentrations seen in HUDS1a are not recorded in HUDS5a (Figure 12). Possibly the slight increase in Ti and Al seen at the base of the 5a core is the start of this increase, but we have insufficient data to confirm if this is so.

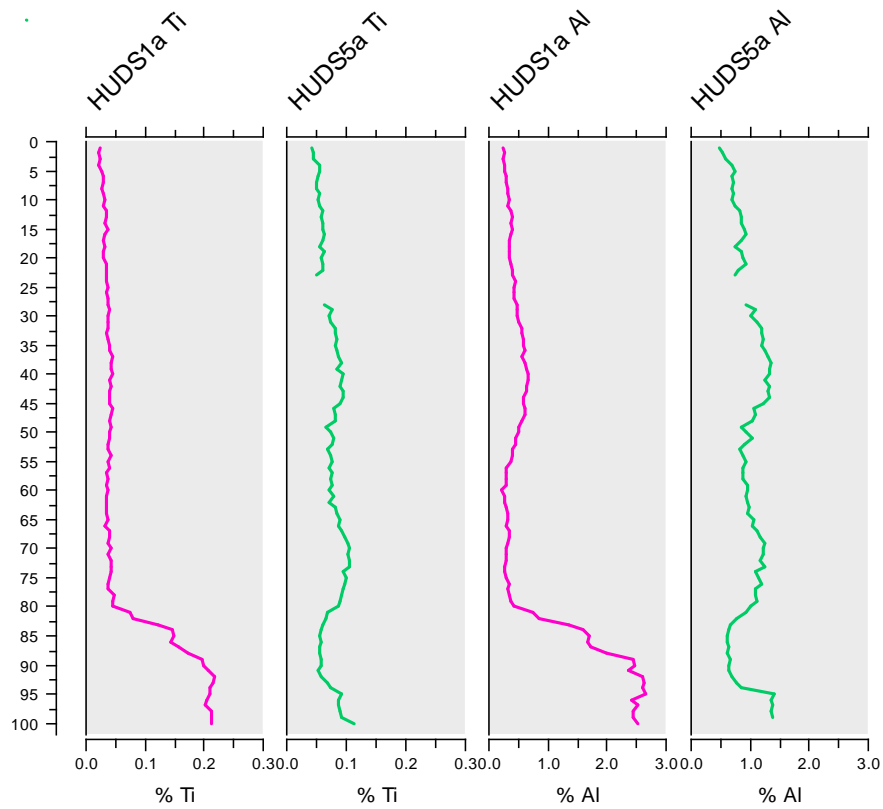


Figure 12 Titanium (Ti) and aluminium (Al) content of the HUDS master cores.

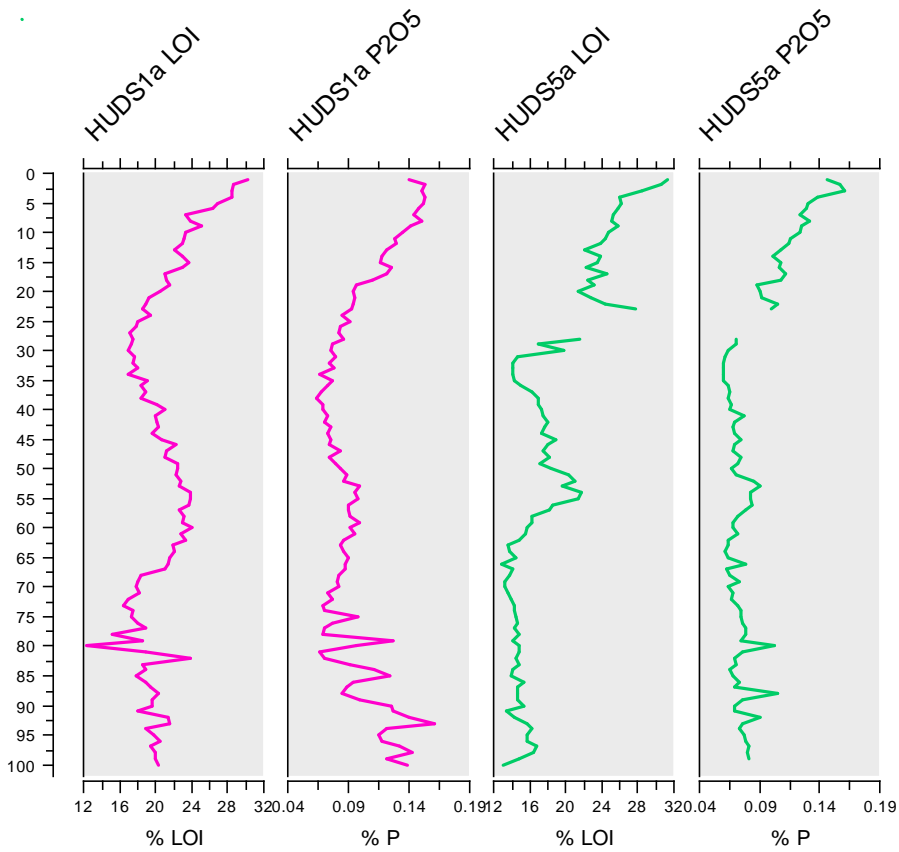


Figure 13 Comparative graphs of sediment P and organic matter

Like the HGB cores, there is an overall increase in P concentrations in the two cores with similar changes in concentration seen (Figure 13) and trend for the P values to follow the same pattern as changes in % LOI, suggesting that P concentrations are in the most part associated with deposition of organic matter and reflect the lake productivity. The peak in sediment P seen in the mid sections of many of the HGB cores, is less evident in HUDS cores, but concentrations in the base of HUDS1a are the same as at the top.

Despite the increased LOI in the uppermost levels of the cores, the concentration of P drops slightly.

### 3.2. Plant macrofossil analysis.

#### Hoveton Great Broad.

Of the five cores analysed from Hoveton Great Broad for plant macrofossil remains, none were particularly species rich in terms of remain types, nor were there many plant seeds or propagules recoded. *Chara* spp. oospores, *Potamogeton* spp. seeds (and fragments of), *Myriophyllum spicatum* seed, *Zannichellia palustris* seeds, *Callitriche* spp. seeds and water lily seeds where the only aquatic seed species recorded and the total taxon count for aquatic species was increased to 10 by the presence of *Ceratophyllum demersum* spines and leaf parts, *Stratiotes aloides* spines and *P. crispus* turion fragments.

The summary fossil data are presented in Figure 14 to Figure 18 below. It should be noted that the summary diagrams only show the core section subsamples from 30 to 80 cm in order to best inform likely sediment pumping options.

