



**Centre for
Ecology & Hydrology**
NATURAL ENVIRONMENT RESEARCH COUNCIL



Restoration of wet grasslands through re-instatement of surface grips



Extended final report BD1322

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Summary

A key tool for restoration and management of lowland wet grasslands is the control of ditch water levels. Past research has shown that ditch water level control alone may have limited effect on in-field water table levels in soils of low hydraulic conductivity that restrict lateral movement of water between the ditches to the intervening land units. The installation of grips or foot-drains (shallow channels that mimic natural surface topography) has been proposed and implemented as a means of linking ditch water levels and in-field wetness.

This project set out to test the effectiveness of grips of different spacing on lowland grazing marshes underlain by mineral soils at three sites across southern England (Pawlett, Somerset; Otmoor, Oxfordshire; Berney, Norfolk), using water table levels and soil moisture measurements to index hydrological response and invertebrates as a measure of ecological response. The three sites had different soil properties (Otmoor heavy clays, Berney and Pawlett had well-structure soils).

Volumetric soil moisture content showed a strong relationship with water-table depth in the well structured soils of Pawlett and Berney, but this was a weaker relationship at Otmoor with its low permeability soil.

Overall, the results suggest that installation of grips can increase invertebrate numbers and biomass in wet grasslands on mineral soils, particularly where the soils are not well structured. Optimum grip spacing varies with soil type; in poorly structured soils (such as Otmoor) grips need to be closely spaced (5m) to drain surface water, but will have little impact on the soil water table. In well-structure soils (such as Pawlett) grips can be about 20 m apart and still strongly influence the water table. Where soils have high permeability (such as Berney) grips or ditches can even be 60-70 m apart.

An adequate source of water, infrastructure to maintain specific seasonal water levels and a means of evacuating excess water are essential requirements for a controlled water-regime. The case studies illustrated the need for a site-specific approach because the combination of these factors pertaining at any particular site will vary.

The bird behaviour studies at Otmoor showed that pools of shallow water with slight slopes and a patchy vegetation structure provide valuable feeding habitats for both redshank and lapwing. The cross-sectional profile of the grips should therefore be shallow to maximise margins. This was supported by the land managers at each site who indicated that shallow grips made it easier to use machinery on the site, such as mowers.

By the end of the project, the grips at Otmoor were already showing infestation by emergent vegetation such as *Typha latifolia* that would reduce conveyance. Grips would need regular management to maintain their hydrological properties, such as clearance or possibly re-cutting every few years.

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1. Background

1.1 General

Through its programme of agri-environment schemes, DEFRA seeks to conserve and, where possible, to enhance the biodiversity value of lowland wet grasslands and their associated habitats, such as surface drainage channels. DEFRA-sponsored research has shown the underpinning role of hydrology in determining the distribution of wetland habitats, in achieving their successful rehabilitation or re-creation, and in creating environmental conditions favourable to both breeding and wintering populations of wetland birds. At a DEFRA research workshop on lowland wet grasslands in September 2001, wetland restoration was identified as a priority topic by RDS Project Officers especially as it related to a) the effectiveness of raised water-level schemes, b) issues of water-quality and c) habitat restoration in a landscape context (Defra, 2002).

In the context of agri-environment schemes, research has focused on ditch water level prescriptions with rather less attention to the efficacy of different means of translating these prescriptions into altered field water table and soil moisture levels. However, DEFRA reviews of ESA prescriptions have noted that, in many lowland grasslands, the once dense surface system of grips has fallen into disuse, and their reinstatement has been proposed as a means of conducting water from the ditch system to the field centres, thus achieving the increased site wetness required for the range of fauna and flora these schemes are intended to target. To that end there is a pressing need to examine the role and effectiveness of grips in achieving agri-environment restoration and management goals, and to determine to what extent effectiveness is dependent upon the spacing of such grips

The project seeks to address key components of this issue, with outputs of relevance to the development and application of DEFRA policy, especially within agri-environment schemes

1. Assessment of the efficacy of grip installation and spacing, in translating ditch water level manipulations into altered in-field hydrological conditions in clay soils.
2. Assessment of hydrological changes created by grip restoration and the consequent changes in physical, invertebrate and botanical characteristics of relevance to the wetland bird community.
3. Guidelines for restoration - both modification of extant guidance and new prescriptions.

The ecology of the grips themselves as habitat was considered beyond the scope of the project and would be considered in other initiatives (such as BD1323 Wetting-up farmland)

1.2 Grazing marshes and their water management

The present proposal focuses on coastal and floodplain grazing marsh, a designated habitat within the UK Biodiversity Action Plan, for which a costed action plan has been published (UK Biodiversity Steering Group, 1995). This plan requires the maintenance of 300,000ha of extant marshes, the rehabilitation of 10,000ha of degraded marsh, and re-creation of 2,500ha of grazing marsh on ditched arable land. Grazing marshes represent a stage in the conversion of natural coastal and floodplain wetlands to intensively farmed land. Traditionally they are characterised by a network of drainage channels (field ditches, rhynes *etc*) separating the fields, linked to a within-field system of more shallow seasonally-wet channels (variously termed grips, gutters, weather-ditches, foot-drains *etc*) that distribute water around the wet grassland. The resulting varied micro-topography increases the biodiversity of such grasslands (Silvertown *et al.*, 1999) by producing great variation in the eco-hydrological niches for plants, and is likely to have a

similar effect on invertebrates. Moreover, detailed work funded by DEFRA has shown that the distribution of breeding waders at both the between- and within-field scales is related to the presence of such surface features (Milsom *et al.*, 2002). However, in many wet grasslands, much of this older surface topography has been removed in recent decades by levelling to ease farming practices. Furthermore, spoil from ditch maintenance has often been placed around the field margins creating shallow embankments that effectively dam the grips. Surface flooding is consequently less frequent because ditch water cannot enter the field readily, but when it does occur (often only after very heavy rainfall events,) it is more prolonged, as the water cannot readily leave the field either. Such a regime is adverse to the requirements of species-rich swards, which have been shown to benefit from frequent but brief periods of surface wetness (Gowing *et al.*, 1996), and is also likely to be detrimental to many invertebrate species and breeding waders (Ausden *et al.*, 2001).

