Factors affecting water plant recovery - A. Overview and sediment influences

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Statement of Use:
This project was commissioned to develop novel techniques to assist in the restoration of shallow lakes. This report provides results of the 'Water plant recovery' research project from 1993 until 1995. The 'Water plant recovery' project aims at finding causes for delayed recovery of aquatic plants in shallow biomanipulated lakes, and designing management answers.

Research Partners:
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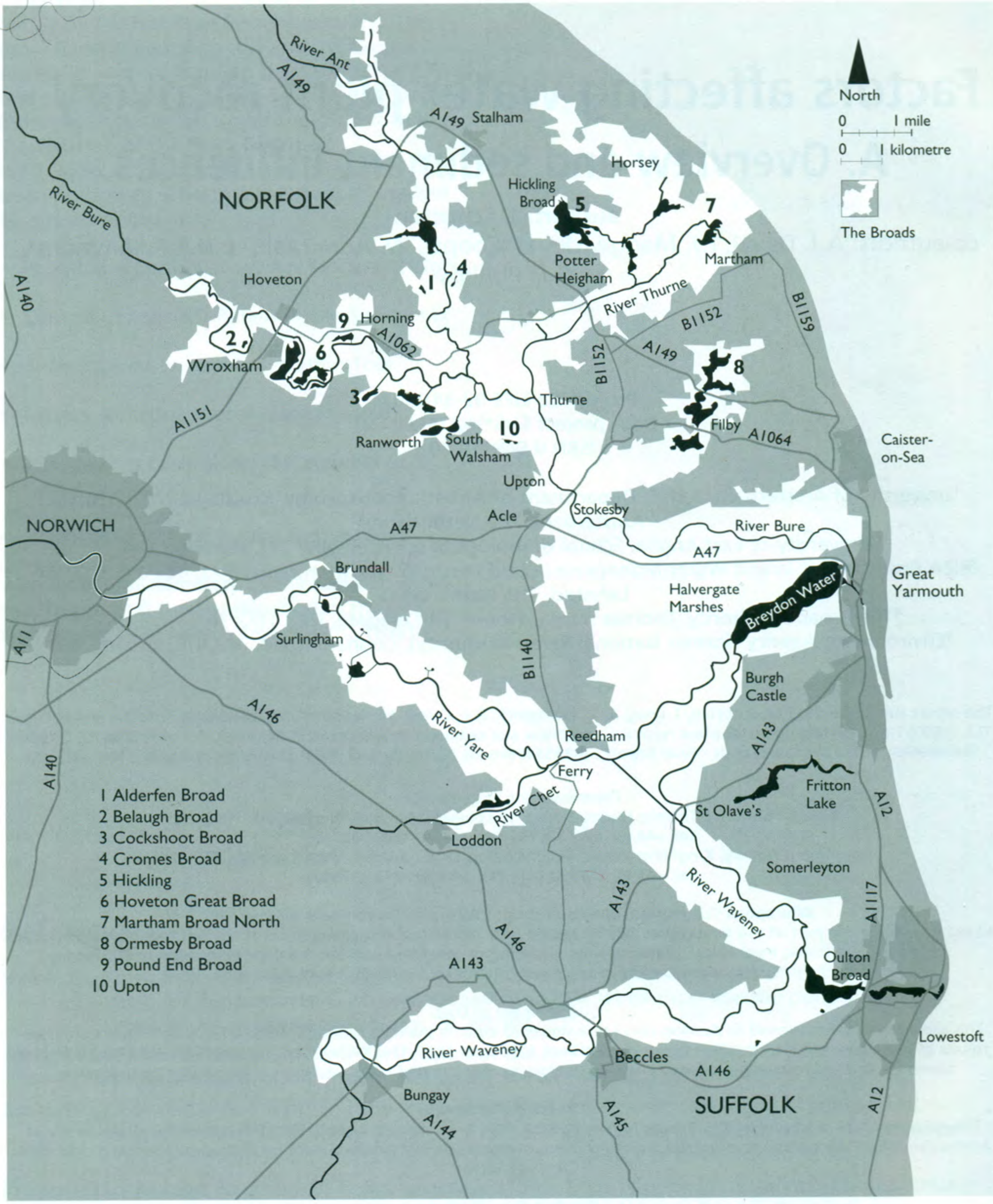
Figure 1:

Map of the Broads area, showing the position of the Broads monitored in 1993.



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A. Overview and sediment influences

Summary

Nutrient reduction and biomanipulation are increasingly used as tools to re-create clear water in turbid, green, eutrophicated shallow lakes. The next step, stabilising the resulting aquatic community so that fish can be re-introduced, depends heavily on the recovery of the submerged aquatic vegetation, as shown for example in other reports in this LIFE-series. This project has sought to discover the reasons for the varying performance of macrophytes in different lakes, and to translate the findings into management advice.

Experience in The Netherlands and the United Kingdom (Norfolk Broads) has indicated that lakes with a firm and mineral sediment usually have a successful recolonisation of aquatic macrophytes, in contrast to the slow and erratic recovery in lakes with a soft and organic sediment. An initial survey in 1993 suggested that light, nutrients and propagule availability were not the main limitations. Hence we have focused on the sediment as a limiting factor for macrophyte recolonisation. A combination of field and glasshouse experiments showed that the sediment was not inimical to the introduced propagules, but that high sulphide concentrations in the sediment seem to impair root extension. A 20-lake survey in 1995 showed that wind exposure and sediment cohesion were the main factors determining the abundance and diversity of the aquatic community. Fertility and alkalinity of both sediment and water were of less importance.

The aquatic plant community in lakes with a firm sediment consisted of a combination of firmly rooted perennials and annuals whereas in lakes with a soft sediment in the Broads, the plant community consisted of only functional annuals that were nearly all easily uprooted. This implies that plants in a soft sediment lake are very vulnerable to physical disturbance such as from wind-induced currents, or bird or fish grazing, because of the combination of the reduced root system and the soft sediment. Once dislodged, the whole plant is lost from the aquatic community. Plants in lakes with a firm and cohesive sediment break before being uprooted, which leaves a rootstock for the plants to regrow from. In the next stage of this project we plan to investigate how to overcome, in a practical way, the unsupportive nature of some sediments, and how to predict in a given lake the probable stability of its recovering macrophyte community.

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1. Introduction

Water managers in the Netherlands (Hosper, 1993) and Great Britain (Broads Authority, 1993) aim to restore clear and diverse lakes in currently algal-dominated systems. Water clarification by nutrient reduction alone takes a long time because of feedback processes which stabilise the turbid state (Hosper *et al.*, 1992, Scheffer *et al.*, 1993; Moss, 1990). In order to speed the recovery process, dredging and manipulation of the fish population have been used (Broads Authority, 1993; Hosper & Meijer, 1993). Macrophytes themselves seem to play an important part in the recovery process and in the stabilisation of the final clear water stage (Blindow *et al.*, 1993; Carpenter & Lodge, 1986; Scheffer *et al.*, 1993).

Beds of submerged and floating macrophytes provide structure to the water layer and separate it into different habitats (Den Hartog & Van der Velde, 1988; Lillie & Budd, 1992), so providing attachment surfaces for sessile zooplankton, macro-invertebrates (Lewandowski, 1983) and periphyton (Carpenter & Lodge, 1986; Den Hartog & Van der Velde, 1988; Pandit 1989; Rabe & Gibson, 1983). The macrophyte zone is also a refuge habitat with lower predation risk (Lubbers *et al.*, 1990; Rozas & Odum, 1988) for different animal groups such as Cladocera (Savino, 1982; Perrow *et al.*, 1997), macro-invertebrates (Beckett et al., 1992; Heck & Timothy, 1981), fish fry and young of the year fish (Chapman & Mackay, 1984; Grimm, 1991; Holland & Huston, 1984). Macrophytes can indirectly improve the water quality by competing for nutrients with limnetic algae (Blindow *et al.*, 1993; Jorga & Weise, 1979), and restricting water-flow so suspended material can settle (Gregg & Rose, 1982; Kemp *et al.*, 1984). The macrophyte roots can improve sediment characteristics by preventing erosion and detoxifying the sediment through oxygen release (Blindow *et al.*, 1993). In addition macrophytes can be a food source for macro-invertebrates, fish (Carpenter & Lodge, 1986) and birds (Carpenter & Lodge, 1986; Jupp & Spence, 1977; Kiorboe, 1980; Perrow et al, 1996b; Schutten *et al.* 1994)

Recent biomanipulation work in European shallow lakes shows that the recovery of vegetation in terms of abundance and species diversity appears to be rather unpredictable, this is particularly so in the Norfolk Broads. That is why this 'Macrophyte Recovery Project' was developed as a part of the LIFE programme 'Restoration of the Norfolk Broads' and RIZA's 'EHS-waterplant'. It is a research project that aims to gain knowledge of the main factors controlling macrophyte recovery after or during large-scale management of shallow eutrophic lakes. A scientific understanding of the limitations for macrophyte recovery will assist in the identification of management prescriptions. The literature suggests several possible limitations of macrophyte recovery.

Limited numbers of propagules germinating

Lack of regeneration can be the result of an exhausted seedbank, or adverse conditions for germination. Field observations of extensive germination in the first year after suction-dredging (Madgwick, pers comm.) and research on seedbanks (Pitt & Pillips, 1994; Handley, 1995) suggests that in the Broads the seedbank is not wholly exhausted, and it is likely to be supplemented from adjacent vegetated upper reaches of the river (Kennison & Prigmore, 1994) and marsh-dykes (Doarks *et al.*, 1990) by water flow and waterfowl. Research elsewhere has not shown any clear correlation between seedbanks and present vegetation (Kautsky, 1990; Skoglund & Hytteborn, 1990; Smith & Kadlec, 1983). Seeds tend to be more dense than the sediment so they sink, and may not germinate if they are buried too deeply, because they do not receive the appropriate environmental cues for germination (e.g. light) (Bartley & Spence, 1987; Forsberg, 1965; Muenscher, 1936).

Limited growth and survival

Growth may be limited by a number of factors (Duarte & Kalff, 1990; Westlake, 1975):

1. Light. Biomanipulation, in the form of nearly complete removal of zooplantktivous fish, has been carried out in the Netherlands and the Broads in severely eutrophicated lakes; this has resulted in clear water and yet macrophyte recovery has not always followed. In such cases, low light and nutrients resulting from enrichment can be excluded as limiting factors. Pilot research **(chapter 2)** has shown that the plants in the Broads are not excessively covered in epiphytic algae.

2.Water flow can enhance growth by reducing precipitation of particulate matter on leaves or by reducing boundary layers that resist diffusion of oxygen and bicarbonate (Scheffer *et al.*, 1992). However water-current induced forces can also uproot the plants.

3. Sediment quality. Unstable sediments may induce high mortality (Rorslett, 1985). Toxicity is likely to be a problem for submerged macrophytes in the highly organic Broads sediments (Barko & Smart, 1983; Smolders & Roelofs, 1993). Particularly high levels of sulphide (Pulich, 1985; Koch *et al.*, 1990) and ammonium ions (Roelofs, 1991) can reduce root growth or winter-survival. Root length may increas with nutrient depletion in the sediment (Mantai & Newton, 1982; McFarland *et al.*, 1992). High nutrient availability increases shoot/root ratios in *Phragmites australis* (Boar *et al.*, 1989) and arable crops (Salisbury & Ross, 1985).

4. Herbivory. Grazing, by birds can assist water plant establishment by dispersal or stimulated growth (Belsky, 1986; Owen, 1980), or it can be deleterious (Carter & Rybicki, 1985; Lauridsen *et al.*, 1993; Van Donk *et al.*, 1994). Herbivorous birds can consume a considerable part of the maximum standing crop (Jupp & Spence, 1977; Kiorboe, 1980; Perrow *et al.*, 1996; Schutten *et al.*, 1994) although recent research has shown that in a typical broad predation by herbivorous waterfowl is negligible during spring (Perrow *et al.*, 1996). Herbivorous fish such as carp, rudd, roach (Prejs, 1984) are not abundant in the Broads, but benthic feeding of bream and tench (Carpenter & McCreary, 1985; Ten Winkel & Meulemans, 1984; Wright, 1992) could have an impact on macrophyte recovery.

Aims and objectives.

Given the wide range of possible interacting mechanisms it was necessary to focus the project on the most important ones. A pilot study in 1993 led to the conclusion that the sediment chemistry and physical properties were most likely to be involved in limiting submerged macrophyte recovery in the clear water broads with highly organic sediments. This work is presented in **section 2.1**

The current project connected the RIZA research project "EHS-Waterplanten" with the joint Broads Authority/NRA project supported by the EU LIFE. The Universities of Amsterdam and East Anglia were also active partners in the project. Thus this report covers the research carried out between 1993 and 1995.

The sequential research questions were:
1. How do the distribution and abundance of submerged macrophytes change through the season in contrasting lake types?
2. What are the most important environmental factors affecting submerged macrophyte species distribution and abundance (e.g. light, periphyton cover, sediment density and grazing).
3. What is the influence of sediment chemistry on survival and growth of submerged macrophytes under natural conditions in the absence of herbivory?
4. What are the specific effects of possible toxic levels of sulphide in the sediment on the survival and growth of selected submerged macrophyte species under glasshouse conditions?
5. What are factors affecting plant resistance to uprooting under natural and controlled conditions?
The overall aim was to design protocols for to the management of macrophyte recovery in the field.

2. Environmental factors influencing submerged macrophyte distribution

2.1. Field survey in 1993

Aim

To characterise species distribution and abundance and their changes through the season; to estimate the influence of light, periphyton cover, sediment density and grazing on the distribution and abundance of submerged macrophytes.

Methods

Ten Broads (Upton, Pound End, Ormesby, Martham-North, Hoveton Great, Hickling, Cromes, Cockshoot, Belaugh and Alderfen, **see Figure 1**) were surveyed, during this pilot study,on four occasions (end of April, end of June, early August and mid October) during the growing season. The abundance of plant species was estimated as vertically projected bottom coverage on three representative transects from shore to shore by snorkel diving. The abundance was recorded using a 7-point Tansley scale (Schutten *et al.*, 1994). A visual estimate was made of periphyton cover, plant colour and vigour, and basic limnological parameters were measured (water temperature and depth, Secchi depth). The top layer of the sediment was sampled using a 35cm perspex manual corer (diameter 7 cm) and visually classified in sediment type based on colour and density. Multivariate analysis, using a unimodal response model (CCA, CANOCO, Ter Braak, 1994) with rare species downweighted, was carried out to correlate species abundance and environmental variables.

Results

There were large changes in the abundance and dominance of submerged macrophytes during the growing season. The small Bure broads, with very fluid sediments, possessed sparse vegetation dominated by filamentous algae in spring and low abundances of superficially rooted and easily uprooted species during the rest of the season (e.g. Belaugh Broad, **Figure 2a**). The larger and more saline Thurne broads, with firm sediments, had diverse, strongly-rooted submerged communities with highly abundant perennial species early in spring (e.g. Martham North Broad, **Figure 2b**). The periphyton and turbidity data (not presented) from the clear broads suggest that the submerged macrophyte community was not limited by water clarity or epiphytic algal growth.

The results of the multivariate analysis (**Figure 3**) suggest that sediment type and physical properties are major factors explaining submerged macrophyte distribution in the Broads (54 % of species / environment relation explained by the first axis (Monte Carlo Permutation test, $n = 99$, $p = 0.01$). Water colour and light penetration were of less importance.

Conclusion

The 1993 survey showed that the submerged macrophyte community changed considerably during the growing season in terms of species abundance and dominance. The plant communities in the Bure broads differed significantly from those in the Thurne area, and this appeared to be associated with sediment type and structure. Light and periphyton cover were not the main factors limiting submerged macrophyte growth or recovery in the lakes examined.

These results suggested focusing the 'Macrophyte Recovery Project' on sediment-related parameters.

2.2 Field survey in 1995

Aim

The aim of this survey was to determine on a wide geographical scale, the most important environmental factors controlling submerged macrophyte species distribution and abundance; to determine the effects on particular species in contrasting types of lake.

Methods

The distribution and abundance of submerged macrophytes was examined, and a range of environmental factors relating to sediment and water were sampled in 20 shallow lakes in The Netherlands (**Figure 4**) and the Broads (**Figure 1**) in July and August 1995

The submerged macrophyte community was sampled at 2 or 3 locations, that differed in wind exposure, in each lake. The abundance of each species was estimated as vertically projected bottom coverage on a 10 x 10m quadrant by snorkel diving. The abundance was recorded using a 7-point Tansley scale (Schutten *et al.*, 1994). A visual estimate was made of periphyton cover, plant colour and vigour. Basic limnological parameters including water and sediment temperature, pH, REDOX, and water depth and Secchi depth were measured and fetch (distance from the shore in the prevailing wind direction) was estimated. The sediment pore water and lake water were anaerobically sampled using Rhizon samplers (10 cm long microporous Teflon filter tubes, pore diameter 2µm, connected to an evacuated sampling container). The force needed to perturb the top layer of sediment (shear force) was measured in situ using a pocket shear meter (Torvane, ELE-international). The top layer of the sediment was sampled using a 35cm perspex manual corer (diameter 7 cm) and visually classified into layers on basis of colour, density. Ionic concentrations of the pore and lake waters were analysed using Atomic Absorption spectrometry for the cations (Fe, Mn, Cu, Mg, Ca, K, Na) and Ion-chromatography for the anions (Cl, NO_3, NO_2, PO_4, SO_4). Sulphide and ammonium were preserved and determined within one week using ion-selective electrodes. The sediment dry-weight (105 °C) and loss-on-ignition (550 °C, 2 hrs) were measured. Multivariate analysis correlating species abundance to the measured environmental variables, was carried out using a unimodal response model (CCA, CANOCO, Ter Braak, 1994) with rare species downweighted.