The macrofossils cores fall into two groups. Cores HGBO3a and 8a are dominated by the leaf and spine remains of *C. demersum* through most of the levels, with *M. spicatum* leaf tips and seeds also present more commonly in the lower samples. *Ceratophyllum* remains are less common in the upper part of core 8a. *Chara* oospores are numerous in only the 40-50 cm and 50-60 cm levels respectively in each core. The presence of water lily trichosclereids coincides with *C. demersum* remains in both cores and although other aquatic species are recorded, numbers are very low.

The other three cores have *Chara* spp. oospores more common in the lowest samples, with *C. demersum* more abundant towards the upper samples. Note that HGBO13a had very large number of oospores present .

These data suggest Hoveton Great Broad to have had a mixed aquatic flora in the past and one typical of eutrophic waters. Interpretation of the exact nature of the shifts in community composition are made difficult by low sample numbers and difficulties correlating the cores, but there is a broad agreement with the findings of Hoare (2007) who suggests a shift from *Chara* dominance to mixed *M. spicatum*, *C. demersum*, fine leaved *Potamogetons* and *Chara* to dominance to by large areas of mixed lily beds. These data are also corroborated by a range of historical plant records collated by Madgwick (2009).

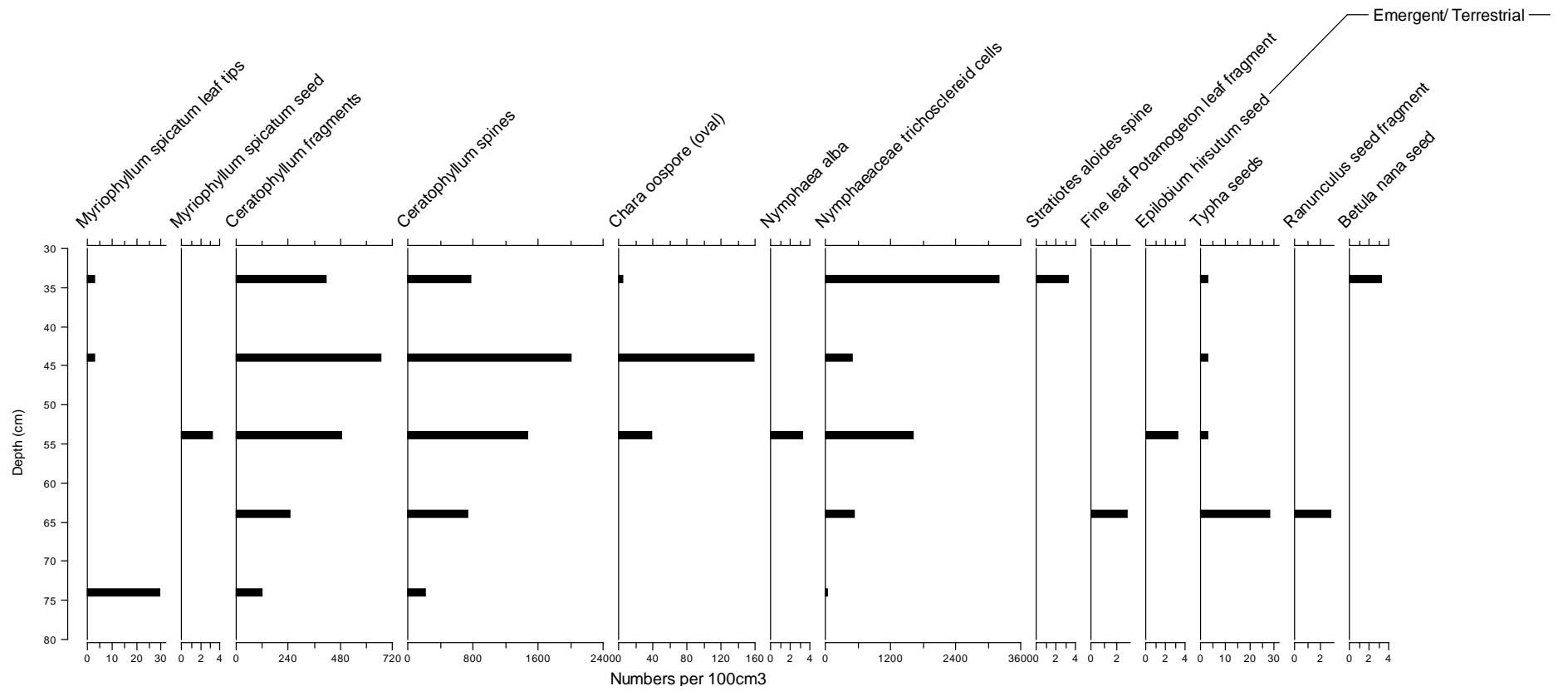


Figure 14 Plant macrofossil summary for core HGBO3a

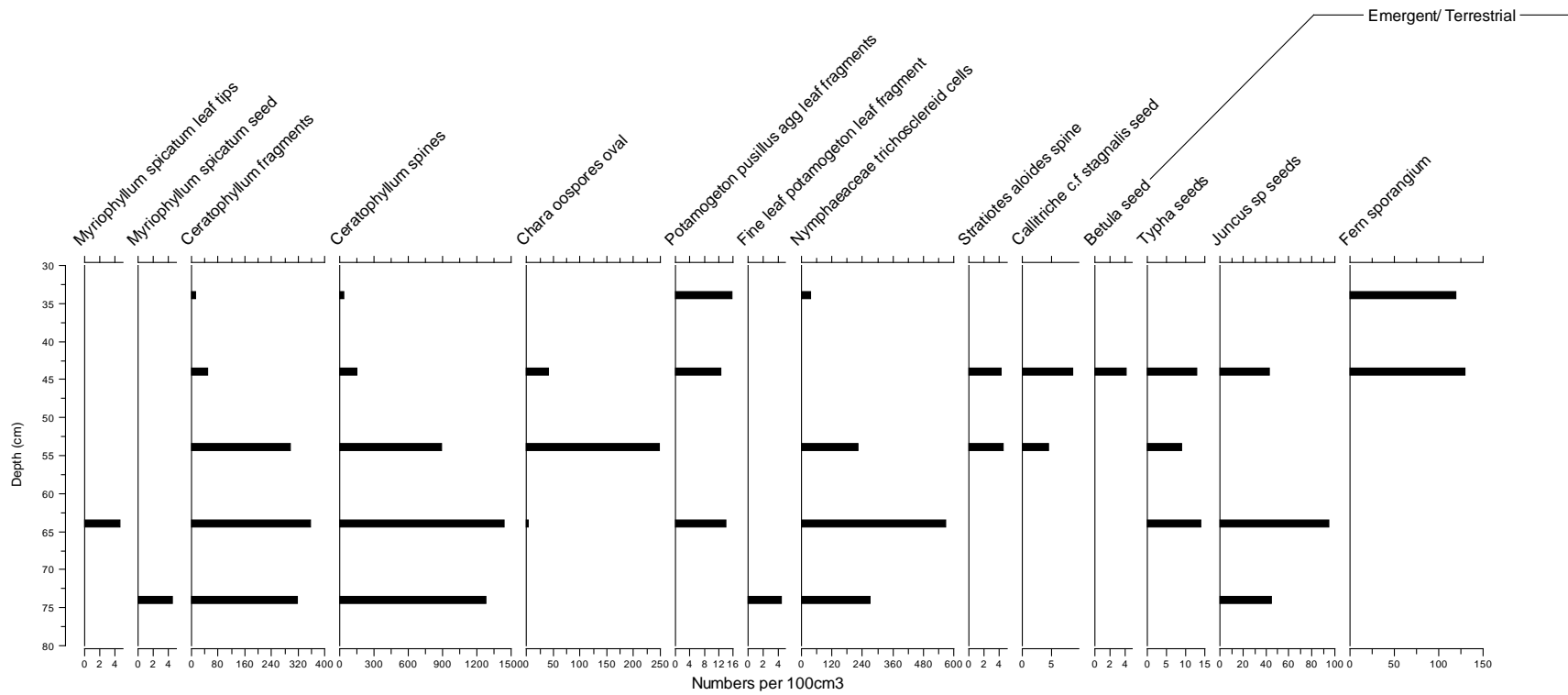


Figure 15 Plant macrofossil summary for core HGBO8a

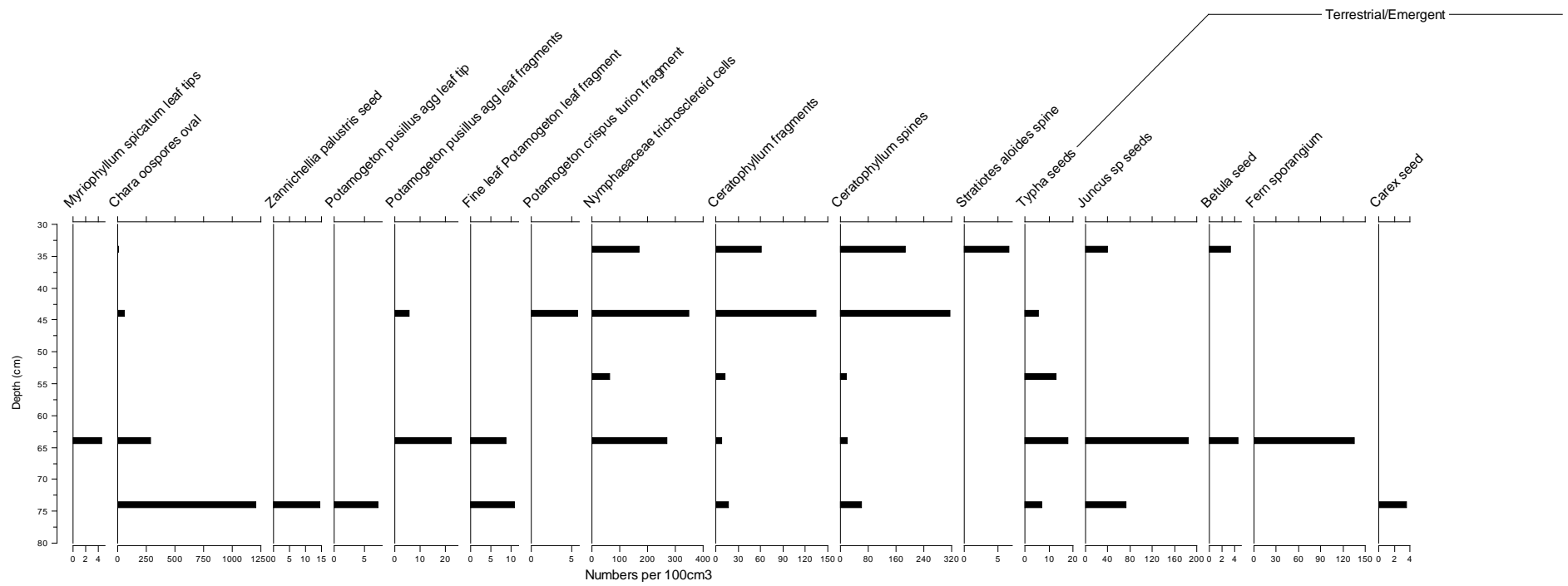


Figure 16 Plant macrofossil summary for core HGBO13a

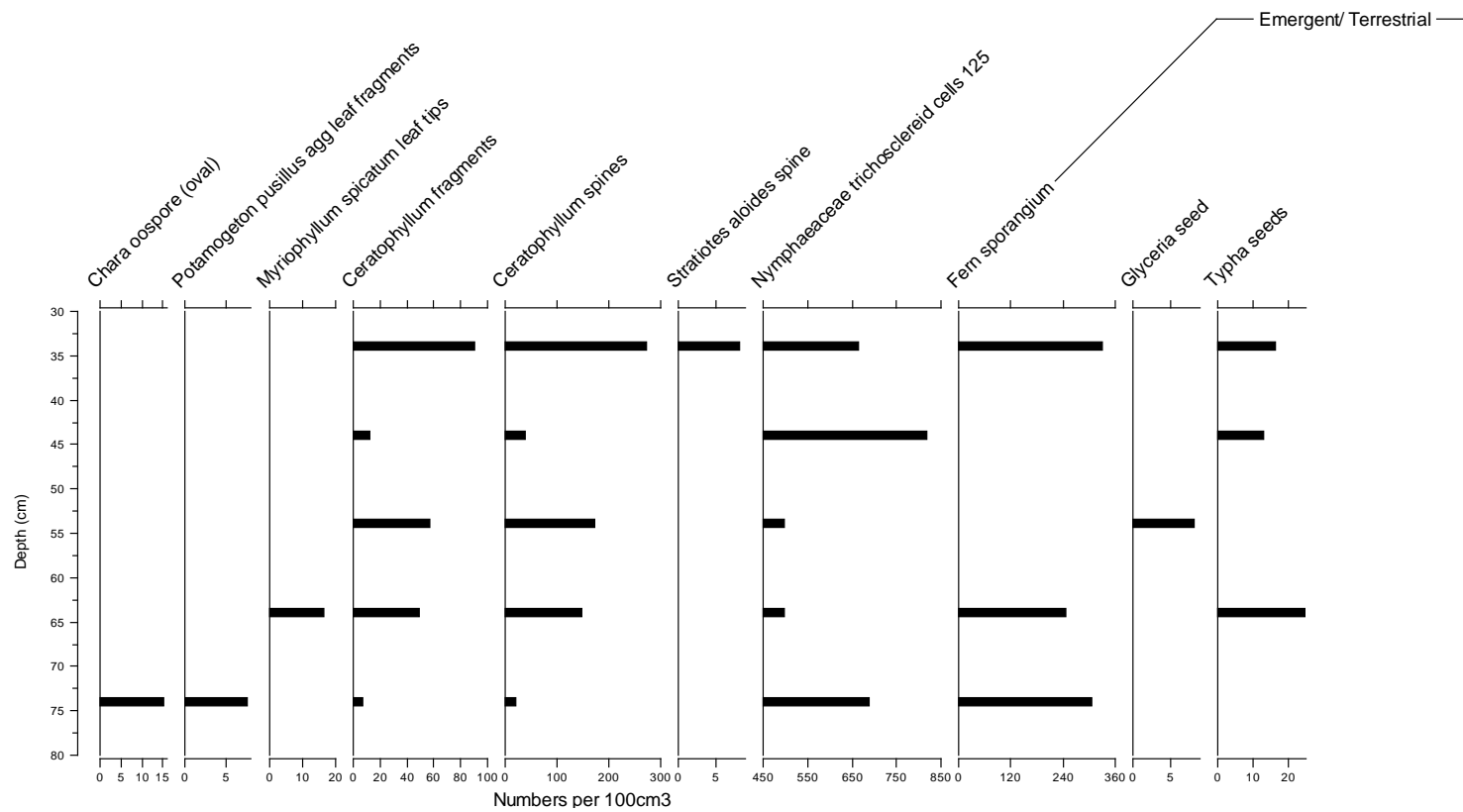


Figure 17 Plant macrofossil summary for core HGBO18a