1.3 Designing seasonally-wet channels

Several research projects funded by MAFF demonstrated the overriding importance of field surface wetness conditions in influencing the spatio-temporal variation in the distribution of both breeding and wintering wetland bird populations (Milsom *et al.*, 2002, Caldow *et al.*, 1999). Yet, various studies (*e.g.* Armstrong, 1993) have shown that the low hydraulic conductivity of the soils in some wet grasslands means that the area influenced by manipulation of ditch water levels may only extend to about 15m from the ditches, even in some peat-based soils. In clay soils the extent of impact from raised water level will be less. Rainfall and evaporation largely control the wetness in the field centres. These factors have led to a recognition that ditch water-level management prescriptions alone cannot produce the in-field soil wetness required to achieve the ecological objectives of wetland restoration, and in particular the creation of suitable conditions for wetland birds (Gowing, 1996). There is a growing consensus that re-installation of surface topography is required to achieve full hydrological functioning of the system, such that when ditch water-levels are high, water can be transmitted throughout fields by infiltration from a system of grips without the need for sheet flooding. However, the optimum size and network structure of grips that will produce desired soil wetness is unclear. It is likely that this will vary according to the soil type (*e.g.* clay or peat soil) and the farming practices (*e.g.* whether the soil has been ploughed or not). When the lowland wet grassland ESAs were originally designated, the prescriptions sought to retain extant grips, but not to increase their number. By the late 1990s, however, MAFF-sponsored research had led to revision of grazing marsh ESA prescriptions for wet grassland restoration and recommended the reinstatement of grips (Gowing, 1996) and surface topographic features, but the eco-hydrological impact of such works were not monitored. Recent results from an eco-hydrological study of the Derwent Ings in Yorkshire (Palmer and Holman, 2002) has emphasised the importance of soil structure for relating hydrological regime to vegetation communities and hence potentially to its value as wader habitat. Grip installation would need to be appropriate to local soil properties.

Studies by Royal Society for the Protection of Birds (Ausden *et al.*, 2001) have shown that areas of lowland grassland subjected to winter flooding, while often holding impoverished invertebrate communities, may provide suitable wader habitat by virtue of maintenance of softer, more penetrable soils and shorter vegetation. Much previous work on grips had focused on peat soils, where increased grip frequency within raised water level schemes increases soil penetrability across the site and creates better feeding habitat for wading birds. On clay soils, low hydraulic conductivity means that closer grips spacing *per se* may not increase general penetrability, but that wetland birds will use the wetted margin provided by the grips to feed in. Hence studies of grip spacing (*i.e.* length of wetted margin per hectare) are important as a

measure of the increased feeding area for birds. The optimal grip spacing may be the one that creates a mosaic of drier areas distant from grips in which terrestrial invertebrate abundance remains high, intersected by grips where the availability of terrestrial invertebrates and aquatic invertebrates may be higher. A research programme is required to quantify the benefits of, and to frame appropriate prescriptions for, the reinstatement of grips to aid wetland restoration, particularly in clay sites.

1.4 Objectives

1. To identify one or more clay sites on which to conduct a controlled experimental study of grip installation.
2. To design and install a network of surface-grips at the site.
3. To install all necessary hydrological monitoring equipment within the experimental areas.
4. To conduct regular hydrological monitoring on experimental areas.
5. To conduct regular monitoring of other relevant environmental parameters.
6. To conduct botanical assessments in the first and final years of the project
7. To conduct surveys of the soil-dwelling invertebrate populations on experimental areas.
8. To quantify the impact of grip installation and spacing on the spatial and temporal variation in the in-field water-table and surface wetness.
9. To quantify the impact of grip installation and spacing on the physical attributes of the soil and vegetation, abundance and availability of soil-dwelling invertebrates and hence suitability of conditions for wetland birds.
10. To draw up guidelines for the installation of grip systems in lowland wet grasslands on clay

All of these objectives were fully met.

2. Site selection

A wide range of sites was considered for this project, all with mineral soils on wet grassland. A major limitation was getting permission to install grips. At first, the search was focused on the Somerset Levels and Moors to ease logistics. Two sites were identified prior to submission of project CSG7 at Pawlett and Athelney. Detailed discussions were held on their appropriateness with local Defra staff (Trevor Mansfield), Environment Agency (Murray Bush) and English Nature (John Leece). They felt that characteristics of the proposed raised water level scheme at Athelney (bowl-shaped fields and low summer water pen level) made the site un-typical. Pawlett Hams was part of on-going restoration project, where water management infrastructure had already been planned and where design of grips specifically for a scientific experiment was welcomed; at other sites land owners were not supportive. Pawlett had some existing relic grips, but discussion with Defra staff suggested this was not unusual and inclusion of such a site would be a good idea. Pawlett has always been a grazing marsh and there was no under-draining (such as mole drains) in addition to the relic grips. Defra staff also suggested selecting sites with a geographical distribution rather than just focusing on Somerset. Agreement to use Pawlett was delayed slightly, awaiting the establishment of a steering committee for the site's restoration plans. The committee approved CEH use of the site in January 2004.

Discussions with RSPB staff highlighted a new programme of gripping on RSPB reserves, with the then new rotary ditcher and their keenness for research. As a result, a replacement second site was selected on Otmoor in Oxfordshire. This was supported by ESA Project Officer in Oxford (Alistair Helliwell). The Otmoor reserve is on previous arable land. Some areas had been under-drained, but a site was selected with no obvious drains. The soils were quite compacted.

During project finalisation, RSPB had offered part of its reserve at Berney Marshes in Norfolk as a possible site. Project funds were not sufficient to cover all the costs of a third site. However, cost savings on the project were made by using the RSPB ditching machine to cut new grips. These funds were used to undertake some monitoring at Berney site, but were insufficient to study this site to the same intensity as Pawlett and Otmoor. RSPB agreed to undertake invertebrate surveys during the 2004 breeding season. The three sites make a transect across England (Figure 2.1) and cover a range of climatic situations in which clay-based wet grasslands are found.

Further details of all three sites are given in section 4.2 below, following soil analysis.



Figure 2.1 Location of study sites

3. Experimental design

Various designs of grip layout and monitoring station network were discussed by the project team with RSPB and with statisticians at CEH and Open University. The agreed layout takes the form of 3 blocks each with an identical replicate of the experiment. In each block, grips are instated at 5, 10 and 20 m spacings. Monitoring stations are sited at 0.1, 0.5, 1.5, 4 and 9 m from each grip edge along two independent transects in each block. This totals to 6 replicates of each spacing/distance. Clearly not all combinations are possible; *i.e.* stations cannot be placed at 4 and 9 from grips with a spacing of 5 m and not at 9 m with a spacing of 10 m. The total number of sampling stations at each site is 72. Proposals for instatement of grips at the three sites were submitted to the relevant organisations; RSPB at Otmoor and Berney and Wyvern Waste at Pawlett. The proposals were agreed in Spring 2004 at committee meetings of the various organisations. Images from the 3 sites are shown in Figures 3.1, 3.2 and 3.3.