Results

Multivariate analysis suggested that wind influence and sediment density were primary factors and sediment and water alkalinity and nutrient status were secondary factors explaining submerged macrophyte distribution (19 % of species / environment relation was explained by the first axis and another 15 % by the second axis; Monte Carlo Permutation test of whole analysis for $n = 99$, $p = 0.03$).

The species were clustered using TWINSPAN (Hill, 1994), which resulted after two divisions in the following clusters: **Table 1.**

The species clusters were graphically correlated to the most important environmental factors which showed that clusters 2 and 7, the non-rooted, floating leaved and *Najas marina* tended to be present on less wind exposed locations than the other clusters **(Figure 6a)**. The mean shear force of the sediment **(Figure 6b)** increased from cluster 2 to cluster 6 indicating that the more rooted species were present on the more stable sediments. Clusters 1 and 7 were present on the whole range of sediment stabilities.

Conclusion

The 1995 survey suggested that the submerged macrophyte species distribution was mainly governed by wind influence and sediment stability, and secondarily by sediment, water alkalinity and nutrient status.

Table 1:

Twinspan clusters of the 1995 survey data.

number	group	species
1	Floating-leaved species	*Nymphaea alba, Nuphar lutea, Nymphoides peltata*
2	Non-rooted and floating leaved species	*Utricularia vulgaris, Lemna minor, L. trisulca, Ceratophyllum demersum. Myriophyllum verticillatum, Potamogeton natans, P.obtusifolius, Ranunculus circinatus, Stratiotes aloides Fontinalis antipyretica* and *Elodea nuttallii* were only found once.
3	Algae group with *Zannichellia*	Filamentous algae, *Enteromorpha intestinalis* with *Zannichellia palustris*
4	Rooted species	*Potamogeton pusillus, Elodea canadensis*
5	Strongly rooted species	*Potamogeton perfoliatus, P. lucens, P. crispus, Hippuris vulgaris* the fragile *Callitriche spec.* and the *Charophyte Nitellopsis obtusa*
6	Narrow-leaved species	*Potamogeton pectinatus, P. mucronatus, M spicatum, Ruppia maritima and the Charophytes Chara aspera and C. connivens*
7	*Najas marina*	*Najas marina*

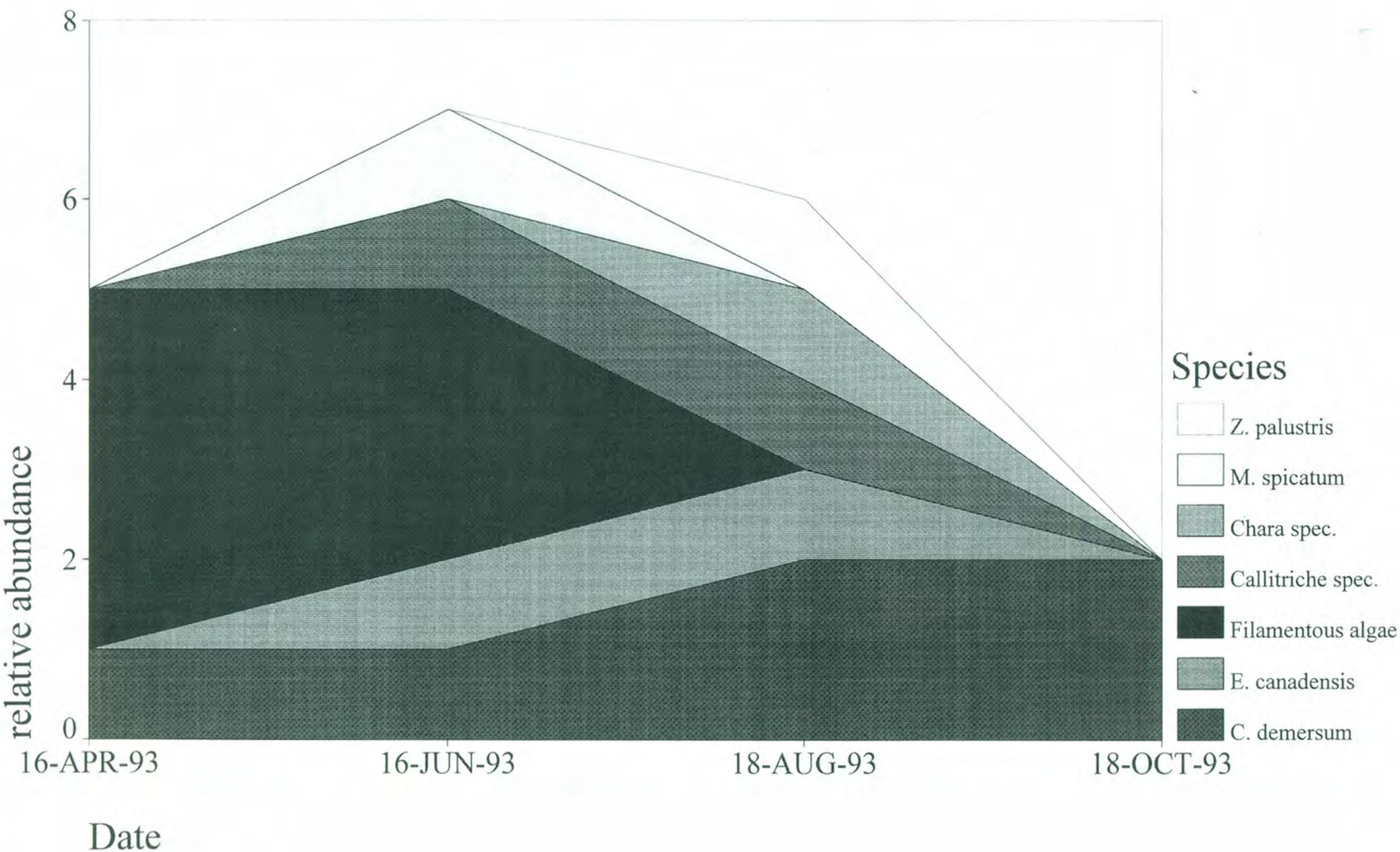


Figure 2a.
Abundance of submerged macrophytes in Belaugh Broad during 1993.

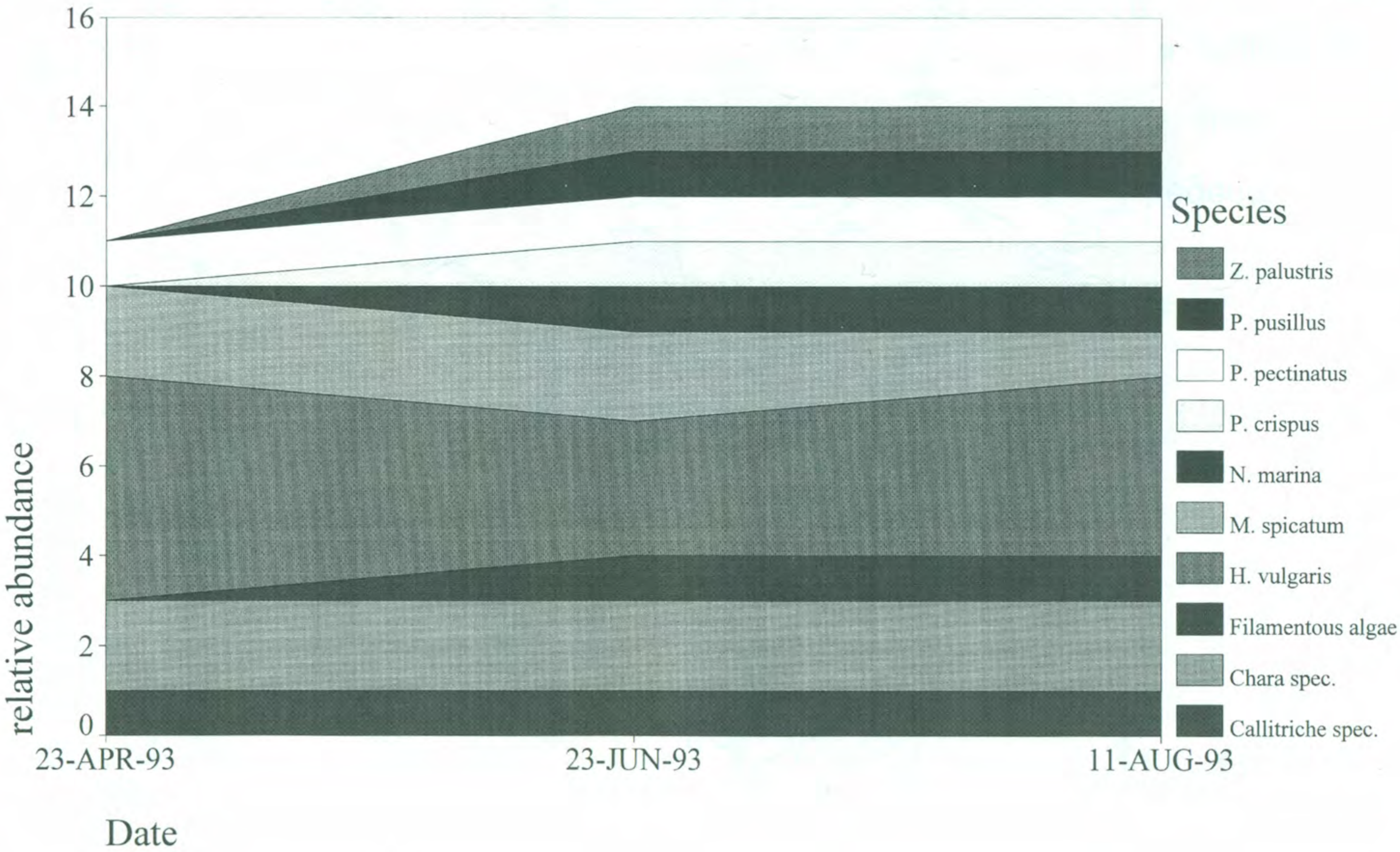


Figure 2b.
Abundance of submerged macrophytes in Martham-North Broad during 1993.

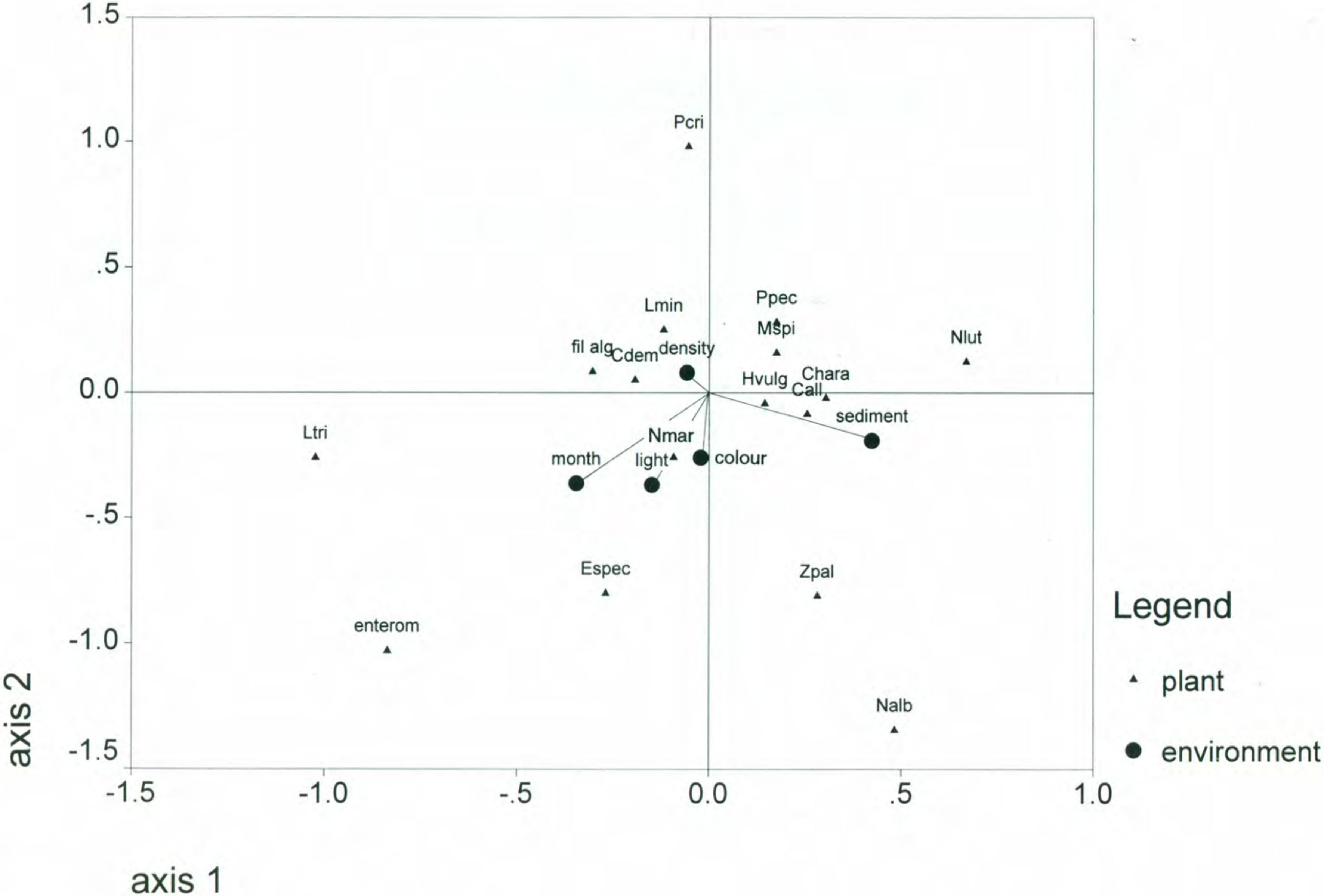


Figure 3.
Canonical correlation plot of species abundance, locations and environmental factors of the 1993 survey data.

Figure 4.

Map of The Netherlands showing the position of the lakes surveyed.

1 Volkerak
2 Binnenschelde
3 Oude Venen
4 Bovenwater
5 Gouwzee
6 Veluwemeer
7 Naardermeer
8 Ankeveenseplassen
9 Breukeleveense plassen
10 Botshol

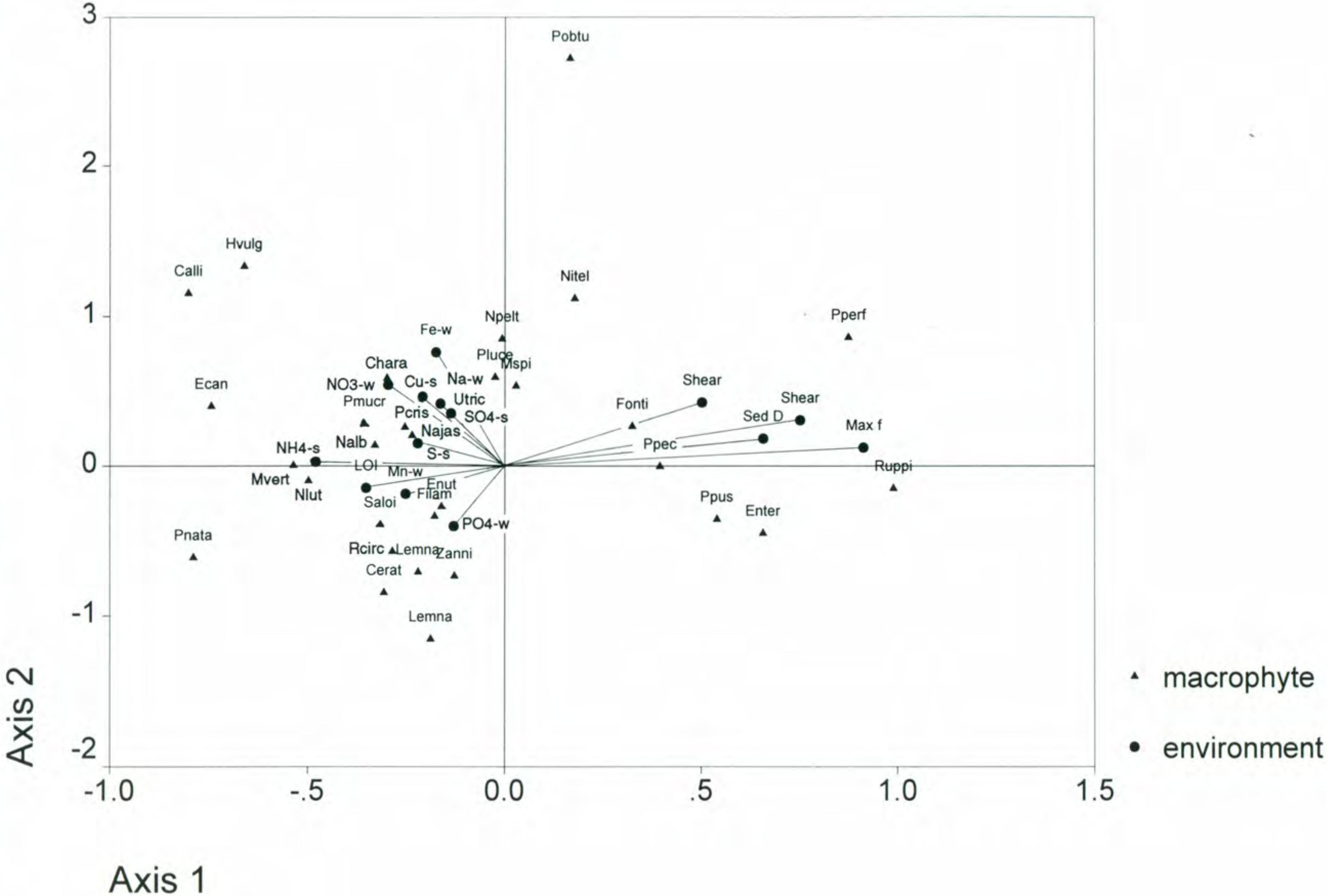


Figure 5.
Canonical correlation plot of species abundance and environmental factors of the 1995 survey data.