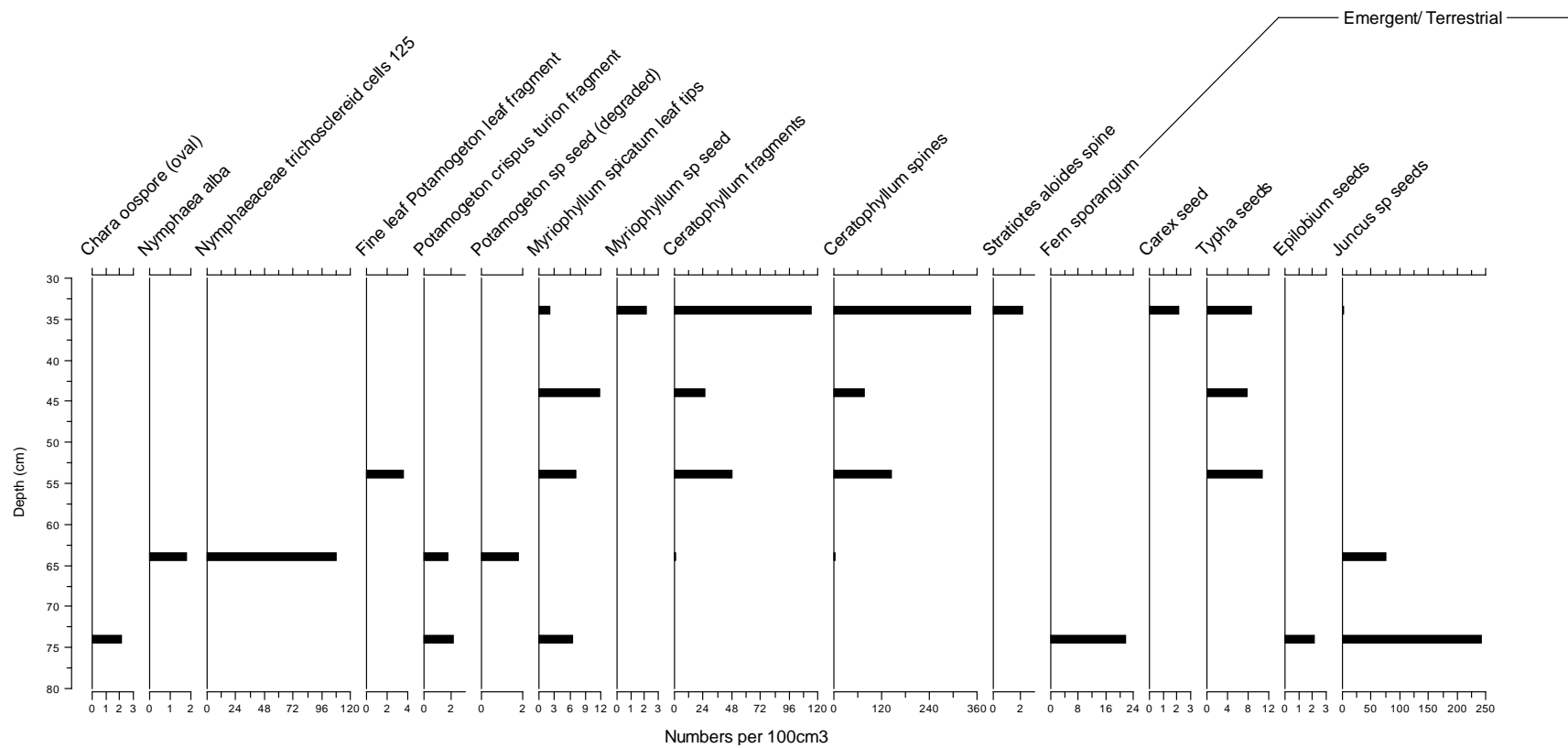


Figure 18 Plant macrofossil summary for core HGBO23a

## Hudson's Bay

The two HUDS cores are quite similar in their plant macrofossil records. Neither core had any *Chara* oospores recorded, suggesting that sedimentation rates were significantly higher in this more sheltered basin and thus the 100 cm cores do not extend back to a time when *Chara* was present in any quantity. Below 50 cm there is good evidence to suggest the broad supported a mixed aquatic flora with *C. demersum* likely to have been common, alongside fine leaved *Potamogeton* spp as well as water soldier (*S. aloides*), *Callitriche* spp. and water lilies. Above 50 cm, there appears to be a marked change from submerged species to floating leaved taxa. Water lily trichosclereids become more numerous, *C. demersum* almost disappears and the presence of *Azolla* appears common within the record.