Figure 3.1a Pawlett Hams



b



Figure 3.2a Otmoor



b



Figure 3.3a Berney Marshes



b

The RSPB agreed to lend to the project a specially designed and built machine for cutting grips. This has adjustable blades to enable any size or shape of grip to be cut. The RSPB also agreed

that only the time of operator needed to be paid by the project. Costs saved from the budget line for installation were re-invested in measurements at Berney. The dates available for cutting the grips were: Berney 14-23 July; Pawlett 30 August – 1 September; Otmoor 2-3 September. These dates fitted with access restrictions at the sites; at Pawlett, Wyvern Waste requested that cutting of grips should coincide with other earthworks on the site; at Otmoor cutting of grips needed to wait until after the bird breeding season.

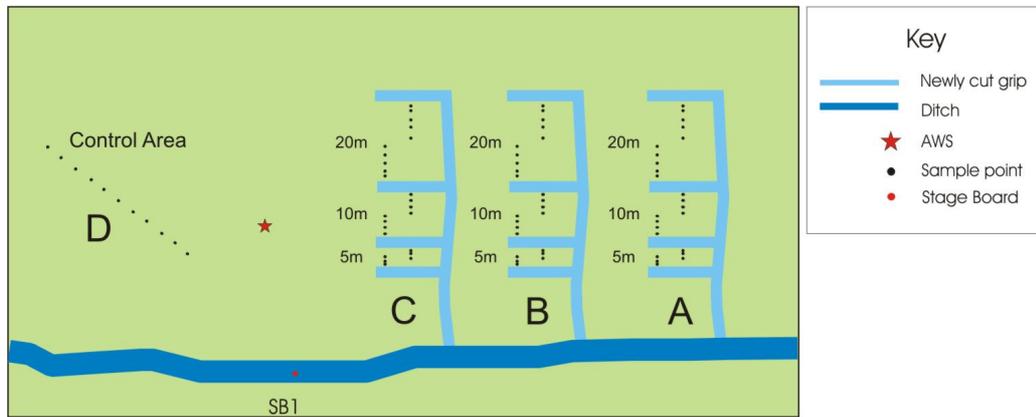


Figure 3.4 Generic experimental design

3.1 Otmoor

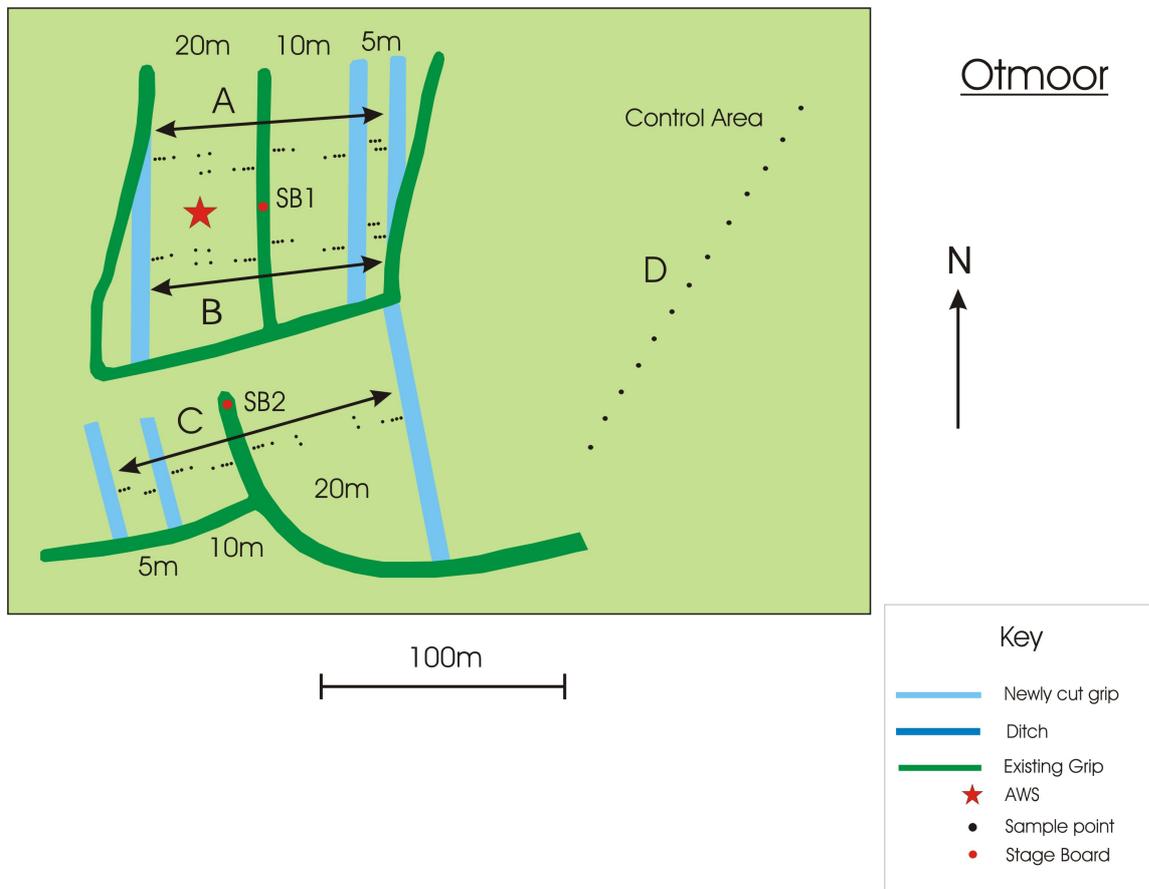


Figure 3.5 Otmoor. Grip and station layout

An ideal experimental design for the layout of grips and measurement stations was defined; this is shown in Fig. 3.4. Because of availability of land, existing grips, ditches and infrastructure, the actual layout varied slightly between sites. The layout of grips and measurement stations at Otmoor, Pawlett and Berney are shown in Figures 3.5, 3.6 and 3.7. Tables 3.1, 3.2 and 3.3 give details of the distribution of sampling stations at each site.