Figure 6a.

Abundance of submerged macrophyte clusters related to fetch (distance from the shore in the prevailing wind direction).

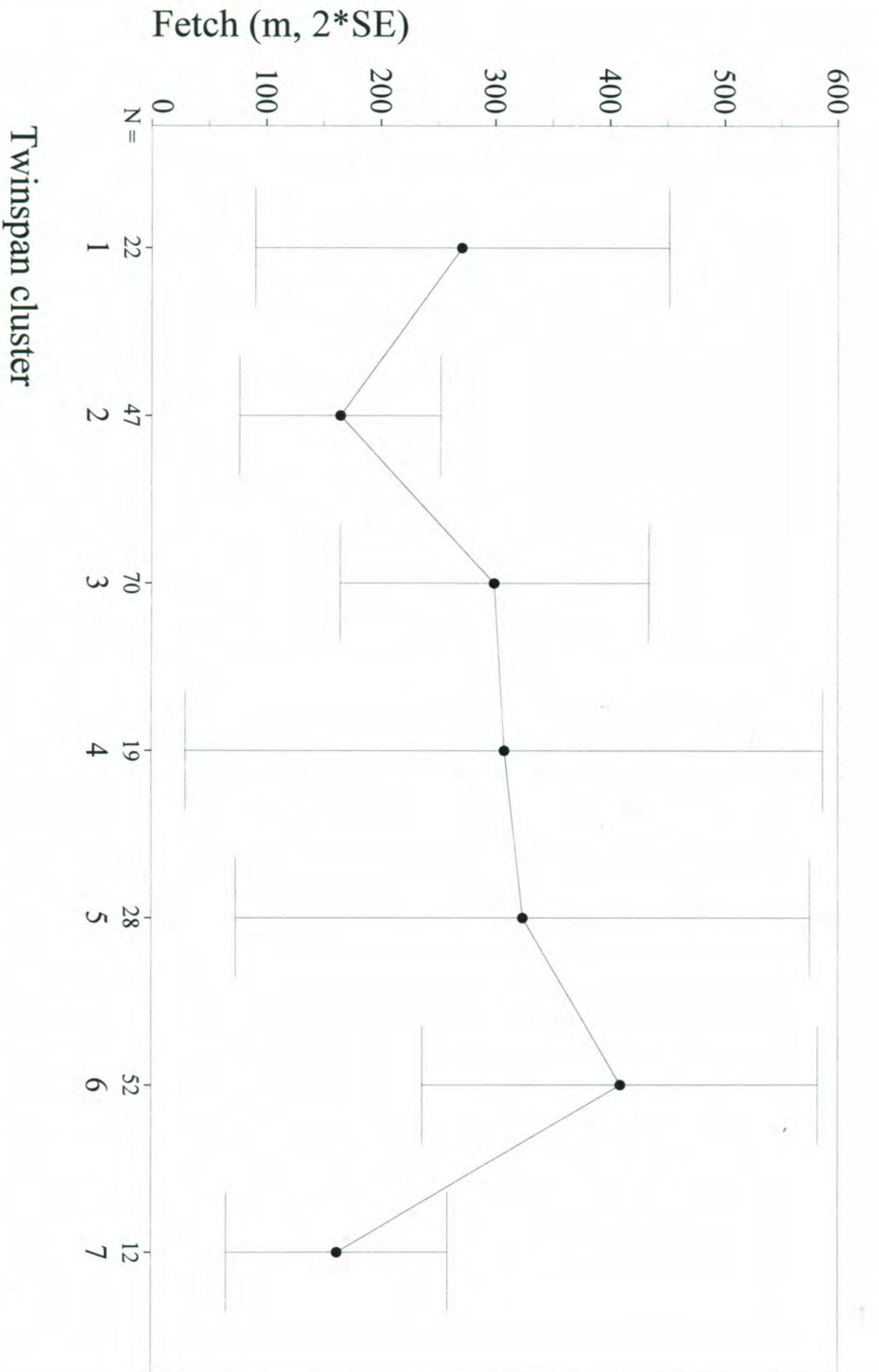
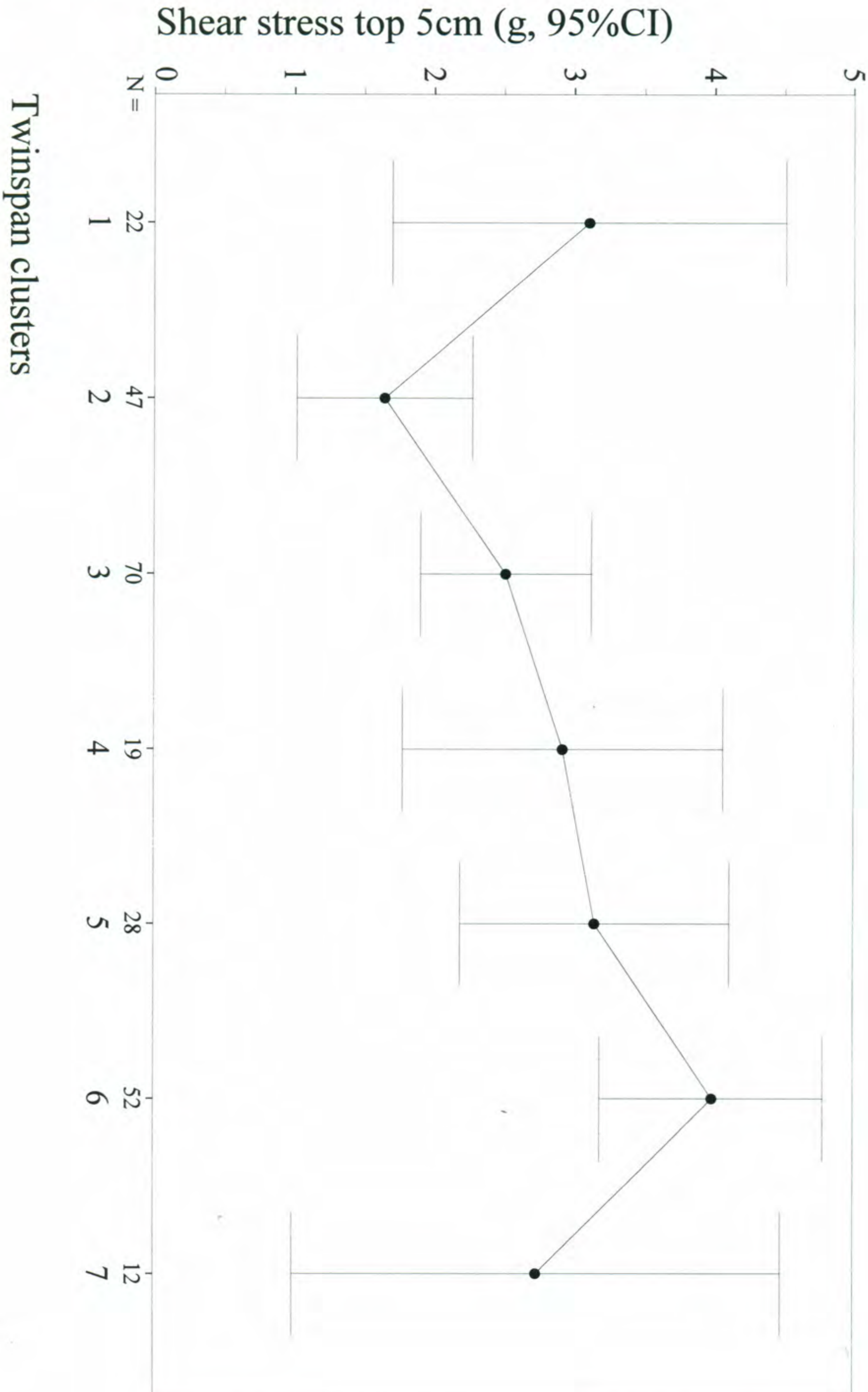


Figure 6b.

Abundance of submerged macrophyte clusters related shear stress (force needed to perturb the top layer of the sediment).



3. Effects of sediment chemistry and physical properties on submerged macrophyte survival and growth

Experiments were performed on three species of submerged macrophytes that are rapid colonisers and widespread in both the Netherlands and the United Kingdom:

Ceratophyllum demersum is usually free-floating in the water layer, although parts may be loosely buried in the top layer of the sediment. It has no roots, but underground parts can act as absorption sites (Pond, 1903). Sediment would be expected to have little influence on growth and development.

Elodea canadensis is a rooted plant that can absorb nutrients from both the water layer and sediment (Pond, 1903; Weeda *et al.*, 1991). Influence by the sediment and water would be expected.

Zannichellia palustris is a rhizomatous rooted plant that absorbs nutrients entirely from the sediment (Pond, 1903; Weeda *et al.*, 1991) and thus large influence of the sediment would be expected.

3.1 Experiments with transplanted sediments in a clear-water lake

Aim

To test the relative importance of sediment chemistry on survival and growth of the 3 submerged macrophyte species.

Method - 1994 experiment.

In May 1994, 12 containers (18 l) of sediment from each of 5 different broads (Hickling, Alderfen, Cockshoot, Hoveton Great and Pound End) were transported to the bird-free exclosure in Alderfen Broad (**figure 8**). The containers were buried in the Alderfen sediment with only the top 5cm protruding. Three replicate containers per sediment type were planted each with 9 vegetative propagules (10 cm stem-tips with at least one node for *C. demersum* and *E. canadensis*, or 1 shoot with roots and rhizome section for *Z. palustris*) of one the 3 species. Three containers (one per sediment type) were left unplanted as a control for colonisation. Shoot lengths, and water and sediment chemical properties **(see 2.2)** were measured on a 3-weekly basis until the middle of October.

Method - 1995 experiment

In May 1995, 20 of the same (see 1994) containers were used for each of five different sediments, and transplanted into the bird-exclosure in Alderfen Broad. The five treatments were sediment transported from elsewhere in Alderfen, in situ Alderfen sediment, in situ Alderfen sediment without protection against fish, sediment transported from Ormesby and artificially fertilised coarse sand. The containers were buried in the Alderfen sediment with only the top 5cm protruding. Five replicate containers were planted with each 9 vegetative propagules (10 cm stem-tips with at least one node for *C. demersum* and *E. canadensis*, or 1 shoot with roots and rhizome section for *Z. palustris*) of one the 3 species. Five containers were left empty as a control for colonisation. All containers, except the unprotected in situ sediment were covered with 5cm plastic mesh to prevent fish affecting the plants. Shoot lengths, and water and sediment chemical properties **(see 2.2)** were measured on a 3-weekly basis until the middle of October.

Result - 1994 experiment

The growth of the three species on the five sediments is shown in **figures 9a, 9b and 9c**.

Statistical analysis (ANOVA for each sampling date) of the shoot lengths showed no significant effect of the various sediments on *C.demersum* after the turbid period (**Figure 9a and 10**) caused by a persistant blue-green algal bloom. *C. demersum* colonised from 10 August onwards on all sediments. *E. canadensis* died quickly on the brackish Hickling sediment, but there was no significant difference between the other sediments. Strangely only one individual invaded and this was on Hickling sediment. *Z. palustris* survived the best on Cockshoot sediment, grew reasonably well on Cockshoot and Pound End and Alderfen sediment. Only one plant colonised Cockshoot sediment.

Analysis of the sediment chemistry data gave no apparent explanation for the observed differences. pH and REDOX measurements (not shown) and field observations showed that experimental artefacts such as transient oxidation and acidification associated with transportation of the sediment, the effect of resting young perch, and very limited light conditions in Alderfen because of a persistent blue-green algal bloom, had more effect on the plant performance than the sediment itself. Colonisation of the control containers by C. demersum (and one plant of *E. canadensis* and *Z. palustris*) after the turbid period showed the weak influence of the sediment and that these species were able to disperse.

1995 experiment

The growth of the three species on the five sediments is shown in **figures 11a, 11b and 11c**.

The 1995 results for *C. demersum* show growth and survival on all sediment types. Statistical analysis of the results for each sampling date show no significant difference between the treatments. *C. demersum* colonised all sediments during the experiment. Analysis of *E. canadensis* lengths in 1995 show significantly longer plants on Alderfen or Ormesby sediment than on fertilised sand on 9 June and 4 July. There was no significant difference in growth or survival of plants grown in transplanted sediment or in plots protected against fish predation compared with the control plots. *E. canadensis* did not colonise any sediments during the 1995 experiment. Analysis of *Z. palustris* lengths showed no significant difference between the sediments. *Z. palustris* colonised on all sediments, but was most successful on Ormesby sediment. *Z. palustris* is a common species in Ormesby, so propagules were probably present in the transplanted sediment. This can explain the high recruitment of plants.

Conclusions

These experiments show that *C. demersum* is not sediment-dependent, and can grow on all sediment types used. The species is however very mobile, even within one growing season. *E. canadensis* showed poor survival and growth on Hickling sediment, but was able to grow well on Alderfen, Hoveton Great, Pound End and Cockshoot sediments. *Z. palustris* grew well on Cockshoot, reasonably well on Pound End, Ormesby and Alderfen sediments but not on Hickling sediment. These two experiments show that only the brackish Hickling sediment can restrict growth and survival of the 3 species tested. Conditions in the water (light, algae) during the course of the experiments were more important than the nature of the sediment. The sediments used were not able to limit colonisation of *C. demersum*.

3.2 Effects of sulphide on the survival and growth of 3 species of submerged macrophytes in a microcosm experiment.

Aim

To test the effect of possible toxic levels of sulphide in the sediment on the survival and growth of three submerged macrophytes.

Method

Two consecutive experiments were carried out in the greenhouse of the UEA during the summer of 1995. Four replicates of the four sulphide concentrations (0, 300, 600, 900 μM sulphide) were maintained in the sediment compartment of the tanks (**Figure 12**), whilst the overlaying Alderfen surface water was the same for all of the treatments. Ten shoot tips of the 3 species were planted in each tank so that 5 cm was below the rubber membrane. Shoot length was measured weekly. Sediment pore water and tank water were sampled weekly using Rhizon samplers and analysed for anion and cation content (**see 3.1**). Shoot and root length and biomass were harvested in each tank. After poor growth in the first experiment it was repeated with ortho-phosphate addition to the sediment compartments to mimic the natural nutrient-rich conditions in the broads sediments (referred to as experiment 1 and experiment 2 respectively).

Results

The growth of the two species grown on the different treatments are shown in **Figures 13a, 13b, 14a and14b**. Unfortunately *Z. palustris* did not grow on any of the sediments. *C. demersum* plants did not differ in length during the beginning of experiments. However at the end of the experiment plants grown on sediment with added sulphide were longer than grown on sediment without sulphide. *E. canadensis* plants grown with or without sulphide addition in the sediment did not differ in length. There was a trend (not shown) that the highest sulphide level had the lowest number of roots compared with other treatments. All plants in experiment two were longer than in experiment one, which showed the effect of the fertilisation with phosphate.

Conclusion

The main conclusion is that at the concentrations used, sulphide was not restricting the presence and growth of the sediment-independent *C. demersum* or the partly sediment- dependent *E. canadensis*. There was a clear stimulatory effect of phosphate fertilisation in the sediment compartment on the growth of *E. canadensis*. *Z. palustris* did not grow on any of the sediments.

Figures 7a, 7b & 8.