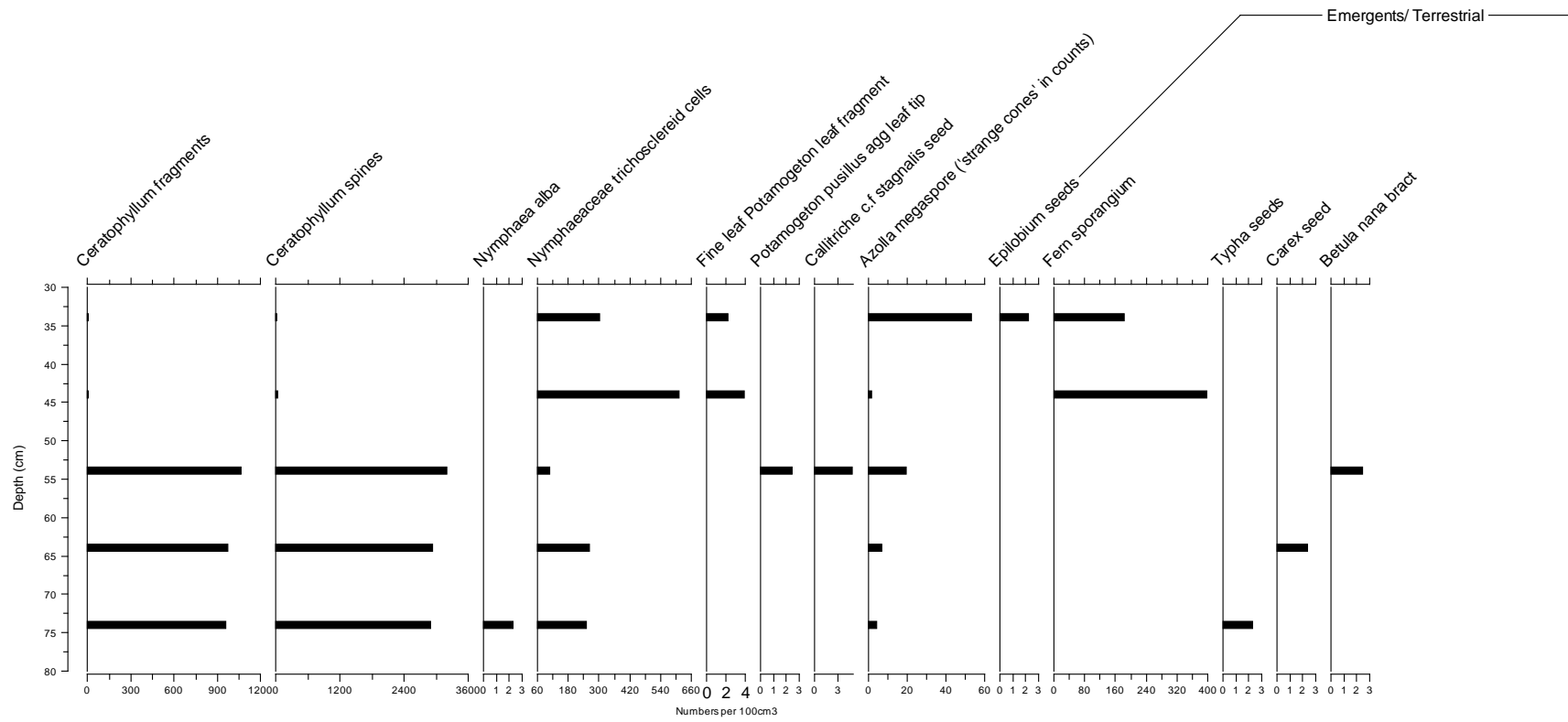


Figure 19 Plant macrofossil summary for core HUDS1a

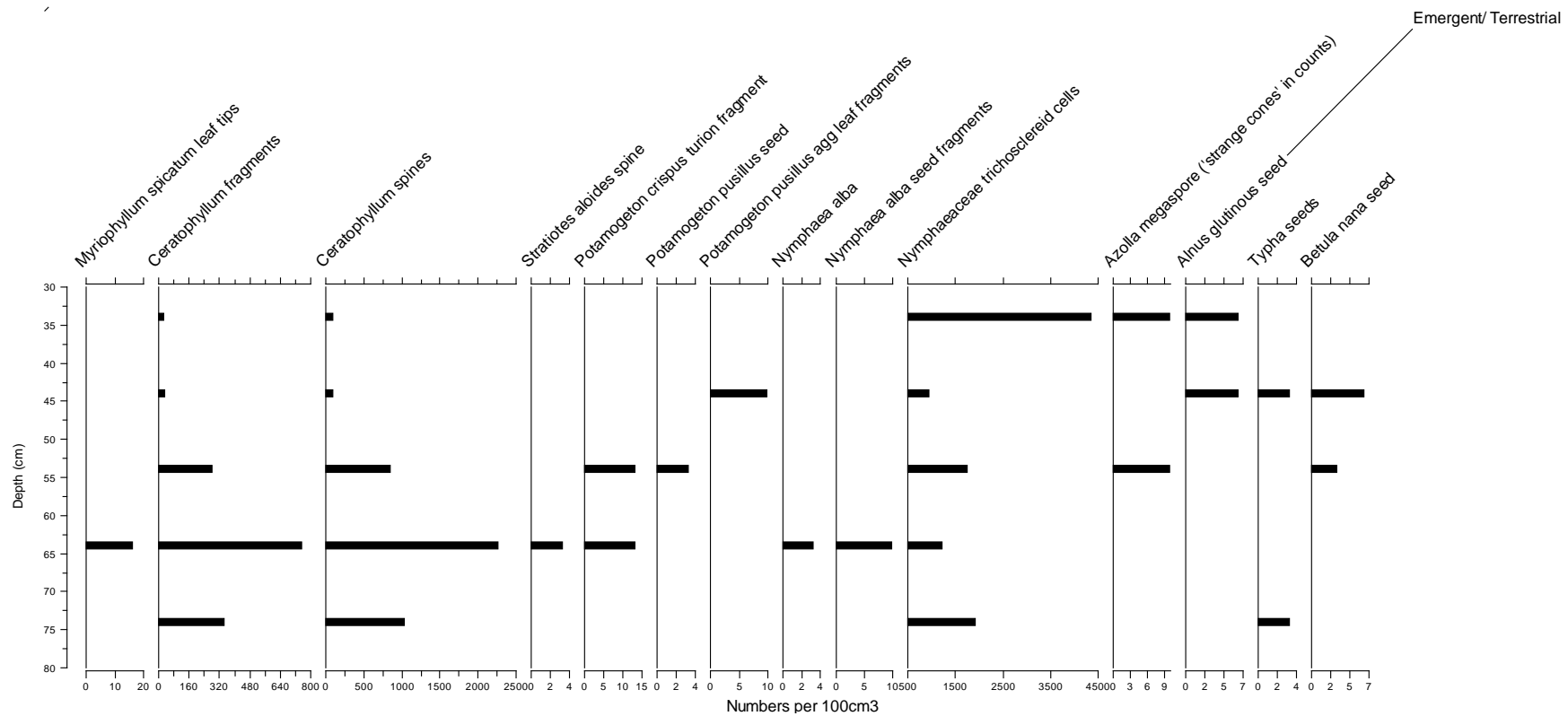


Figure 20 Plant macrofossil summary for core HUDS5a

### 3.3. Contemporary Macrophyte Surveys

#### Hoveton Great Broad

With the exception of some relatively large beds of *Nuphar lutea* and few smaller beds of *Nymphaea alba*, HGB has only very sparse aquatic vegetation as summarised in Table 2 and Table 3. *Ceratophyllum demersum* was the most commonly recorded species, but it was absent from much of the open water, but found growing over a relatively wide area to the north-east of the broad. Rarely did more than a single plant appear on the grapnel, although where present most 4 m grapnel hauls would yield a plant. *Potamogeton pectinatus* was recorded only very rarely in the east and north of the lake. There remain large areas of the open water in the central and south-west of the site that had no submerged plants.