Table 3.1 Otmoor Sampling stations

Count of Station		Distance from grip (m)						
Grips spacing (m)	Block	1.1	1.5	2.5	5	10	Control	Total
5	A	2	2	2				6
	B	2	2	2				6
	C	2	2	2				6
5 m total		6	6	6				18
10	A	2	2	2	2			8
	B	2	2	2	2			8
	C	2	2	2	2			8
10 m total		6	6	6	6			24
20	A	2	2	2	2	4		12
	B	2	2	2	2	4		12
	C	2	2	2	2	4		12
20 m total		6	6	6	6	12		36
Control	D						13	13
Total		18	18	18	12	12	13	91

3.2 Pawlett

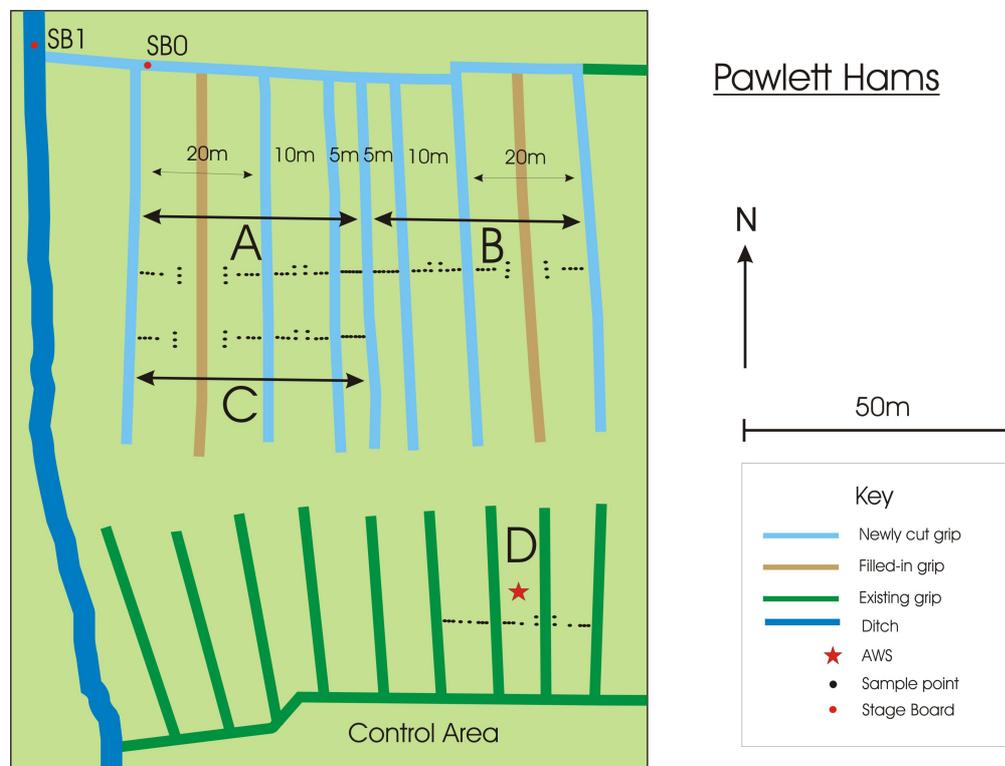


Figure 3.6 Pawlett. Grip and station layout

Table 3.2 Pawlett. Sampling stations

Count of Station		Distance from grip (m)					Control	Total
Grip spacing (m)	Block	1.1	1.5	2.5	5	10		
5	A	2	2	2			6	
	B	2	2	2			6	
	C	2	2	2			6	
5 m total		6	6	6			18	
10	A	2	2	2	4		10	
	B	2	2	2	4		10	
	C	2	2	2	4		10	
10 m total		6	6	6	12		30	
20	A	2	2	2	2	6	14	
	B	2	2	2	2	6	14	
	C	2	2	2	2	6	14	
20 m total		6	6	6	6	18	42	
Control	D						20	
Total		18	18	18	18	18	20	110

Some parts of the Pawlett site had existing grips, though these were very degraded. These historical grips were at 10 m spacing. This created an issue where a 20m spacing between grips was required. For the 20m spacings, sites were selected for the transects of measurement stations where the remnant grips were least apparent, ie most degraded. However, there were parts of 20 m spacing experimental plot, away from the measurement station transects, where remnant grips were evident. These were filled, compacted and re-sown. The soil moisture and water table data from the 20m spaced areas were examined in detail; they showed no sign of influence of the remnant grips.

3.3 Berney

Berney Marshes

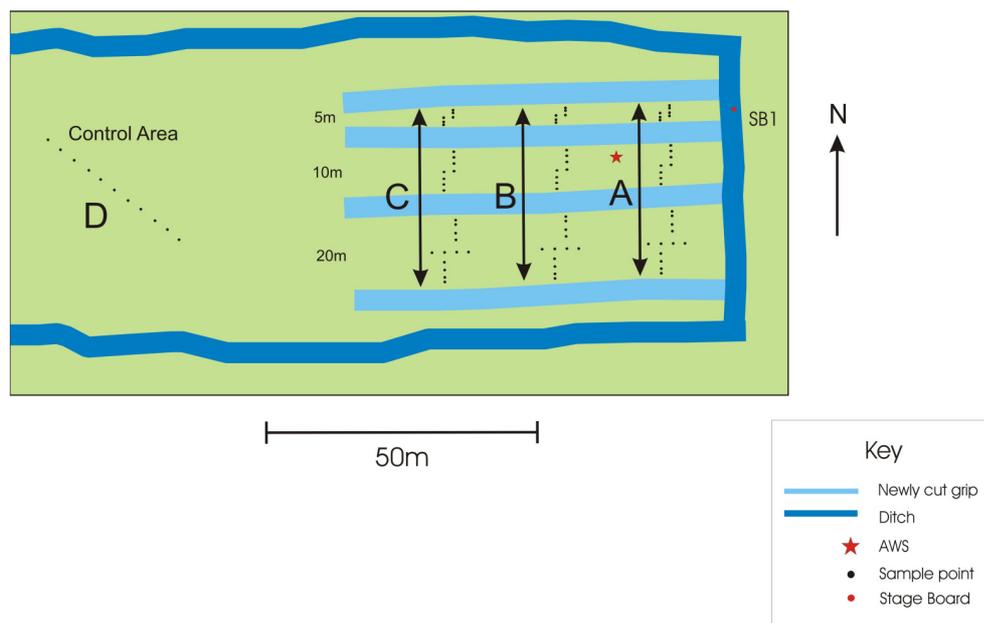


Figure 3.7 Berney Marshes. Grip and station layout

Table 3.3 Berney Marshes. Sampling stations

Count of Station		Distance from grip (m)						
Grip spacing (m)	Block	1.1	1.5	2.5	5	10	Control	Total
5	A	2	2	2				6
	B	2	2	2				6
	C	2	2	2				6
5 Total		6	6	6				18
10	A	2	2	2	2			8
	B	2	2	2	2			8
	C	2	2	2	2			8
10 Total		6	6	6	6			24
20	A	2	2	2	2	4		12
	B	2	2	2	2	4		12
	C	2	2	2	2	4		12
20 Total		6	6	6	6	12		36
Control	D						11	11
Total		18	18	18	12	12	11	89

Surface topography was an issue at all sites. At Otmoor, the treatment areas were down-slope of main site and so received runoff, compounding the water evacuation problem. At Berney, the experimental area was very slightly higher than the ditches (the fields being slightly dome-shaped), which avoided inundation of the site, but required high ditch water levels. At Pawlett, the area in which the experiment was sited was slightly higher than other land; this meant that maintaining high ditch water levels to keep the grips wet led to inundation of lower lying areas adjacent to the experiment.