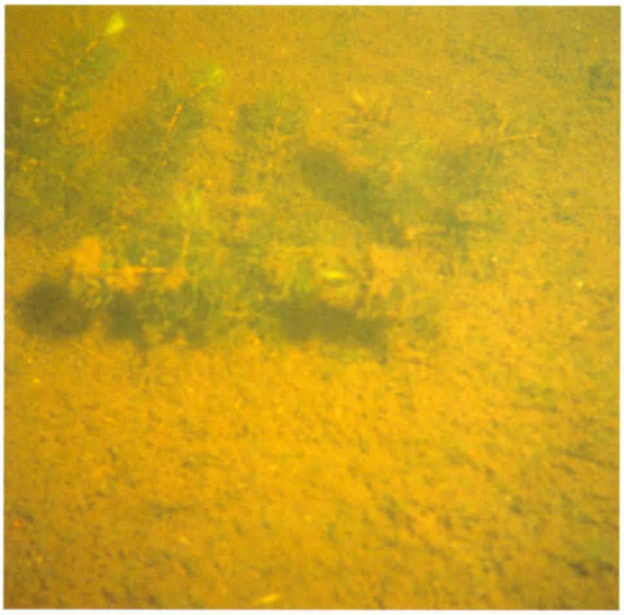


Figure 7a: Photograph of *C. demersum* (Schutten, 1996)

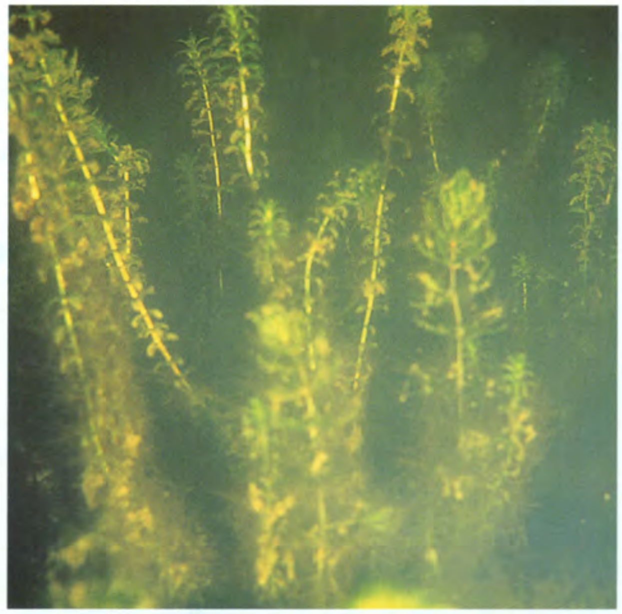
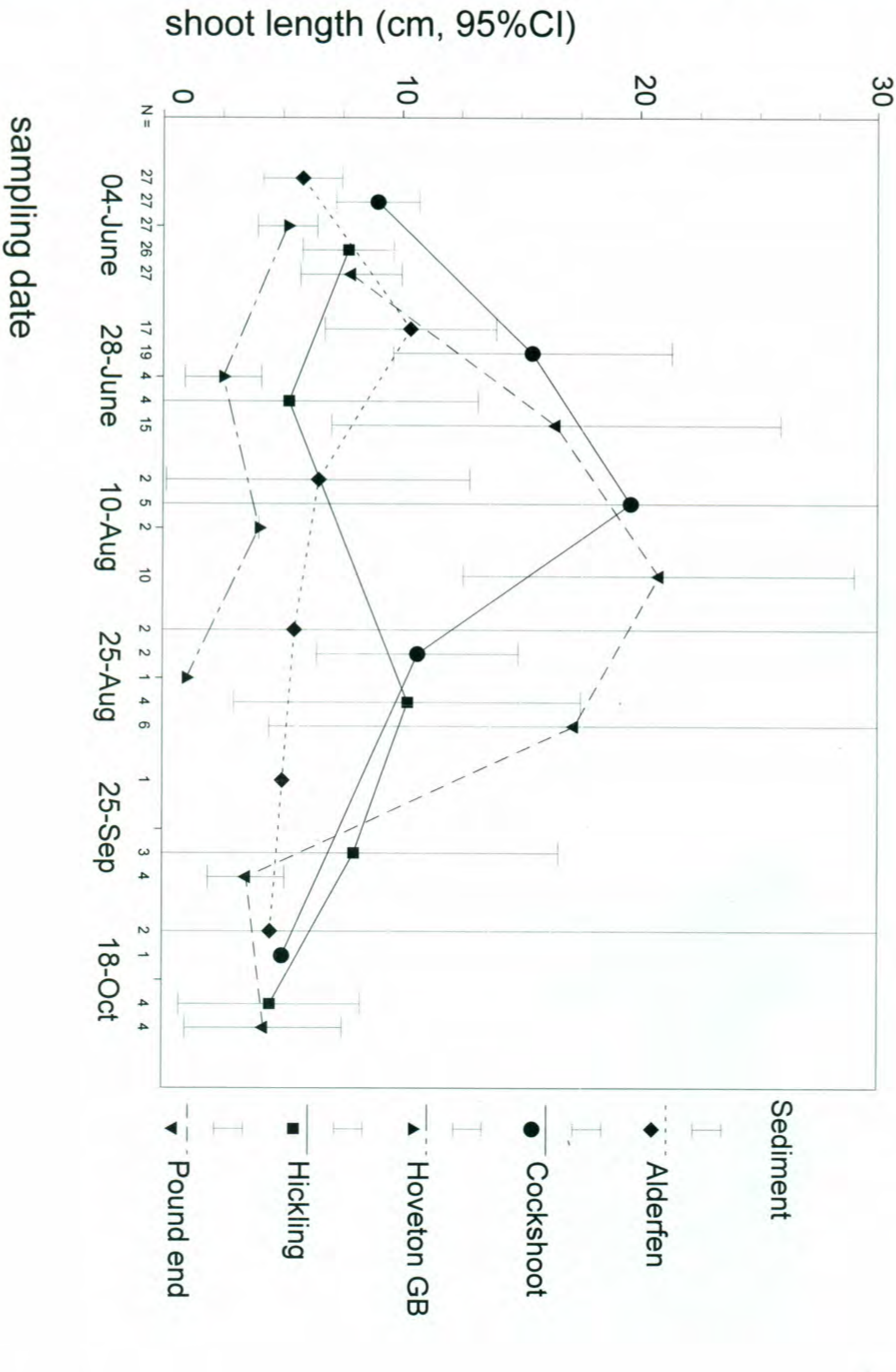


Figure 7b: Photograph of *E. canadensis* (Schutten, 1996)

Figure 8: Photograph of bird-free exclosure in Alderfen Broad (Schutten, 1996).

Figure 9a.

Mean shoot length (and 95% Confidence Interval) of planted *C. demersum*, grown on 5 different sediments in a bird-grazing protected environment in Alderfen Broad during the summer of 1994.



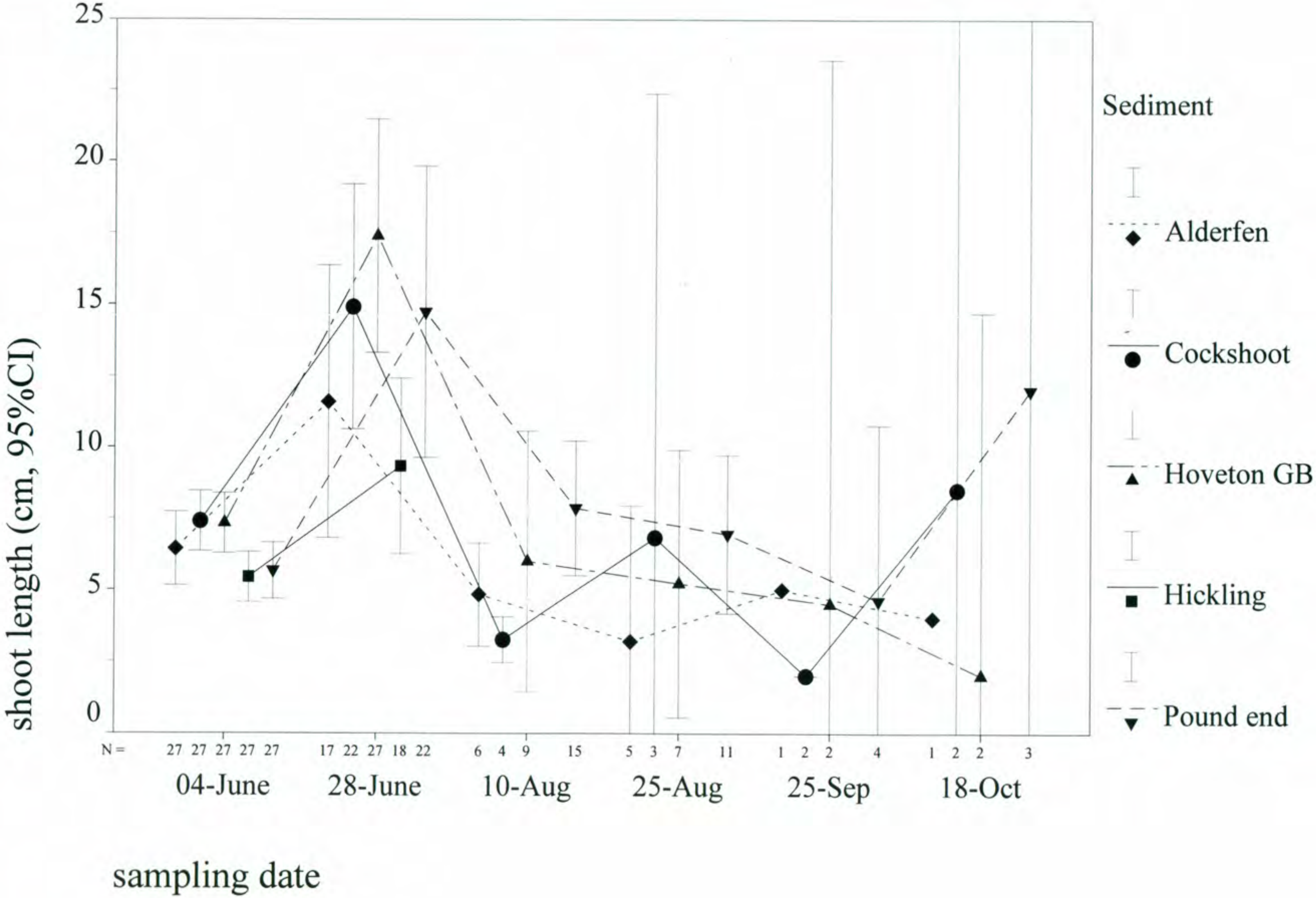


Figure 9b.
Mean shoot length (and 95% Confidence Interval) of planted *E. canadensis*, grown on 5 different sediments in a bird-grazing protected environment in Alderfen Broad during the summer of 1994.

Figure 9c.

Mean shoot length (and 95% Confidence Interval) of planted *Z. palustris*, grown on 5 different sediments in a bird-grazing protected environment in Alderfen Broad during the summer of 1994.

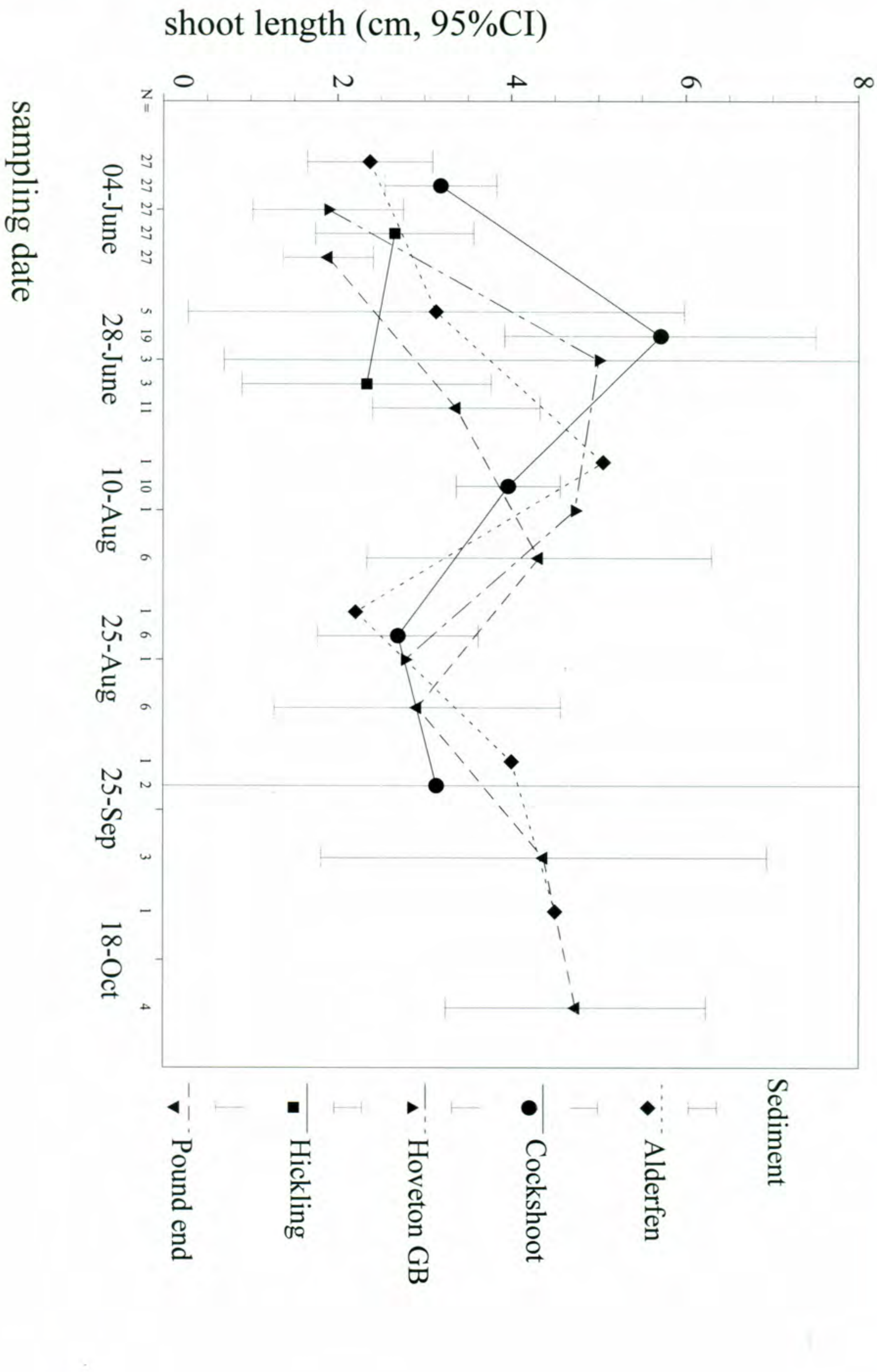
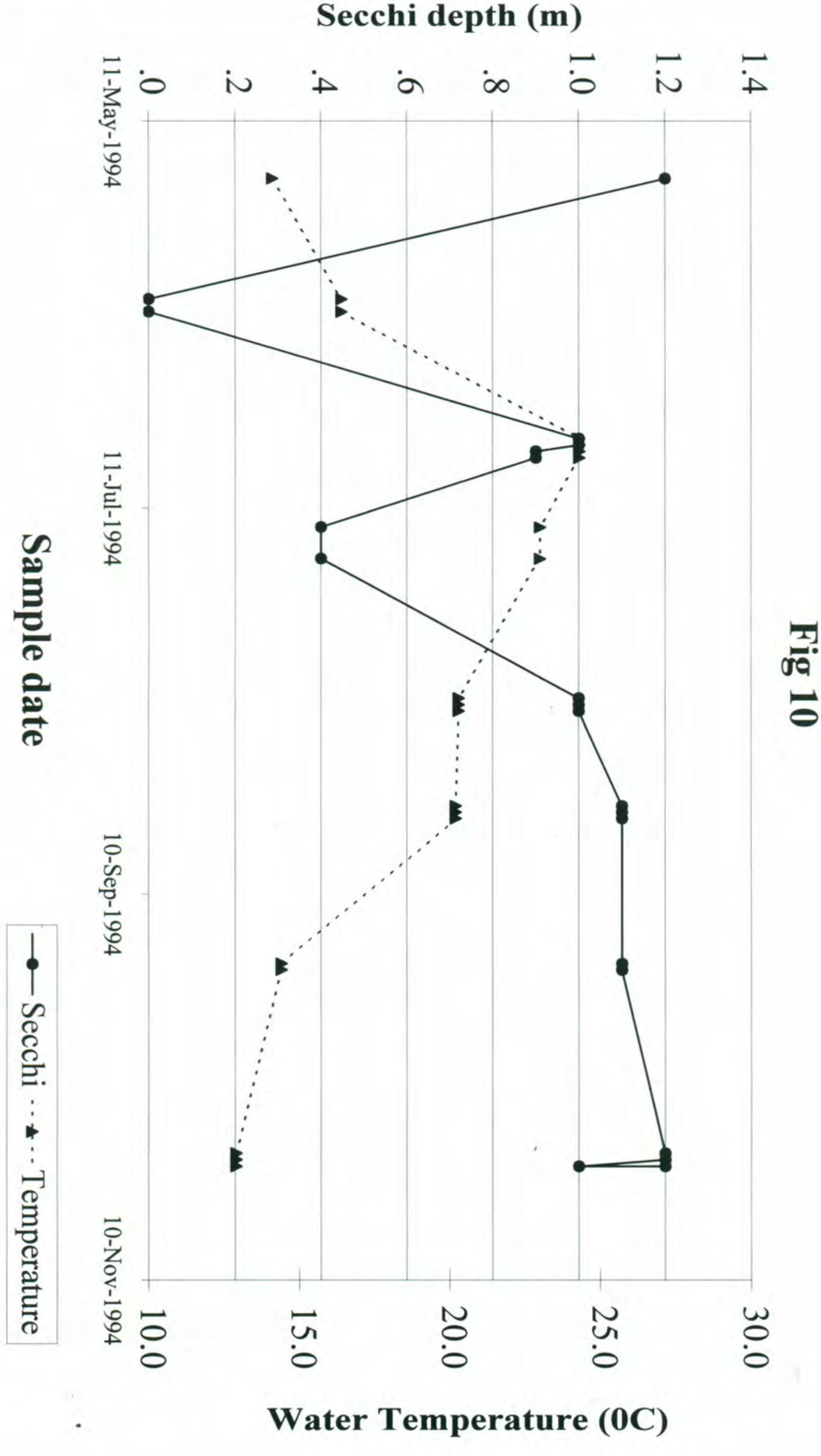


Figure 10.