*Lemna minor* was seen growing in sheltered areas of the bank, mainly within stands of rooted emergent plant e.g. *Carex acutiformis*, *C. riparia* and *Phragmites australis*.

Section Number	Location	Species	DAFOR
Section 1	TG3127016075	No aquatic plants recorded	
Section 2	TG3154116341	<i>Nuphar lutea</i>	F
		<i>Ceratophyllum demersum</i>	R
Section 3	TG3196916385	<i>Ceratophyllum demersum</i>	O
		<i>Potamogeton pectinatus</i>	R
Section 4	TG3229616070	<i>Ceratophyllum demersum</i>	O
		<i>Potamogeton pectinatus</i>	R
Other	TG3158316001	<i>Nymphaea alba</i>	F
	TG3139916019	<i>Nuphar lutea</i>	O

Table 2 Aquatic plant species recorded in Hoveton Great Broad 16 July 2014

Species	Site DAFOR
<i>Nuphar lutea</i>	O
<i>Ceratophyllum</i>	O
<i>Potamogeton pectinatus</i>	R
<i>Lemna minor</i>	R
<i>Nymphaea alba</i>	R

Table 3 Aquatic plant species summary for Hoveton Great Broad 16 July 2014

#### Hudson's Bay

Much of the south end of Hudson's Bay is less than 50 cm in depth and without any aquatic plants. Sediments were also noted as being very fluid and easily re-suspended thus making them poor rooting media for most species. The broad opens out more towards the northern end and reached depth of 90 cm. White and yellow water lilies are common in the northern half of the site with *N. alba* being slightly more frequent. Other species were rare in the site.

Section Number	Location	Species	DAFOR
Section 1	TG3145816749	<i>Nuphar lutea</i>	O
		<i>Nymphaea alba</i>	F
		<i>Ceratophyllum demersum</i>	R
Section 2	TG3153816849	<i>Nuphar lutea</i>	F
		<i>Nymphaea alba</i>	F
		<i>Ceratophyllum demersum</i>	R
		<i>Lemna minor</i>	R
		<i>Hydrocharis morsus-ranae</i>	R
Section 3	TG3137516561	No aquatic plants recorded	
Section 4	TG3126416516	No aquatic plants recorded	
Other	TG3139116602	<i>Potamogeton pectinatus</i>	R

Table 4 Aquatic plant species recorded in Hudson's Bay 16 July 2014

Species	Site DAFOR
<i>Nuphar lutea</i>	O
<i>Ceratophyllum demersum</i>	R
<i>Potamogeton pectinatus</i>	R
<i>Hydrocharis morsus-ranae</i>	R
<i>Lemna minor</i>	R
<i>Nymphaea alba</i>	F

Table 5 Aquatic plant species summary for Hudson's Bay 16 July 2014

### 3.4. Germination results

From the 184 aquaria set out at Woodbastwick a total of 234 germinations have been recorded over a 193 day period. Of these, only seven were angiosperm plants; one a low growing species, possibly a broad leaved *Potamogeton*, but too small to identify to species level, (Figure 21A), and the other 6 were all fine leaved *Potamogeton* species (Figure 21B),



Figure 21 Germinations within trial aquaria: A. Broad-leaved species, B) Fine leaved *Potamogeton* spp. C. Charophyte showing fertilized oospores (black dots on branchlet nodes).

The other 227 germinations were all charophytes. The highest number of germinations occurred at 30-40 cm depth of core sections, but this figure is heavily skewed by the results from one core section HGB011 at 30-40 cm in which seventy five charophytes germinated and the next highest number of germinations (twenty two) occurred from the subsequent lower section (40-50cm) of the same core (

Core sections	Chara germinations HGB Cores	Angiosperm germinations HGB Cores	Chara germinations HUD Cores	Angiosperm germinations HGB Cores	Totals for both broads
0-10 cm	0	0	0	3	0
10-20 cm	0	0	0	0	0
20-30 cm	1	0	0	0	1
30-40 cm	99	0	0	0	99
40-50 cm	62	0	1	2	63
50-60 cm	25	0	1	0	26
60-70 cm	14	0	8	2	22
70-80 cm	4	0	12	0	16
Base+10	0	0	0	0	0
<b>Total</b>	<b>205</b>	<b>0</b>	<b>22</b>	<b>7</b>	<b>234</b>

Table 6 Germination summary for Hoveton Great Broad and Hudson's Bay (193 days)

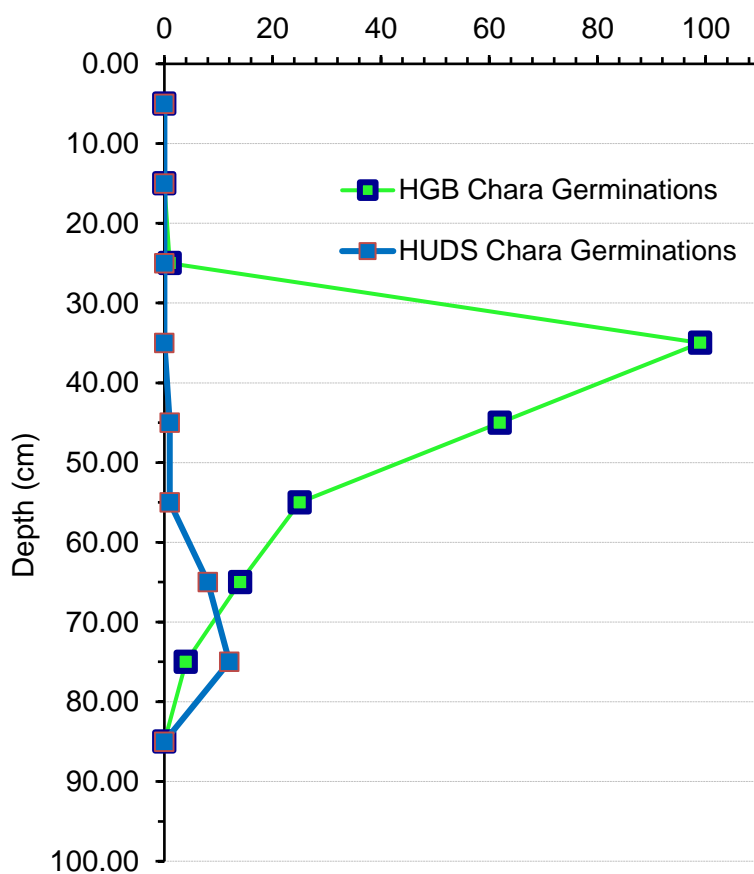


Figure 22 Germination summary for Hoveton Great Broad and Hudson's Bay (193 days)