The advantage of using the rotary ditching machine was that it was possible to produce grips at all sites with consistent dimensions. This meant that grip size and shape was excluded as a factor in the analysis. The width of each grip was 3 m and maximum depth 30 cm (Figure 3.8) with some variation along the length (25-35 cm). The basic shape is semi-circular, cut by the rotary machine and then with shelved edges, cut by the plough blades.

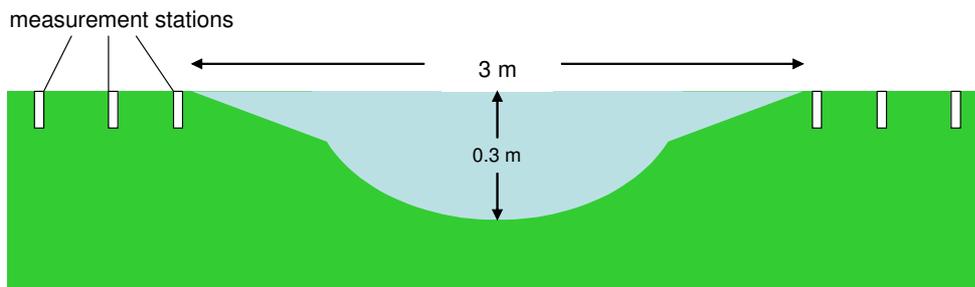


Figure 3.8 Cross-section of grip

4. Soil analysis

The structure of a soil determines its ability to retain and conduct water, its strength at any given water content and its aeration status. Soil structure is therefore central to the relationship between a site's water regime and its habitat quality. This aspect of the project set out to describe the structural properties of the soil at each of the three experimental sites and to investigate how moisture status related to both soil aeration status and to its strength. This was achieved through field observation, the construction of a soil-moisture release curve for undisturbed cores and from soil strength measurements made in the laboratory. As a secondary task, this group also investigated whether distance from grip affected vegetation productivity at any of the sites.

4.1 Methods

Soil description

Soil pits were dug at all three sites and the soil profile described in terms of its texture and structure. In addition, the single auger-hole method was used to assess hydraulic conductivity.

Soil sampling

The soils for soil moisture release characterisation were sampled using brass cores of 5 cm diameter and depth (i.e. total volume of 98 cm³). The soils were extracted in the field using a cutter and trowel in such a manner to avoid disturbing their structure. 15 replicate cores were taken for each site.

Soil cores for penetrometry measurements were collected from the field in large PVC cores of dimensions 19 cm diameter and 15 cm depth (i.e. total volume of 4,253 cm³). Three replicates were taken from each site.

Soil moisture release curve

Soil-moisture-release-characteristic curves were constructed by subjecting cores to stepwise increases in soil-water tension from 0 kPa to 1500 kPa (namely, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 100, 400, 1500 kPa).

Water tensions were achieved by subjecting saturated soil cores to set tensions on a sand suction table for tensions <10 kPa and on a pressure plate for tensions > 10 kPa. The cores were left on the sand suction table for 72 hours or until constant mass, while on the pressure plate device they were left for 160 hours to equilibrate fully. At each step the cores were weighed to measure the amount of water lost by drainage. The apparatus were air tight and kept at constant temperature to avoid evaporation. At the end of the measurements, each core was dried in the oven at 103°C for 48 hours to obtain its dry weight.

Bulk density

Soil bulk density was calculated from the weight of oven dried cores, as a ratio of the oven dry weight of soil to the volume of the soil core.

Air-filled porosity

Air-filled porosity (AFP) is the fraction of the total soil volume that is occupied by air. Total pore space (TPS) is the percentage of soil volume not occupied by solids. In moist soils, AFPS is obtained as the difference between TPS and the volumetric water content (V). (Ball and Smith, 2001)

$$AFP = TPS - V$$

This assumes the soils do not shrink significantly. However, for soils that do shrink during drying, loss of volume needs to be accounted for.

Shrinking

Change in soil volume i.e. shrinkage when progressing from saturated to drying tensions was made as follows. Four white dots were placed on the soil cores, after saturating the cores with water. Then the distance of the dots from the edge of the surrounding metal ring and from the top of the ring were measured using a digital calliper (sensitive to $\pm 0.001\text{mm}$). The change in the distance of the dots from the edge and top (i.e. as a result of shrinking during drying) was used to calculate the change in volume. This was then used to correct calculations for air-filled pore space.

Biomass

Biomass was harvested in the area between grips using 50×100 cm quadrats, with 3 replicates per treatment. The vegetation was clipped to 2 cm above ground level. The harvested biomass was immediately weighed in the field to obtain a fresh weight, then a sub-sample was then taken to the laboratory, where it was dried at 60°C for 72 hours to determine dry weight. The fresh weight was then corrected using this factor to give a dry weight yield.

Penetrometry on soil cores

Soil cores were subjected to pre-set tensions by placing them on a sand table. The achieved soil water tension was verified using micro-tensiometers (type SWT5, Delta-T[®] Devices Ltd, Cambridge, UK) placed inside the cores.

Once the desired tension was achieved, penetration resistance and soil shear strength were measured using a ‘‘Pocket Penetrometer’’ (model CL-700A, Soiltest Inc.[®] IL, US) and a fall-cone penetrometer (Rothamsted Research, Harpenden) respectively.

Penetration resistance was measured by depressing the pocket penetrometer to depth of 5 cm in the soil core and reading the penetration resistance directly (kg cm^{-2}). A minimum of 5 samplings per core were made at each level of water tension.

For the fall-cone penetrometer, the distance a standard cone (of known weight and angle) dropped in the soil core (measured to ± 0.1 mm) was used to calculate shear strength (Watts *et al.*, 2003). A minimum of 10 replicate drops per core were made on each core at each water tension.

Analysis of field penetrometry results

In the field the soil tension at the surface depends on the boundary conditions imposed by the surface evaporation and rainfall rates and the depth of the water table. In the steady state, the tension at the soil surface can be obtained from the formula

$$T = z - \frac{1}{c} \ln \left[1 + \frac{V}{K} (1 - e^{cz}) \right] \quad (1)$$

where T is the soil-water tension at a height z above the water table, c is a parameter of the soil dependent on the rate of change in hydraulic conductivity as the soil dries, K the hydraulic conductivity of the saturated soil and V the vertical flux through the soil given by the

evaporation rate minus the rainfall rate. The evaporation rate is the potential evaporation rate if the water-table depth is less than the critical depth when the evaporation rate is limited by the soil. When limited by rate of capillary rise through the soil, the vertical flux V is given by

$$V = \frac{K}{e^{cz} - 1} \quad (2)$$

Equation (1) shows that for shallow water tables the tension T is equivalent to the water table depth in the static situation when $V = 0$.