Water temperature and light penetration (Secchi depth) in Alderfen broad during 1994



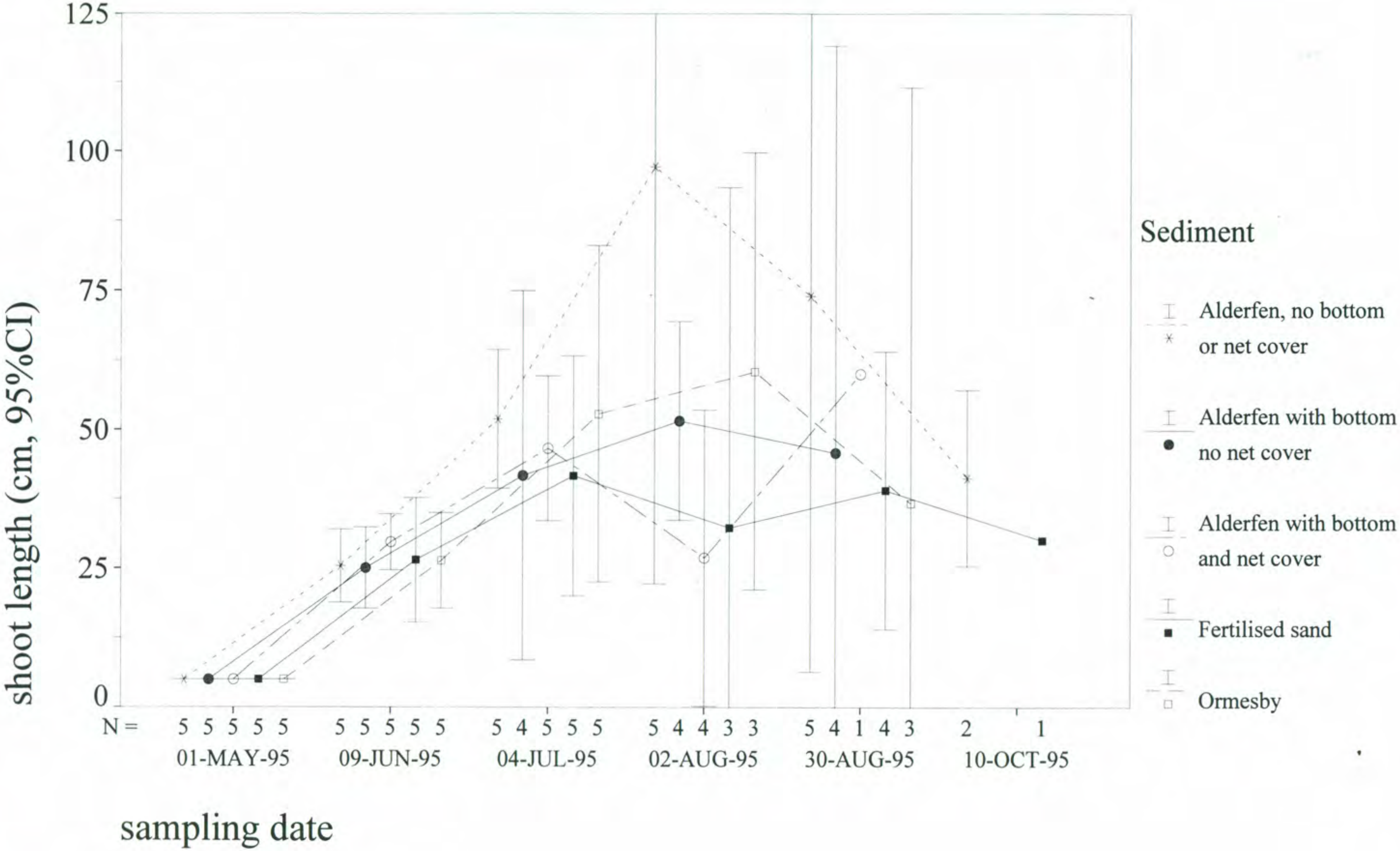


Figure 11a.

Mean shoot length (and 95% Confidence Interval) of planted *C. demersum*, grown on 5 different sediments treatments in a bird-grazing protected environment in Alderfen Broad during the summer of 1995.

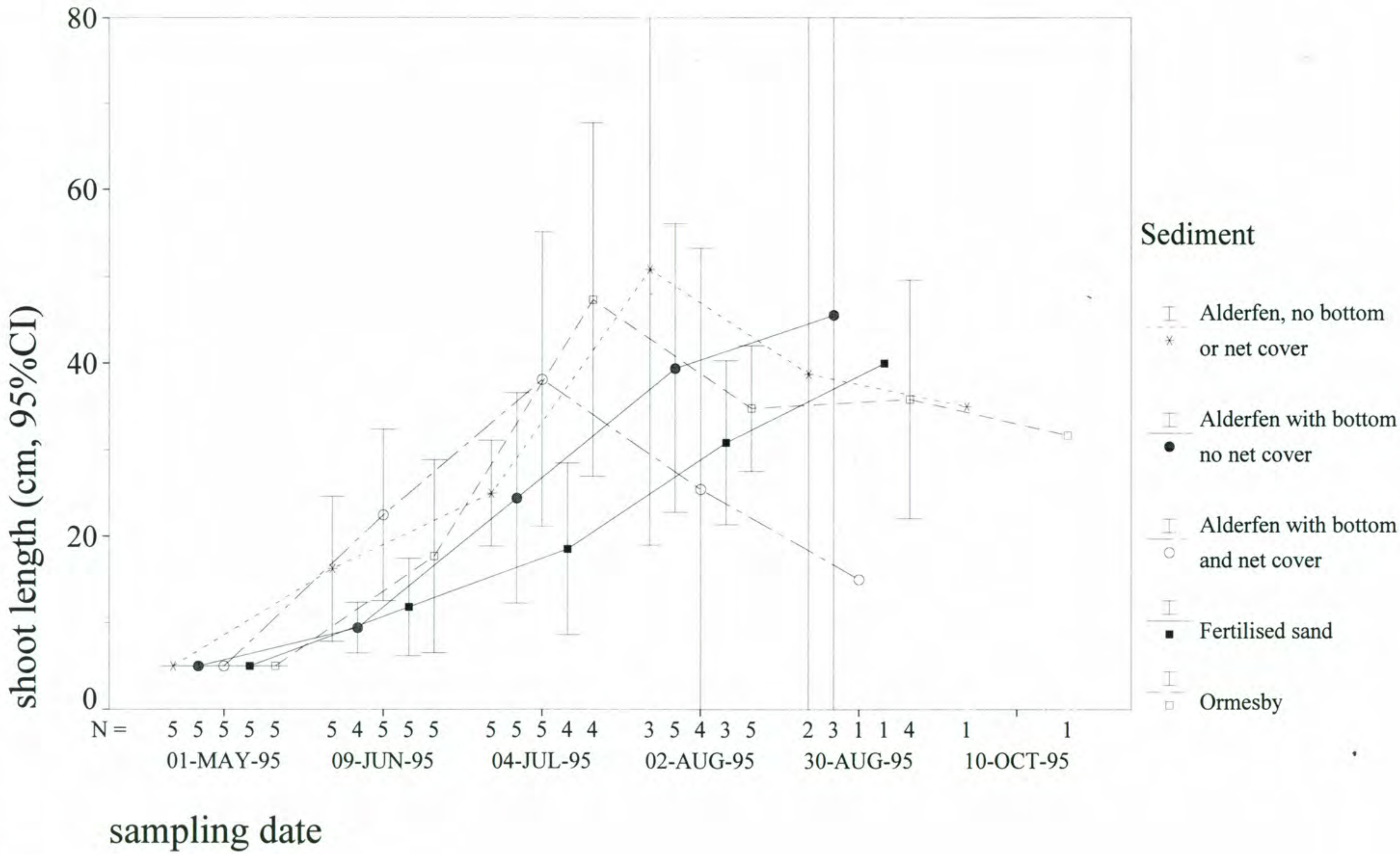


Figure 11b.
Mean shoot length (and 95% Confidence Interval) of planted *E. canadensis*, grown on 5 different sediments treatments in a bird-grazing protected environment in Alderfen Broad during the summer of 1995.

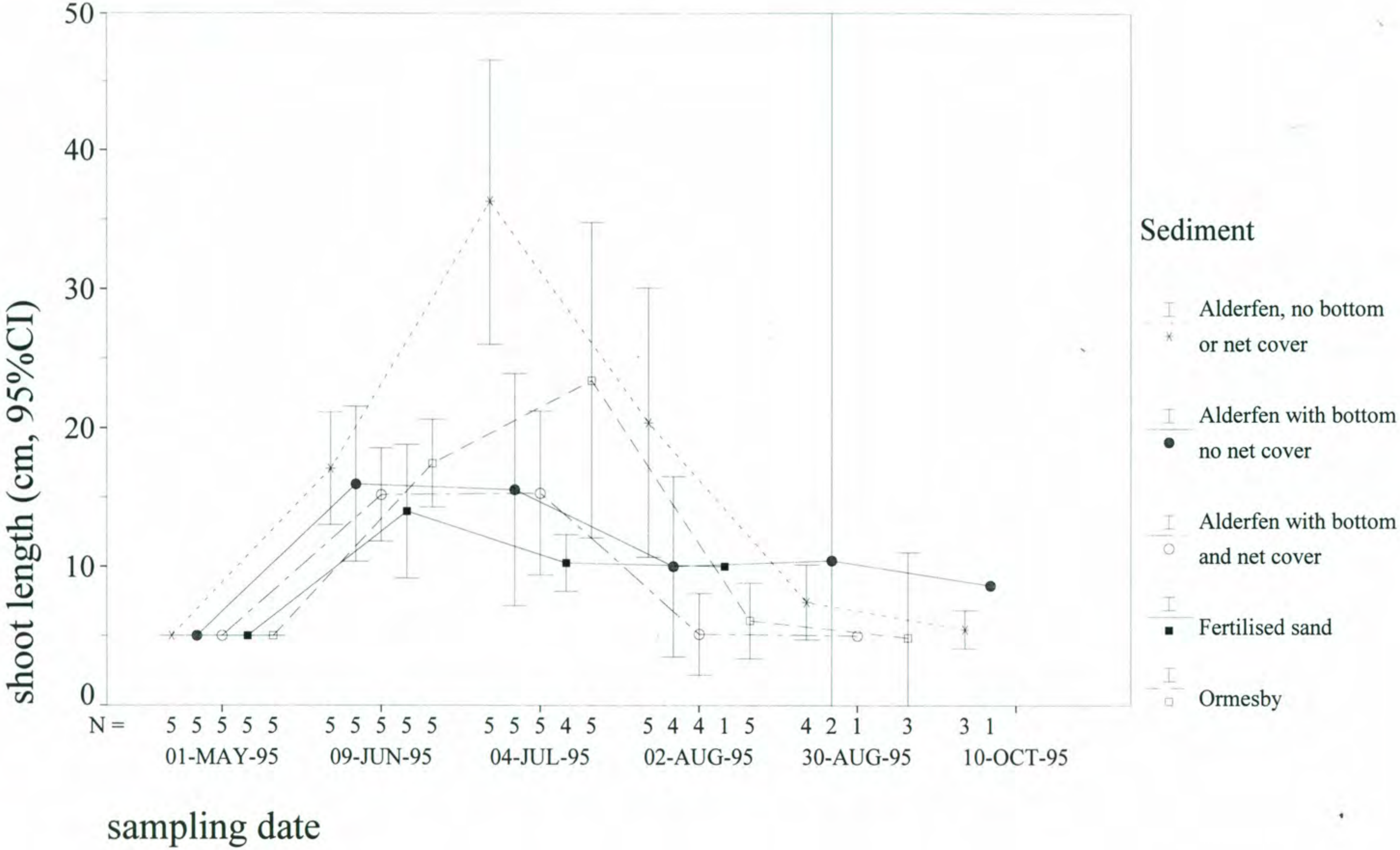
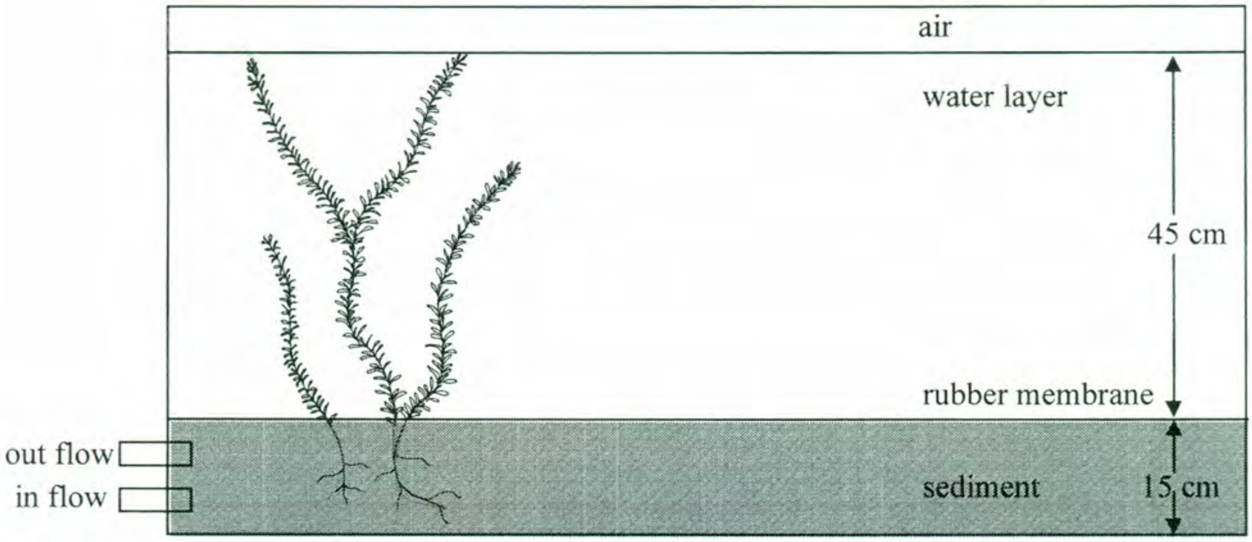


Figure 11c.
Mean shoot length (and 95% Confidence Interval) of planted *Z. palustris*, grown on 5 different sediments treatments in a bird-grazing protected environment in Alderfen Broad during the summer of 1995.

Figure 12.

Schematic drawing of a tank used in the Sulphide experiments.



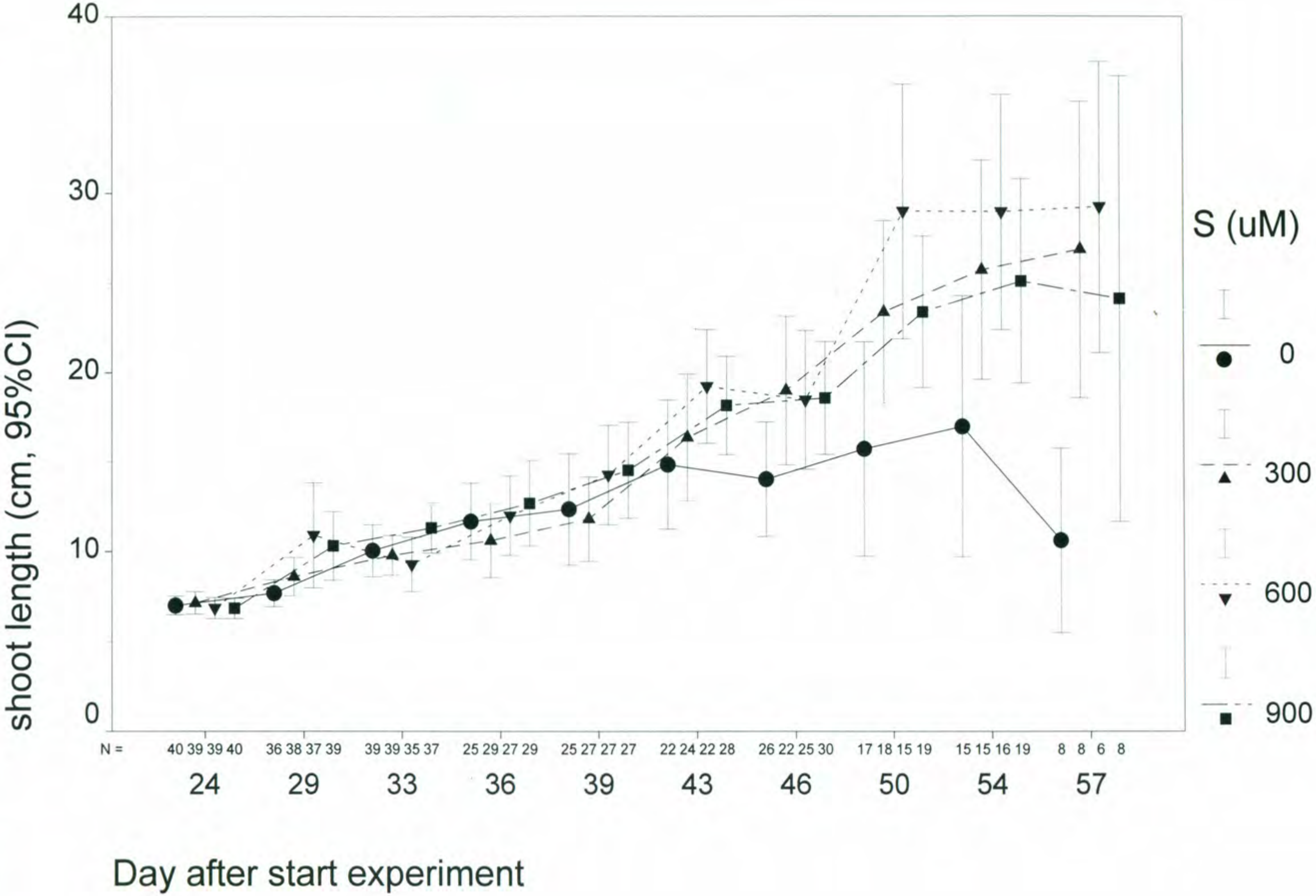


Figure 13a.
Length of *C. demersum* shoots grown on sediment with different sulphide concentrations, in the greenhouse at the UEA, summer 1995, experiment 1.