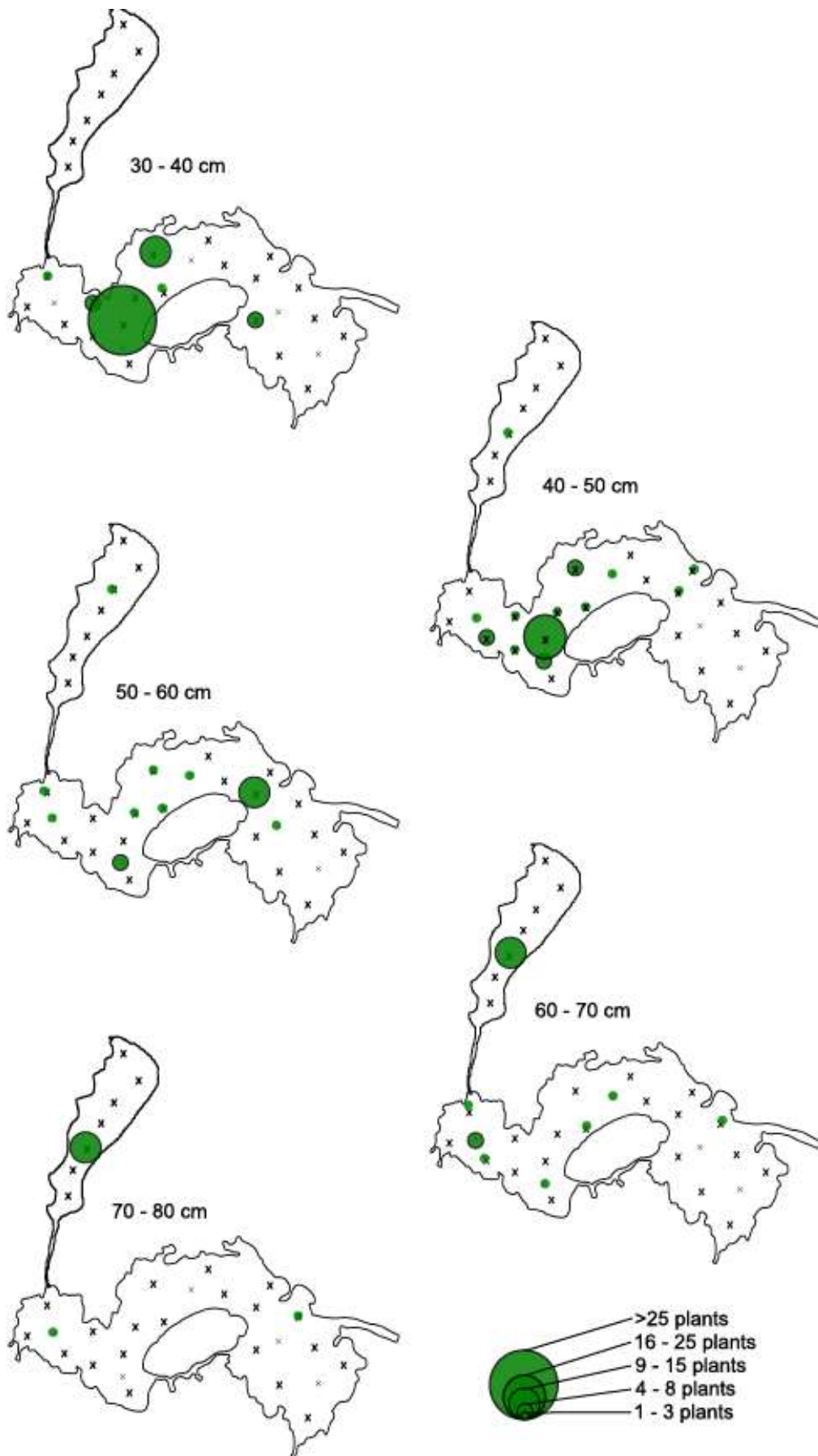


Figure 23 *Chara* germination summaries for Hoveton Great Broad and Hudson's Bay showing geographical variation by depth (193 days)



It can be seen that Hudson's Bay is rather different to Hoveton Great Broad with fewer *Chara* spp. germinations and those that did germinate, did so from lower in the cores. The low numbers of *Chara* germination from the Hudson's Bay cores is perhaps not surprising given the lack of any oospores recorded from the macrofossil analysis.

It is also clear from the germination data, that not only do germinations vary with depth, but also by locality in the site. Within HGB, there were very few germinations from the eastern end of the broad at any depth in the sediment, whereas the central part of the broad had relatively high numbers of germinations from 30 to 50 cm.

Again, these results are borne out by comparison with the macrofossil data that show there to be very few oospores in the eastern side of the broad (HGBO18a and 23a - Figure 17 and Figure 18). That is not to say however, that the numbers of oospores present in the macrofossil samples bears a direct relation to germination success. HGBO13a for example had over 1000 oospores per 100 cm<sup>3</sup> in the 70 – 80 cm section (Figure 16), yet none germinated in the aquaria, and only one from the section above that had over 200 oospores per 100 cm<sup>3</sup>.

Unfortunately, we do not have macrofossil data from the cores that showed the highest germination success e.g. HGBO11 and 13 and cannot therefore ascertain if these cores simply had very high numbers of oospores, or if conditions were in some way better for maintaining viability of the propagules.

## 4. Discussion

There are a number of findings from this work that contribute to the understanding of Hoveton Great Broad and Hudon's Bay within the context of the restoration plans, these are discussed below.