While the steady state formula [eq.(1)] may give a good approximation to the tension if the rainfall and evaporation rates remain steady over a period of time, generally the surface tension depends on current changes of surface conditions. During rainfall, the moisture tension at the soil surface will decrease with a corresponding decrease in the soil's strength, whereas during intense evaporation, the soil's moisture tension at its surface will increase, giving an increased soil strength.

To account for this potential source of variation, we used meteorological data collected on site to calculate the soil moisture tension at the soil surface for each of the dates on which field penetrometer data were gathered. The measurements were taken in early afternoon and therefore the evapotranspiration calculated at 14:00 was used in the calculation.

4.2 Results

Soil structural appearance and hydraulic conductivity

Pawlett Hams: The soil structure was well developed with fine crumb structure to at least 400 mm depth and a hydraulic conductivity in the order of over 0.3 m per day. This permitted rapid lateral water movement between the grips and intervening land blocks, making grips an effective management tool. The good soil structure is likely to be a product of good drainage and long-term management under grass.

Otmoor: The soil structure was large blocky to massive; hydraulic conductivity is less than 0.1 m per day. This severely limits hydrological interaction between the grips and land blocks and thus the effectiveness of the grips. This is likely due to the impact of the recent reprofiling of a clay-rich soil, resulting in some compaction and loss of structure. The low humic content (estimated by colour) and the liability to surface water-logging is likely to retard soil structure re-developing. Sub-soiling or mole drains would assist water management on such soils. Indeed a sub-soil plough had been used at Otmoor to break-up the compacted soil structure. Some areas of Otmoor had reputed been mole drained, but we believe that the experimental block chosen had not undergone drainage. However, the large tractors required may have the unfortunate side effect of increasing soil compaction. The need to consider was discussed at the workshop and mentioned in the guidance.

Berney marshes: The soil structure was well developed to depth, being crumb structured to fine blocky. The humus content was very high (estimated by eye). The reasonable standard of drainage and long term grassland would have assisted and maintained the good structure and high permeability of the soil in spite of its fine texture.

At Berney, the structure was extremely well developed with hydraulic conductivity up to 1.7 m per day. These results demonstrate that the sites selected, whilst all on fine-textured mineral soils, represent the broad range of hydrological conditions that can be expected for clay soils.

Table 4.1. Soil characteristics at the three sites

site	Soil series	type	Particular size	definition	pH	Olsen P mg/kg	K mg/kg
Pawlett Ham	Newchurch series	Marine alluvium	50% clay, 49 % silt & 1% fine sand	silty-clay soil	7.7	1	260
Otmoor	Fladbury series	River alluvium	58% clay, 34 % silt & 9% fine sand	Shrinking clay	7.5	4	160
Berney marshes	Wallasea series	Marine alluvium	48% clay, 50 % silt & 2% fine sand	silty-clay soil	7.5	31	320

Soil moisture release curve

Figure 4.1 shows the results over the tension range 1-10 kPa

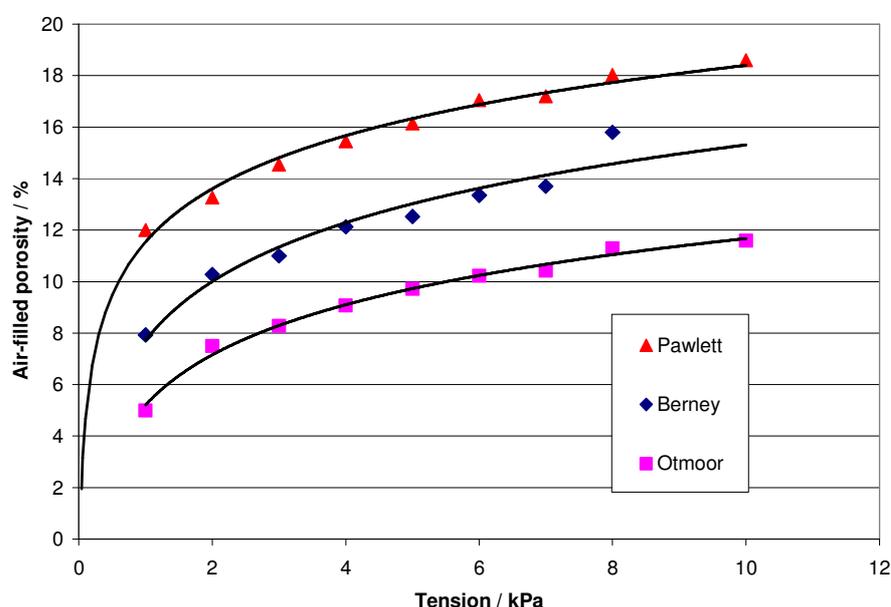


Fig 4.1. Air-filled porosity in 3 soils as a function of soil moisture tension.

The critical value of air-filled porosity is taken as the volume required for relatively free diffusion of oxygen in the gaseous phase. This is generally taken to be 10% of the soil volume (Taylor, 1952). Therefore, using the graph above (Figure 4.1), we are able to estimate the minimum soil moisture tension necessary to achieve this value in the surface layer of soil (Table 4.2). To achieve 10% air-filled porosity to a depth of 5 cm the tension at 5 cm depth needs to exceed this minimum value.

Table 4.2. Water-table depths required to aerate the surface layer of soil.

Site	Tension required for 10% AFP / kPa	Water table depth required to aerate top 5 cm of profile (assuming zero flux) / cm
Berney	1.9.	24
Otmoor	5.6	61
Pawlett	0.8	13

These values can then be used as threshold to interpret the soil hydrograph, thereby estimating the degree of aeration stress experienced by living organisms in the surface layer of soil. Notice the four-fold variation in threshold depth, which reinforces the need for soil specific management. A generalised threshold depth is not useful.

Bulk Density

Mean values for each site are shown in Table 4.3. The value for Berney is very low reflecting the very high organic matter content and well developed structure of the soil's A-horizon.

Table 4.3 Bulk density of soils by site.

Site	Bulk density (g cm^{-3})
Berney	0.79
Otmoor	1.15
Pawlett	1.07

Penetrometry on soil cores

Tension tables designed to control the moisture status of large cores proved successful as evidenced by the tensiometers monitoring moisture tension within the core. Figure 4.2 shows the response of a core to a rise in water table in the form of an output trace from a tensionmeter embedded within it.