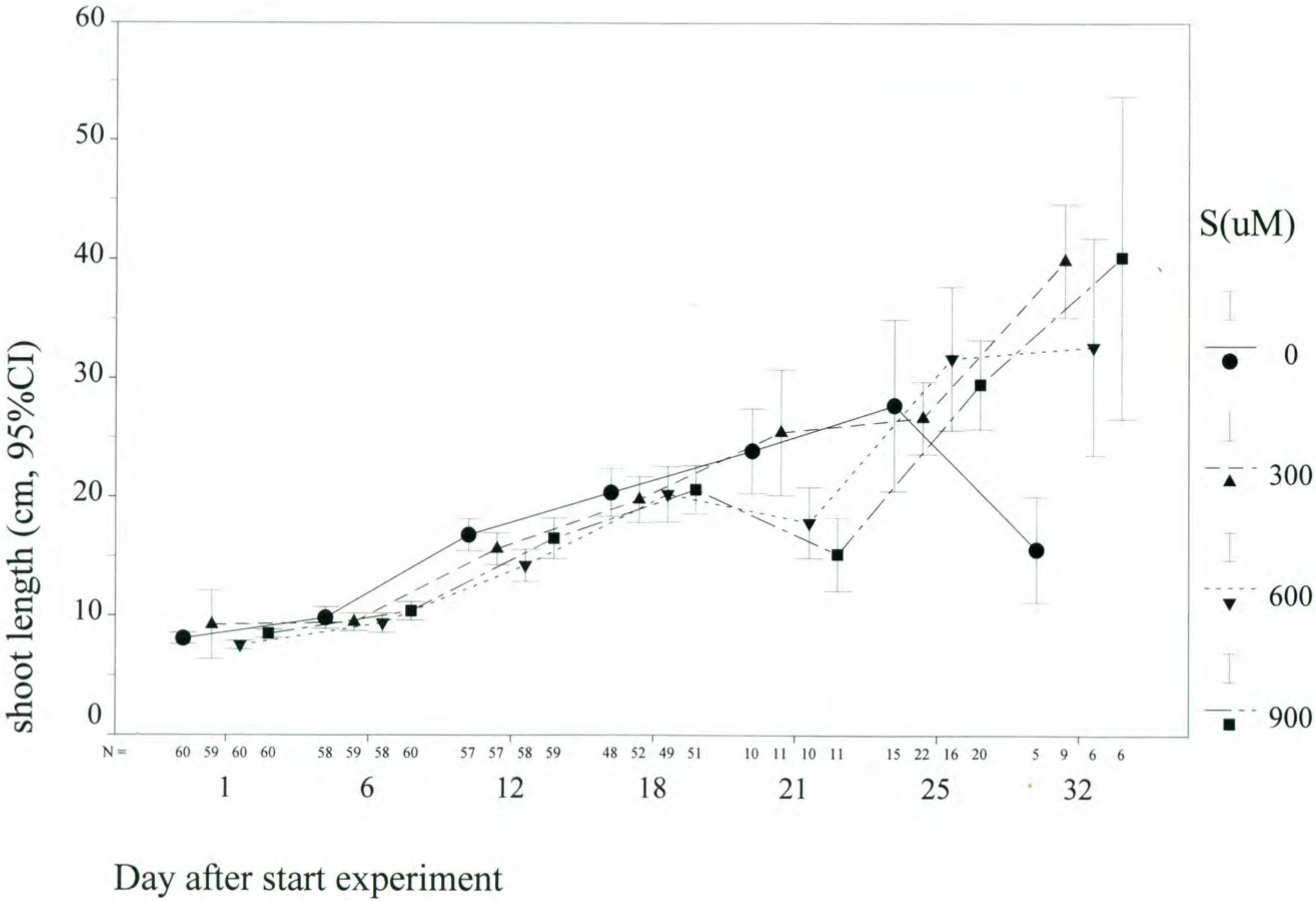


Figure 13b.
Length of *C. demersum* shoots grown on sediment with different sulphide concentrations, in the greenhouse at the UEA, summer 1995, experiment 2.

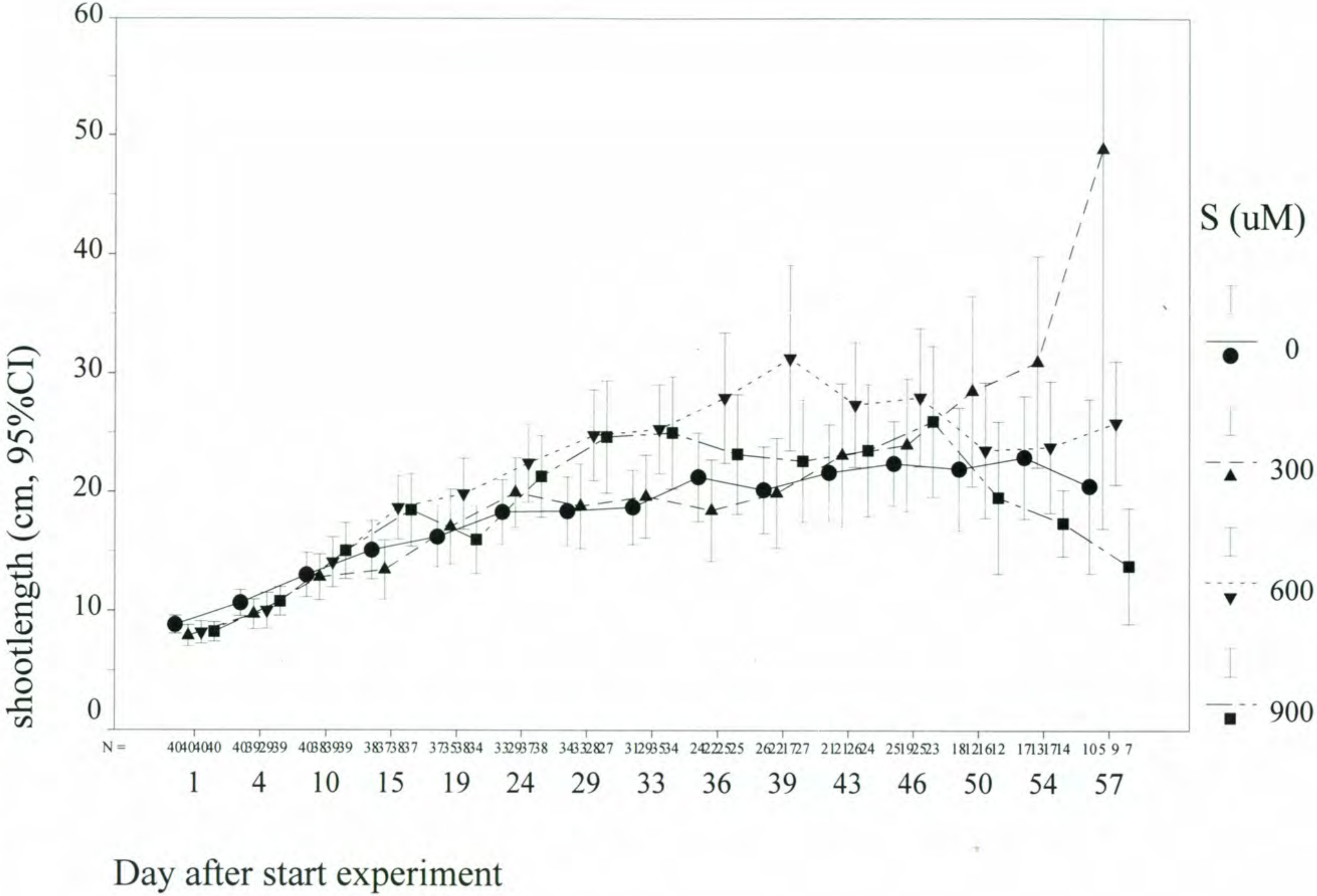
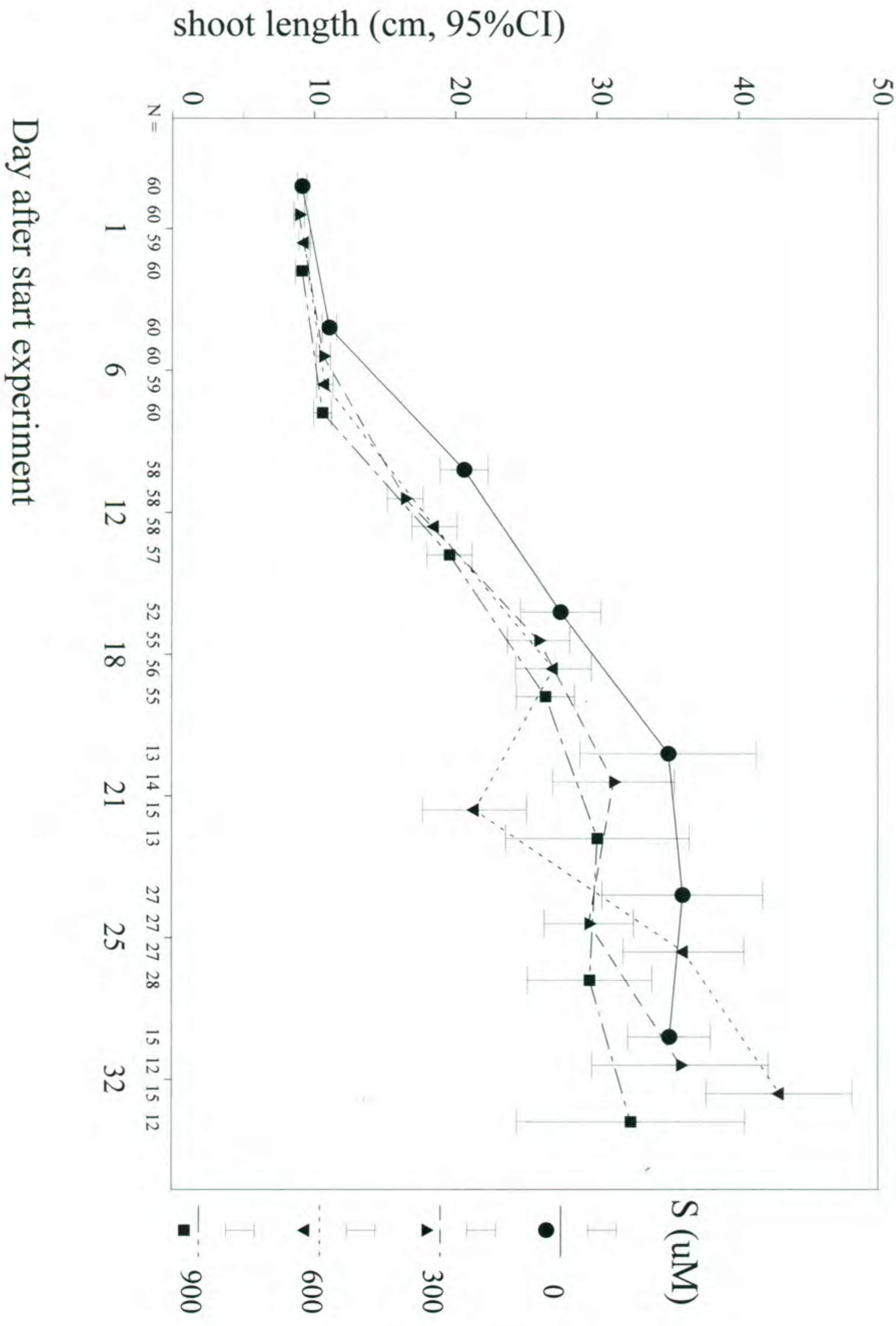


Figure 14a.
Length of *E. canadensis* shoots grown on sediment with different sulphide concentrations, in the greenhouse at the UEA, summer 1995 experiment 1.

Figure 14b.

Length of *E. canadensis* shoots grown on sediment with different sulphide concentrations, in the greenhouse at the UEA, summer 1995 experiment 2.



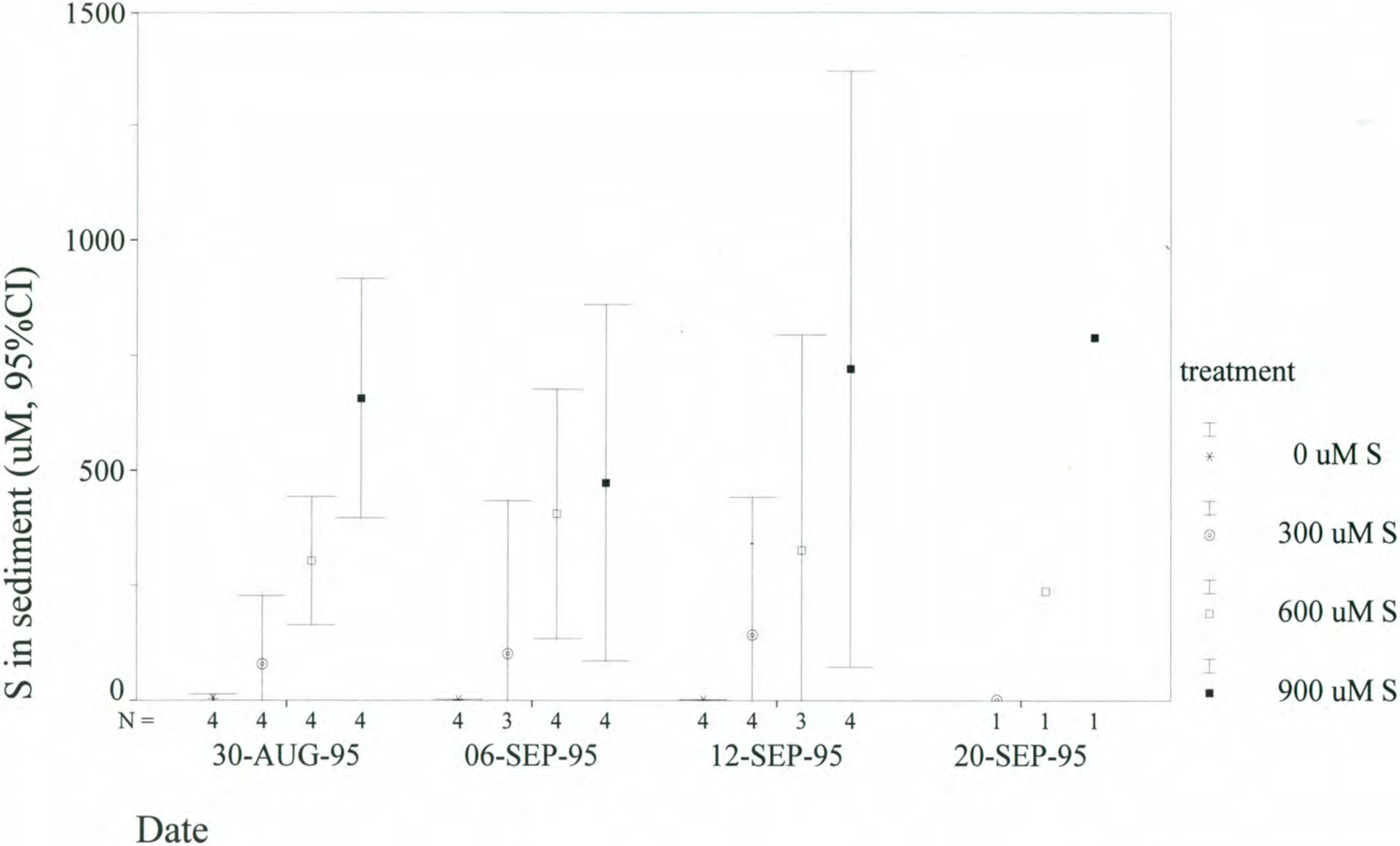


Figure 15.
Mean sulphide concentrations in the sediment compartments of the tanks during experiment 1 and 2.

4. Effects of sediment chemistry and physical properties on susceptibility of submerged macrophytes to physical disturbance

The research in this chapter seeks to link sediment chemical and physical properties to the force needed to pull a plant out of the sediment (uprooting resistance). The uprooting resistance of a plant growing at a specific site should indicate the potential impact of wind-induced currents or predation on the plant. It will either be uprooted and lost from the system or break and, possibly, regrow.

4.1 Correlative survey in 20 shallow lakes in the Netherlands and the Broads

Aim

A correlative survey was carried out to in July and August 1995 to determine the most important environmental factors controlling plant uprooting resistance.

Method

The force needed to dislodge a plant from the sediment, whether or not the plant had roots (uprooting force) and a range of environmental factors relating to sediment and water were measured in 20 shallow lakes in the Netherlands (**Figure 4**) and the Broads (**Figure 1**) (**see also chapter 2.1**).

The uprooting force of at least three individuals per species was measured on two or three locations in each lake that differed in exposure. A string was attached to the base of a plant and to a spring balance at the other end. Vertical force was increased slowly until the plant came loose from the sediment or snapped. The force applied was read from the spring balance. Then the remaining underground parts of the plant (stem, root and rhizomes) in the sediment were excavated and the plant was stored in a refrigerator until the length of root and shoot and dry-mass could be measured. Basic limnological characteristics of water and sediment (temperature, pH, REDOX) and depth and Secchi depth were measured. The fetch (distance from the shore in the prevailing wind direction) was estimated . The sediment pore water and surface water were sampled anaerobically using Rhizon samplers (**see chapter 2.2**). The shear force (force needed to perturb the top layer of sediment) was measured in situ using a pocket shear meter (Torvane, ELE-International). The top layer of the sediment was sampled using a 35-cm perspex manual corer (diameter 7 cm) and visually classified into layers on basis of colour, density and sediment type. Ionic concentrations of the pore and lake water were analysed using Atomic Absorption spectrometry for the cations and Ion-chromatography for the anions. Sulphide and ammonium were preserved and determined as soon as possible using ion-selective electrodes. The sediment dry-mass (105 °C) and loss-on-ignition (550 °C, 2 hrs) were measured. Multivariate analysis of the uproot data (not including broken plants) using a linear model (RDA, Canoco, Ter Braak, 1994) was carried out to identify the most important factors influencing uprooting resistance.