### 4.1. Evidence of past plant communities and habitats

Lake restoration targets for open water habitat and plant species composition are effectively informed by the sub-fossil remains from the sediments. It is clear from this study, and those done by Hoare (2007) that the site had greater aquatic plant diversity in the past than the site has supported in the last c. 50 years. Lower portions of the sediment cores had remains of stoneworts (*Chara* spp.), fine-leaved pondweeds (e.g. *Potamogeton pusillus* type), horned pondweed (*Z. palustris*), rigid hornwort (*C. demersum*), Holly-leaved naiad (*Najas marina*) and Water milfoil (*M. spicatum*) and both white and yellow water lilies (*N. alba* and *N. lutea*). Furthermore, historical plant records from the site suggest it to have supported broad-leaved pondweeds (e.g. *P. lucens*) as well as several species of water crows-foot (*Ranunculus* spp.), water soldier (*Stratiotes aloides*) and even an affliction of Canadian waterweed (*Elodea canadensis*) in the latter part of the 19<sup>th</sup> century (Madgwick 2009).

The reduction in macrophyte species composition and abundance can almost certainly be linked to changes in water quality and clarity. Cores taken by Moss (1988) show a significant shift from benthic communities, typical of clear water conditions, in basal sediments to a community dominated by planktonic species towards the top of the cores. This palaeoecological and historic evidence demonstrates the link between good water clarity and increased plant diversity and therefore the need for clear-water conditions to be re-established at these broads.

### 4.2. Sediment composition and stability

Clear water conditions are not simply a function of planktonic algal biomass however, but are also dependent on suspended solids, which in a large, shallow site such as HGB are likely to be exacerbated by the re-suspension of material from the lake bed. The likelihood of this in hyper-eutrophic lakes is increased due to high sedimentation rates, flocculent organic sediments and lack of consolidation by plant roots. It is interesting to note that HGB has not always consisted of open water as it does today, but in the past, had large areas of floating "hover" (Rick Southwood, pers. comm.), breaking the site into a mosaic of more sheltered ponds. Although these pre-date aerial photos from the 1940s, it is suggested that the site existed like this in the early part of the 20<sup>th</sup> century. There is evidence to suggest that the Bure Broad were already experiencing rapid eutrophication by the 1900s (Moss 1988), and the loss of plant species in HGB may have coincided not only with increased planktonic algal production, but also the opening up of the site due to loss of the hover and shelter it provided.

Sediment stability and structure may therefore be important in future restoration work with the removal of the uppermost organic sediments helping to reduce sediment re-suspension. The complexities of the hydraulic actions within these broads are many. Water depth, fetch, sediment structure and sediment composition will all interact to determine how material arrives and leaves at any given point and it has been

demonstrated that these forces have a strong influence on the success of aquatic macrophyte establishment (Schutten *et al.* 2004). The organic content of all the cores analysed from HGB and Hudson's Bay showed the uppermost sediments to be the most organic, with a slight reduction between 15-50 cm (depending on the core), followed by a second peak lower down. If de-siting is to take place, it is recommended therefore that some consideration is given to determining the depth of sediment to be removed that will expose more consolidated material that is less likely to be re-suspended and also provide a more stable substrate into which aquatic plants can root.

One further consideration for restoration may be to use the geotextile tubes to divide HGB into a series of smaller, linked sites separated by reed beds (planted on the sediment filled geotextiles), that will act to reduce the wind stress across the broad. While changing the present character of the site, it would potentially go some way towards reproducing the conditions in the site when it was partially covered by hover. This work would be informed further by applying the models developed for shallow lakes by Schutten and Davy (2000), and this is recommended.

#### 4.3. Sediment phosphorus

Like many from sites that have suffered from eutrophication, the HGB and Hudson's Bay cores show an increase in sediment phosphorus concentrations in the uppermost samples. These data broadly corresponds with figures for sediment P generated by Phillips (Broads dossiers) for the Bure Broads.

It is clear however, that although sediment P is at its highest at, or just below the surface sediments for the majority of cores, concentrations rise to similar levels at depths ranging from 30-50 cm; the target depth suggested for sediment removal.

Sediment removal would remove P from the system, but there is no reason to expect a reduction in the exchange of P from the sediment to water following dredging. Evidence from previous de-silting studies and laboratory-based experiments have shown only short term reductions of internal P loadings for partial sediment removal, after which the sediment P equilibrates with the overlying water and flux rates approach pre-intervention levels (e.g. Kleeberg and Kohl, 1999, Reddy *et al.* 2007).

Given the relatively high concentrations of sediment P within the target depth of de-silting, there is no evidence to suggest dredging would reduce internal P loading. Irrespective of de-silting at these broads, efforts should remain focused on continued reductions of external P loading to the sites. Isolation from the River Bure may help to prevent relatively nutrient rich waters entering HGB and Hudson's Bay, but this also greatly reduce flushing rates within these broads and potentially result in increased P in the water. Hydrological budgets and nutrient budgets from the feeder streams / ditches to the north of the broads are therefore recommended to assess post-isolation nutrient budgets for the sites.

Further data and interpretation of the P release from the HGB and Hudson's Bay sediments in the germination aquaria will be presented in the MSc Thesis linked to this study (Veronika Matyskova).

#### 4.4. The role of the “seed bank”

This is the first study that we are aware of that attempts to ascertain the distribution and viability of a “seed bank” prior to undertaking sediment removal in a lake. In its simplest form, what the results show is where and to what depths viable plant and macro-algal propagules exist. They also demonstrate the erratic nature of the dispersal of *Chara* oospores within a site and the disparity between presence of oospores and viability. Final counts of oospores will be made by Veronika Matyskova, but initial comparison between the total numbers of oospores per unit weight of sediment and numbers of germinations shows very little correlation.

The germination experiments show there to be relatively high viability of *Chara* oospores, even at sediment depths of over 50 cm – probably equating to 50-100 year old (and older). Whilst the *Chara* oospore viability is of ecological interest, it is not particularly important to the restoration of HGB and Hudson’s Bay because this is not considered to be the restoration target for the sites. Furthermore, despite being viable within the seed bank, charophytes require relatively high water quality to persist within lakes, and these parameters are not currently met, particularly for nitrogen, which remains high in the River Bure system.

What the study does show, is that the removal of up to 50 cm of sediment from these broads is unlikely to threaten any viable seed bank. Factors such as good connectivity to the surrounding wetland areas and ditch system to the north of the sites are likely to provide the best mechanism for the arrival of seeds and propagules to the broads.

Irrespective of how propagules arrive at the site, it will be crucial to maintain clear water conditions within the site for several years in order for aquatic macrophytes to become well established. There is therefore a trade-off between water quality (and clarity) and the depth of silt removal. Light attenuation is rapid where waters are turbid and thus removing too much silt may deepen the sites beyond the depth at which plants can establish. Removing too little silt and plants are more susceptible to grazing by non-diving ducks and swans. There may also be further merit in varying the depth across the site in order to increase the habitat diversity, and also help disrupt hydraulic forces that re-suspend sediments and can damage plants (Schutten *et al.* 2004). This warrants further investigation.

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To be complete