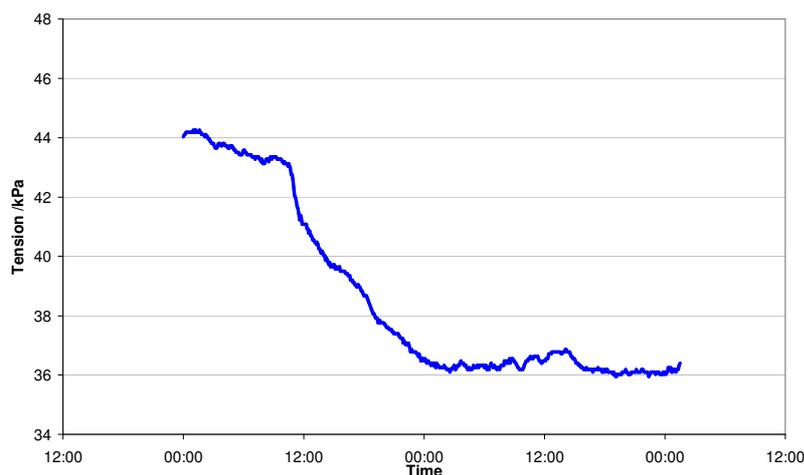


Figure 4.2. Soil moisture tension over a 2 day period, showing the timescale of response to a 10 cm rise in water table (45 cm to 35 cm depth.) the change occurred at 12:00 on the first day. The soil core was 19 cm in diameter and 15 cm in height, taken from Pawlett Ham.

Under controlled laboratory conditions, the shear-strength of the soil was measured by the falling-cone technique (Watts et al., 2003). The results are presented in Figure 4.3 It can be seen that Pawlett showed the greatest response to soil drying using this method.

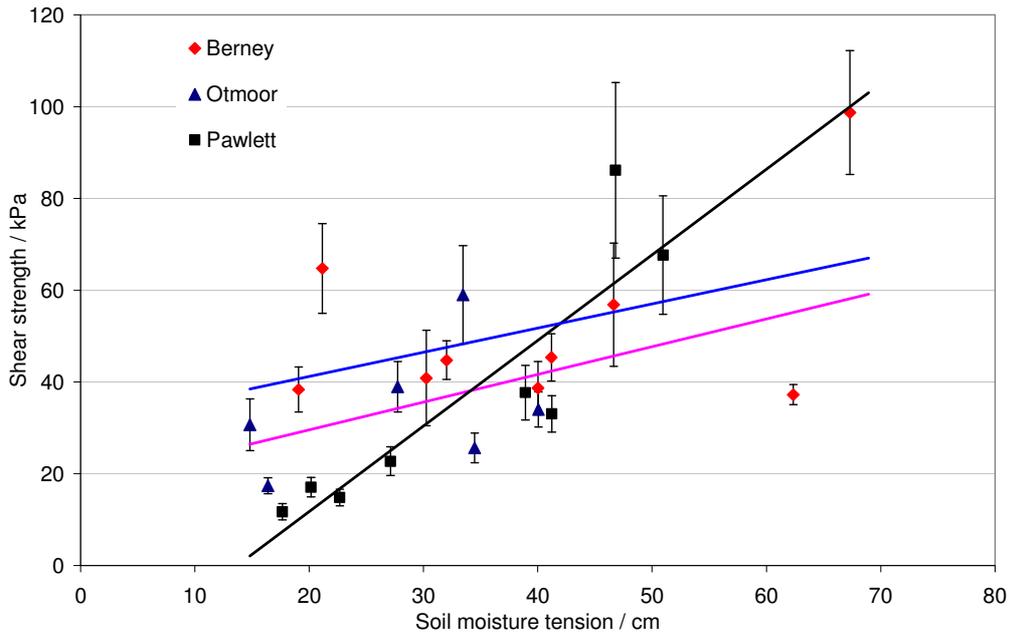


Figure 4.3. Soil shear strength, measured by the falling cone technique, as a function of soil moisture tension. Points are the mean of 10 measurements and error bars show the standard error of the mean. r^2 values are Pawlett 0.79, Berney 0.20, Otmoor 0.19.

To compare these responses to those commonly measured in the field we used the Pocket Penetrometer, as routinely used by site managers to assess suitability of areas for breeding waders. The same cores were measured over the same range on tensions (Figure 4.4.)

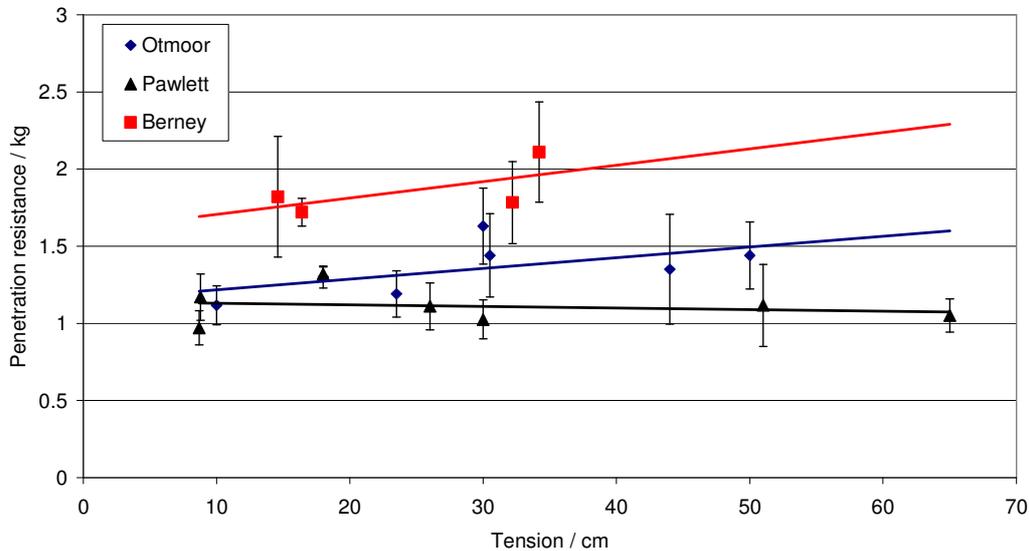


Figure 4.4 . Soil shear strength, measured by the Pocket Penetrometer, as a function of soil moisture tension. Points are the mean of 10 measurements and error bars show the standard error of the mean.