Results

Multivariate analysis suggested a strong relationship between the uprooting force, salinity (Na^+, K^+), nutrients (NO_3^-, NH_4^+, SO_4^{2-}, PO_4^{3-}) and shear stress of the top layer of the sediment (**Figure 16**). The significance of this relationship, using the Monte Carlo Permutation test, n = 99, was 0.08. The first axis explained 31% of the uprooting force / environmental relationship and the second axis added 25%.

The major factors correlated with the uprooting resistance were very variable between species but species could be grouped in their behaviour (**Table 2**). In general the nutrient content of the sediment (PO_4^{3-}, SO_4^{2-}) seemed to reduce the uprooting resistance for the first three groups that have a clear root or rhizoid system. The uprooting resistance for these groups appeared to increase with the sediment stability and the salinity.

C.*demersum* and the filamentous algae group, which do not produce roots, were better anchored in lakes with phosphate-rich water, but worse in lakes with a high salinity or high concentrations of nitrogen compounds in sediment and water.

Najas marina is an unusual species in that it thrives under high sulphide concentrations in un-exposed water bodies with fluid, reduced sediments.

Conclusion

Sediment structure affects plant community composition partly due to the vulnerability of certain species to being uprooted. The results show that the effects of the variables measured differ strongly between the different plant species. This means in practice that a certain species can be expected to be anchored strongly in a certain sediment and is therefore not strongly affected by physical disturbance in that particular situation, whereas other species can show the opposite response.

4.2. Effects of natural and artificial sediments on uprooting resistance and root and shoot growth in a microcosm experiment

Aim

To test the influence of sediment density on root and shoot growth and uprooting resistance of three submerged macrophyte species under controlled conditions.

Methods

Two consecutive experiments, with each four replicates were carried out under controlled conditions in the greenhouses at the UEA during the summer of 1995. In the first experiment fertilised sand and Alderfen sediment were used, and in the second experiment Pound End and Ormesby sediment. Overlaying water for all treatments was Alderfen surface water. Ten shoot tips per species were planted in 40 x 60 x 40 cm cold water storage tanks which contained a 15 cm layer of sediment. Shoot length was measured weekly and two randomly selected plants of each species per tank were uprooted experimentally, and the force required measured with a spring balance (**see 4.1**). Sediment pore water and tank water were sampled weekly using Rhizon samplers and analysed for anion and cation content (**see 2.2**).

C. demersum, the non-rooted plant, grew the best on fertilised sand (**Figure 17a**). There was no difference in shoot length produced between the three natural sediments. The shoot biomass and uprooting resistance (Figures not shown) were significantly higher on the Ormesby and Pound End sediments that were used in the second experiment. However the plants were planted deeper during the second experiment, which increased available surface for nutrient absorption and resistance to being dislodged. The uprooting resistance (**Figure 17b**) was strongly correlated to underground stem length, indicating a physical effect of the sediment. No underground growth measurements were made, so underground growth could not be related to sediment type.

E. canadensis shoots were longer and root biomass was higher on Alderfen sediment and fertilised sand than in the other two sediments (**Figure 18a**). The uprooting resistance was closely related to the root biomass and length. The sediments could be ranked by uprooting resistance: fertilised sand > Alderfen > Pound End and Ormesby (**Figure 18b**).
Z. palustris did not grow well on any sediment (**Figure 19a**), so only one harvest was done. The force needed to uproot the plants was generally greater in the first experiment (Fertilised sand and Alderfen sediment) than in the second and was closely related to root length. Plotting uprooting resistance versus root length shows this relation clearly (**Figure 19b**).

Conclusion

These experiments showed that uprooting resistance is strongly related to the buried length of the species examined. Resistance also increased with sediment density. This means that under field conditions the plants with the longest roots or growing in dense sediment would be better anchored and thus less susceptible to uprooting by exposure or bird grazing.

Table 2:

Major environmental factors correlated with uprooting resistance of particular species

Species	strong positive factors		strong negative factors	
	lake	sediment	lake	sediment
Hippurus vulgaris, Chara aspera, Callitriche spec.	SO_4^{2-}, Na^+, NH_4^+	NO_3^{2-}, Na^+		PO_4^{3-}
Myriophyllum spicatum, Potamogeton pectinatus Ruppia maritima	Na^+, NH_4^+	K^+, NO_3^{2-}, Na^+, dry-mass, shear stress		PO_4^{3-}, S^{2-}
Potamogeton perfoliatus, Potamogeton pusillus, Chara aspera Chara connivens	fetch	REDOX, dry-mass, shear stress	SO_4^{2-}	Sulphide
Ceratophyllum demersum, Filamentous algae		PO_4^{3-}	Na^+, NH_4^+	K^+, NO_3^-, Na, shear stress, dry-mass
Najas marina		Sulphide	Fetch	REDOX, dry-mass, shear stress

5. Synthesis, management implications and future research requirements

Synthesis

This project has shown that recovery of submerged macrophytes after biomanipulation in lakes with firm sediment and clear water can be successful, and normally involves firmly rooted perennial species and less firmly-rooted annuals. The recovery of submerged macrophytes in soft-sediment systems is usually slow and erratic, and consists only of loosely rooted species that are functionally annuals. An exception to this rule is *Najas marina*. This slow and erratic recovery is typical of the Broads which tend to lack the firmly-rooted perennials that some of the Dutch lakes have. Research has shown that macrophyte distribution is strongly correlated with lake size and sediment density, and to lesser extent with sediment and water chemistry. The sediment chemistries of the broads investigated do not appear to prevent plants from growing, but can reduce root development, and thus make the annuals more susceptible to physical disturbances (currents, grazing, benthic feeding). Sediment of low density does not provide a firm, supportive substrate for root systems that are already impaired by sediment chemistry. Field evidence suggests that filamentous benthic algal mats on fluid organic sediments provide plants with a firmer substrate, because they tend to fix the sediment. The reasons for the general absence of firmly rooted submerged species in the newly biomanipulated soft-sediment broads require further investigation.

Management implications

The scientific evidence from this project shows clearly that sediment stability is a major factor in determining recolonisation success and stability of the recovering aquatic plant community. Macrophytes that recolonise in lakes with loose, highly organic sediments are very susceptible to physical disturbance from water flow or grazing. They are easily dislodged from the sediment and consequently will be lost from the aquatic community. This results in functionally annual behaviour. Macrophytes recolonising in firm sediment lakes are firmly rooted and mainly perennial in behaviour. Physical disturbance will cause them less damage. Shoots that break from their roots can easily be replaced by regrowth since the roots are still present in the sediment. The perennials form a matrix that facilitates the establishment of annuals in spring, resulting in a stable and diverse community. This means that managers of firm sediment lakes are unlikely to encounter serious problems with recolonisation of aquatic macrophytes after biomanipulation. However managers biomanipulating soft organic sediment lakes will probably encounter problems with the recolonisation, and the resulting macrophyte community will be very susceptible to currents and grazing. Further research in this project should be aimed at designing techniques to overcome the non-supportive nature of the soft sediment lakes.

Future research

In order to stabilise the aquatic community of the soft-sediment lakes with firmly rooted perennials we must know amongst other things:

1. Are the organic and fluid sediments of the Broads a suitable environment for firmly rooted species otherwise tolerant to organic sediments? Is it necessary and practically possible to protect firmly rooted species from physical disturbance until they are established, either by stabilising the sediment with geotextiles, or by protecting the plants from grazing?
2. Is the growth of roots and shoots affected adversely by ammonium toxicity in the sediment, as the correlative survey suggests, and if so, what is the mechanism (changing root/shoot ratios, root extension, root hair development) involved?
3. What native British and/or Dutch species can root firmly in fluid organic sediments, and how is their rooting strength affected by sediment nutrients through root/shoot ratios, root extension, root hair development? The 1995 survey did not give a coherent answer to this question.
4. What is the role of the benthic filamentous algal layers as rooting substrates for colonising submerged macrophytes after biomanipulation?

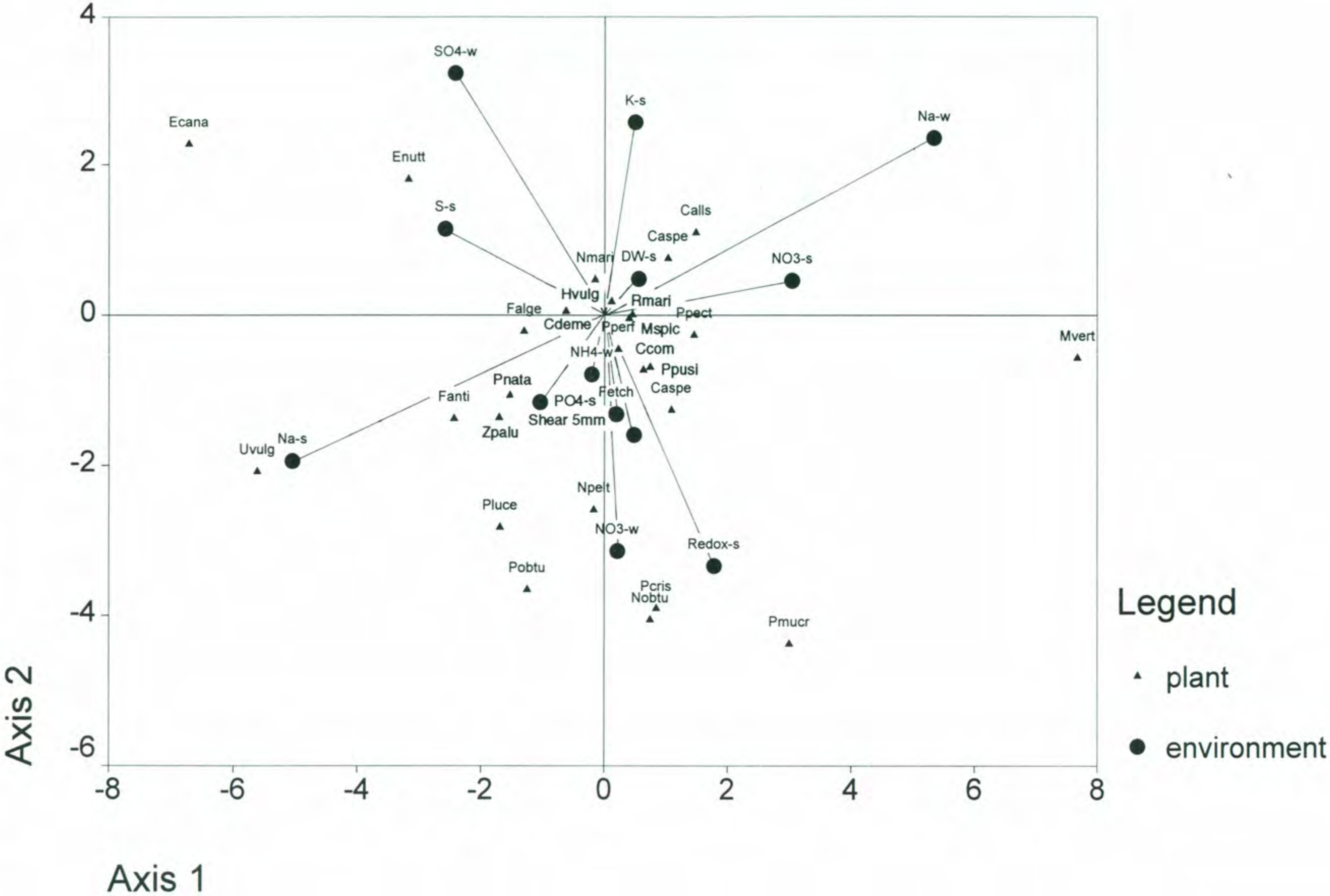


Figure 16.
Canoco correlation plot, using RDA-analysis of the 1995 uproot data.

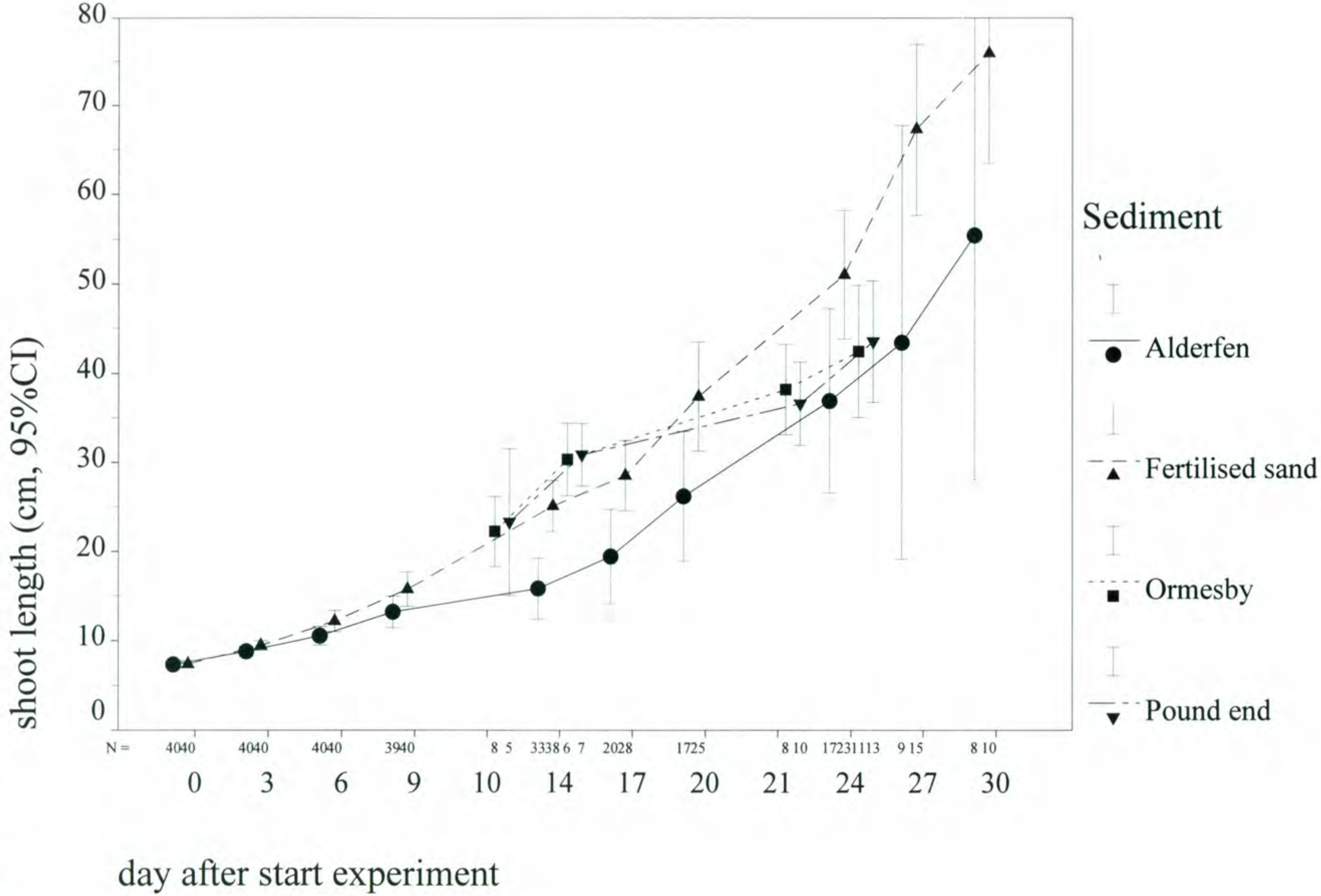
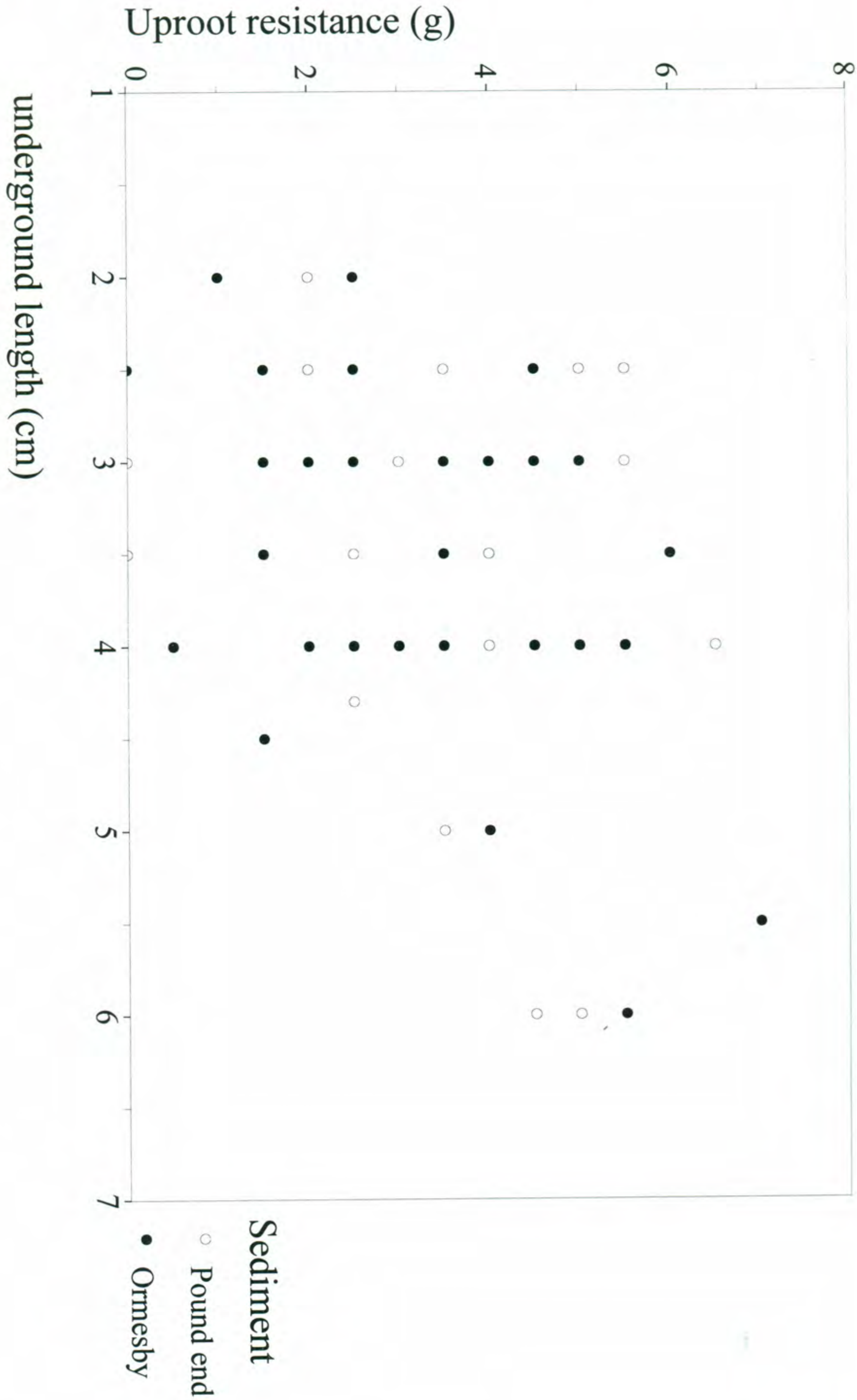


Figure 17a.
Shoot length of *C. demersum*, grown on 4 different sediments.

Figure 17b.

Dislodging force related to underground stem length of *C. demersum*, grown on 2 different sediments.



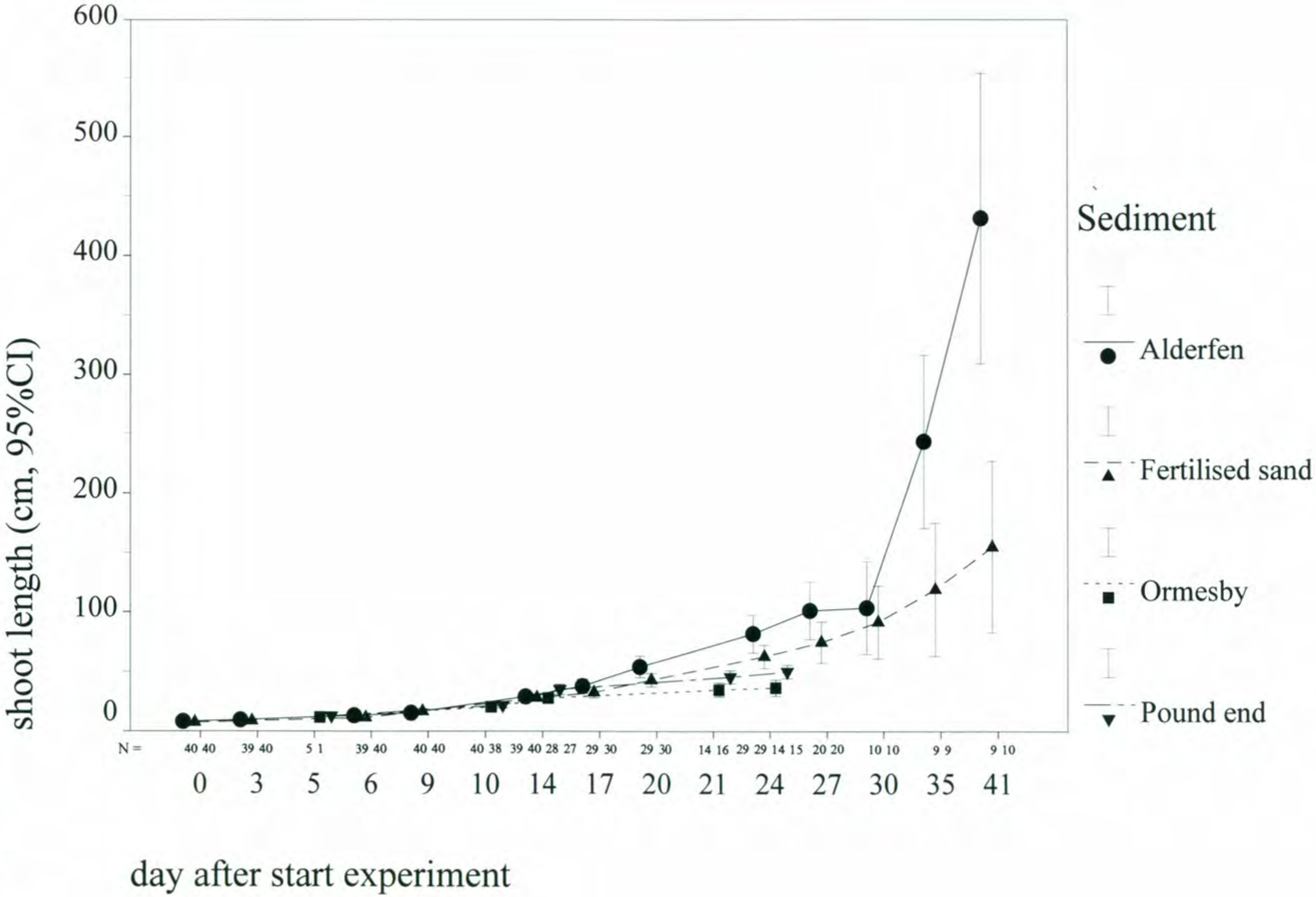


Figure 18a.
Shoot length of *E. canadensis*, grown on 4 different sediments.

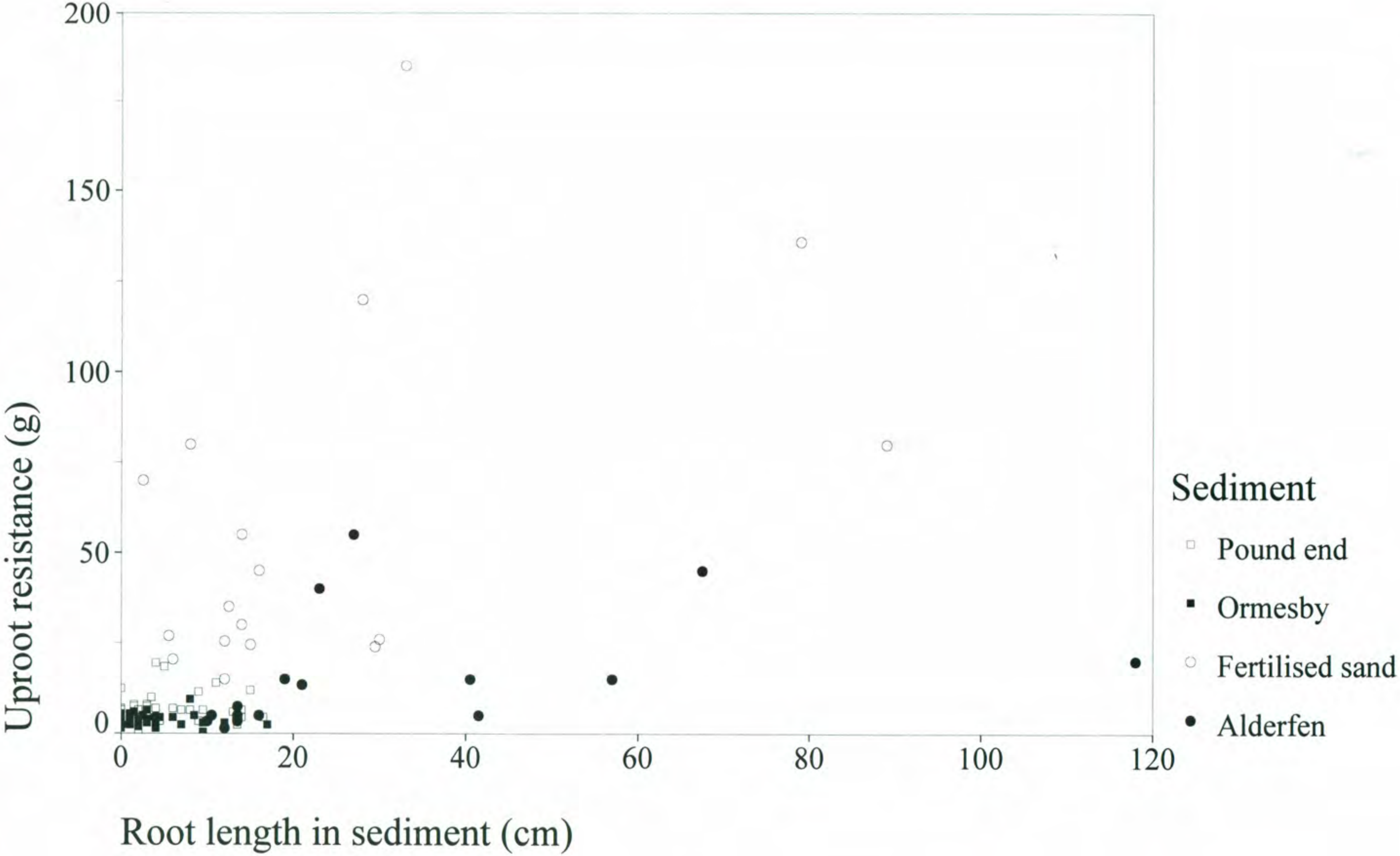


Figure 18b.
Uprooting resistance related to root length of *E. canadensis*, grown on 4 different sediments.

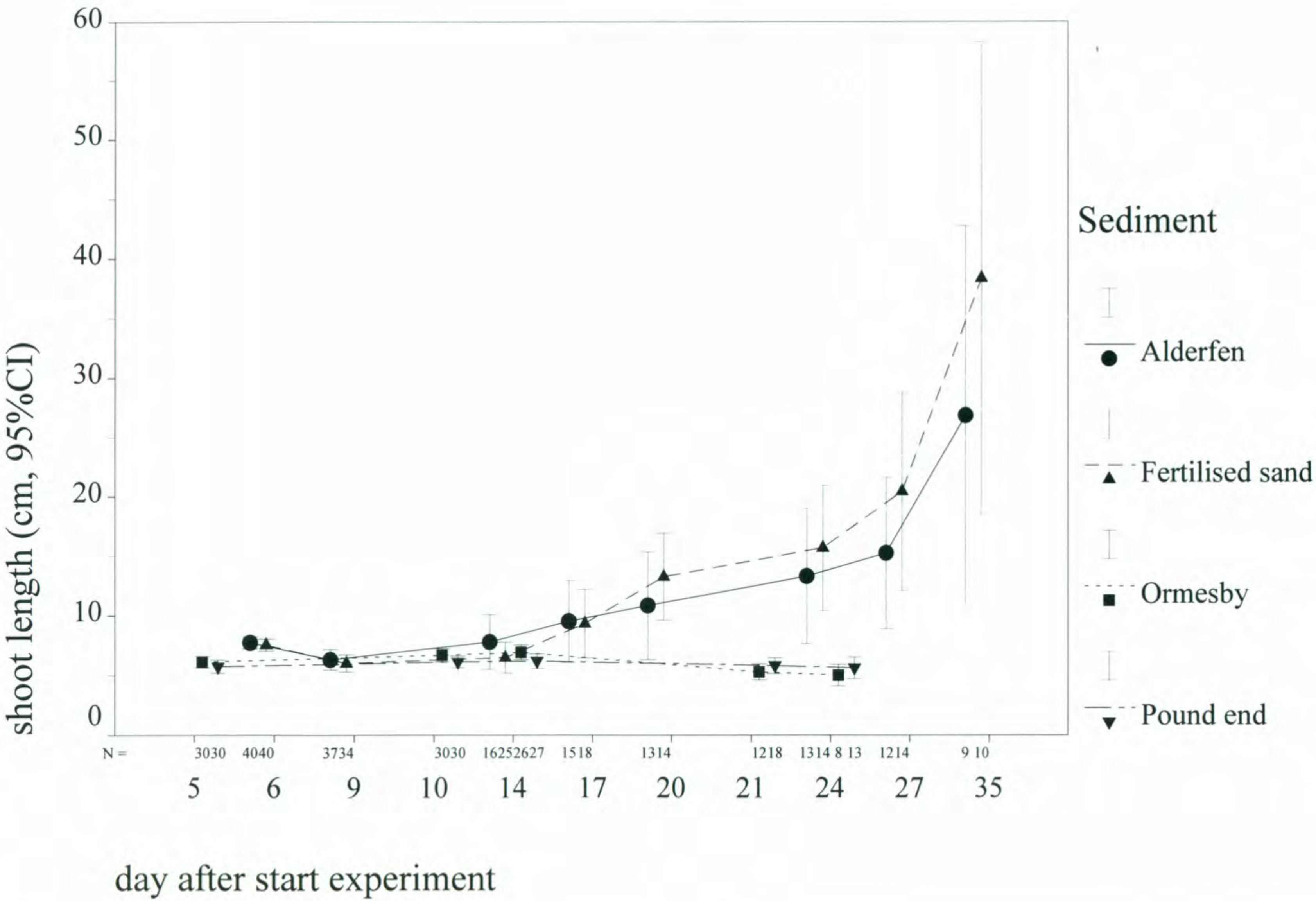
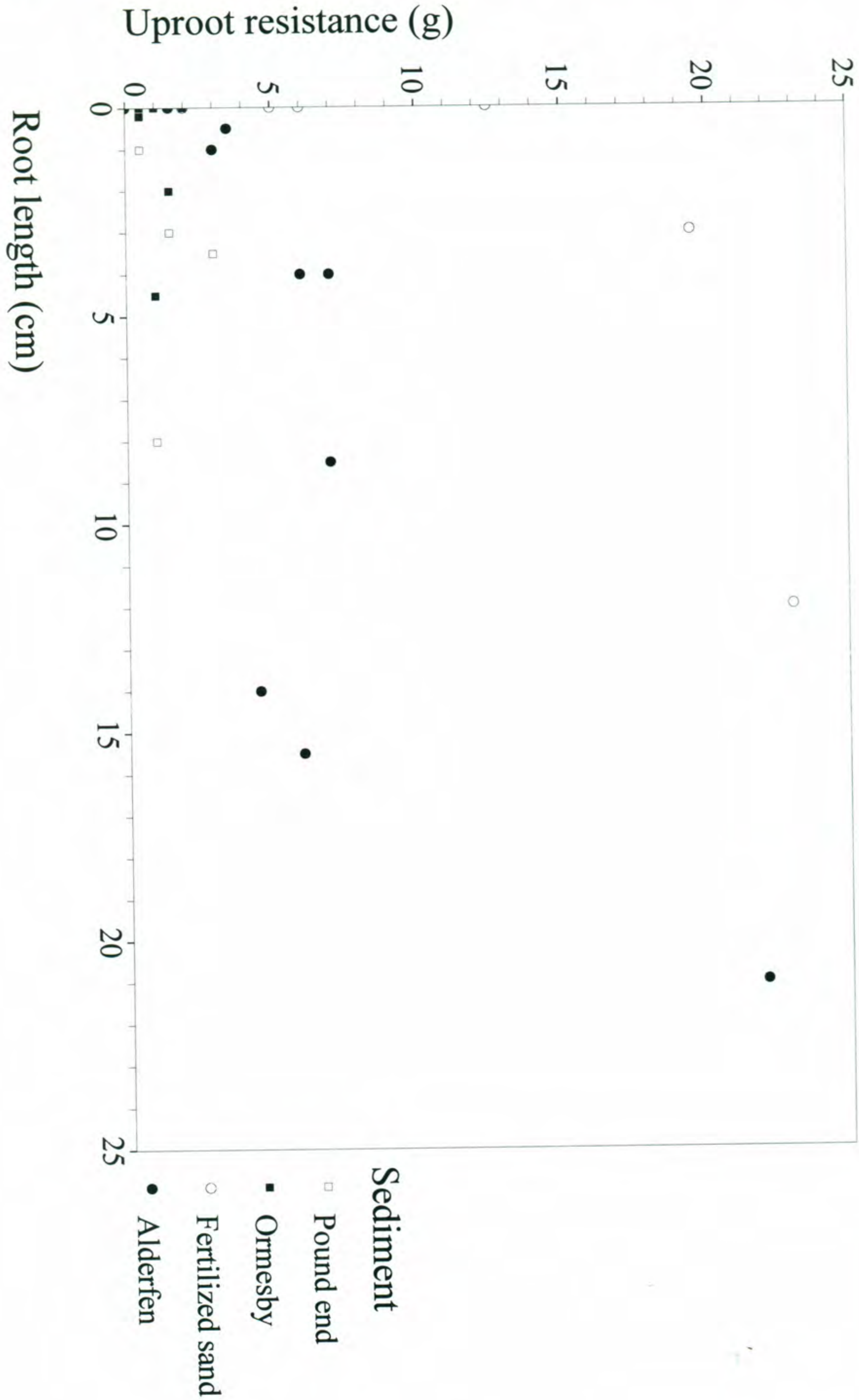


Figure 19a.
Shoot length of *Z. palustris*, grown on 4 different sediments.

Figure 19b.
Uprooting resistance related to root length of *Z. palustris*, grown on 4 different sediments.



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