It is notable that the shear strength of the soil from Pawlett now shows the least response to increasing soil moisture tension. This illustrates the effect of measurement technique on the results. It appears that the high porosity of the silt soil (Figure 1) means that it offers little resistance to the penetrometer needle over a range of tensions, whilst it does offer increasing resistance to the much larger cone.

If we compare the two sets of data on a single graph using the same units for strength (Figure 4.5), we see the penetrometer is giving higher strength estimates than the falling cone.

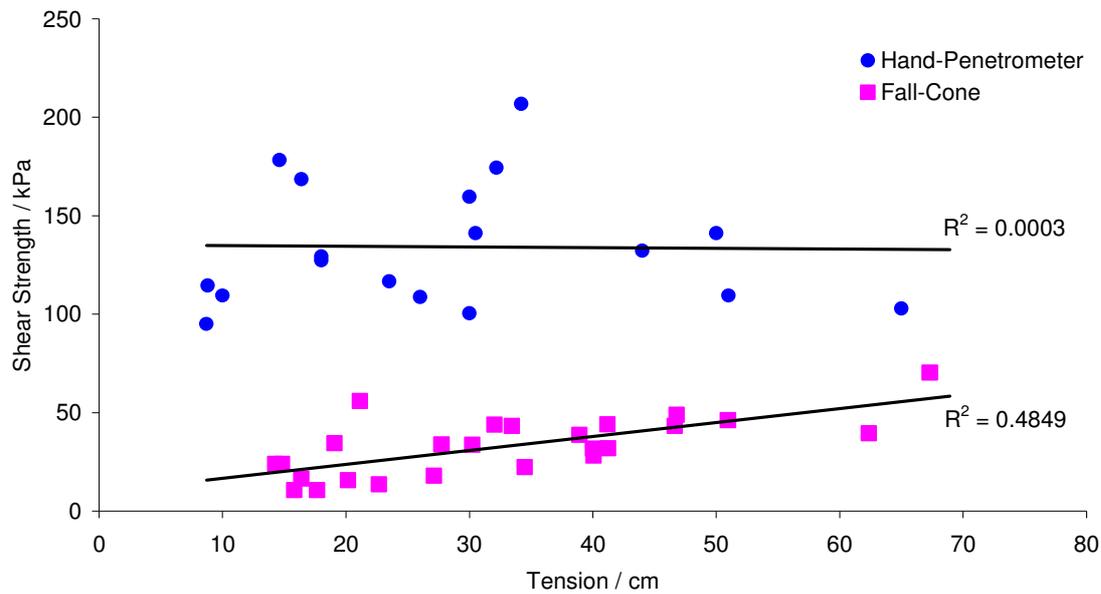


Figure 4.5. Comparison of soil strength estimates derived from both the falling cone and the Pocket Penetrometer. Linear regressions have been fitted through the pooled set of results for each instrument.

This can perhaps be explained by the lower sensitivity of the hand-held Penetrometer. The falling cone produces the expected result with strength increasing with moisture tension across soil types (Whalley *et al.*, 2002).

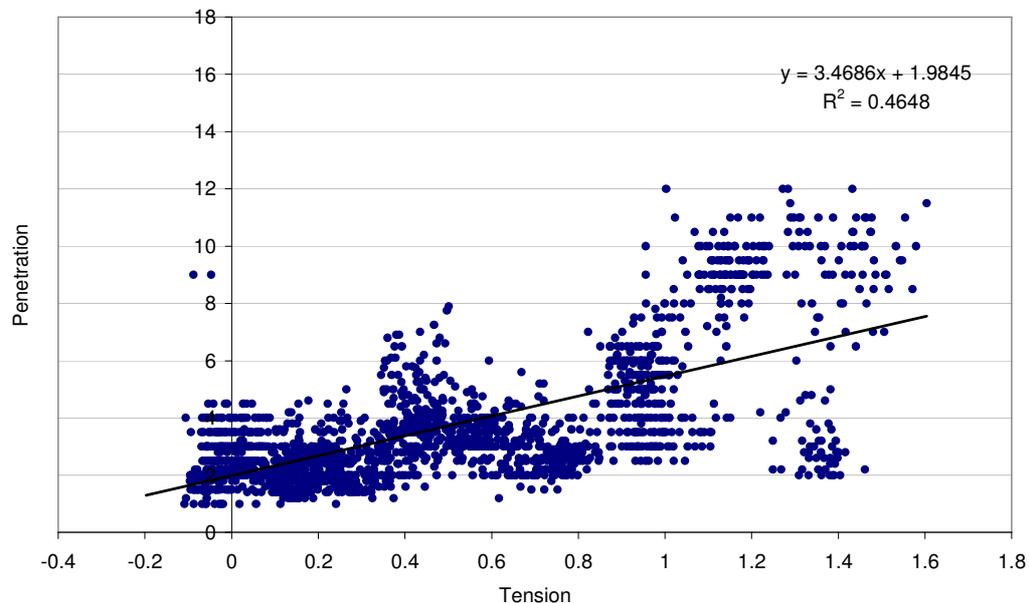


Figure 4.6. The measured penetration resistance at Pawlett Hams (taken on multiple dates) plotted against an estimate of the moisture tension at the soil surface (based on water-table depth and evapotranspiration rate at the precise time the measurement was made (using Richards' equation; Richards, 1931)).

Penetrometry in the field

The penetrometer data collected from the field was analysed with respect to the water table depth. The correlation between the two variables was found to be significant, but the proportion of variation explained was just 31% at Pawlett Hams. However, if the flux (evaporation) on the day of the measurement is taken into account and an estimate of soil moisture tension at the ground surface is made, then the percentage of explained variation rises to 46% (Figure 4.6)

5. Hydrological instrumentation, surveys and analysis

5.1 Installation

Sets of dipwells and soil moisture probe access tubes were installed at Pawlett and Otmoor on the two main sites during the winter of 2003/4 to allow baseline pre-gripping data to be collected. At Berney, only dipwells were installed. Automatic weather stations were installed on Pawlett and Otmoor in July 2004 and October 2004 at Berney.

5.2 Hydrological monitoring

The overall hydrological monitoring period for this project was spring 2004 to winter 2007. At Otmoor and Pawlett Hams, hydrological monitoring was carried out by CEH staff at fortnightly intervals for the 8 weeks before invertebrate monitoring. At other times monitoring was undertaken at monthly intervals. In order to minimise travel costs, monitoring at Berney Marshes was carried out by a combination of CEH staff and University of East Anglia environmental science department. Meteorological measurements were made continuously (see Table 5.1). The most intensive hydrological monitoring was during the two critical periods, over wintering and breeding seasons (Figure 5.2). Water table elevation, surface soil moisture, soil penetrability, vegetation height and grip and ditch water levels were measured on each occasion at each site project. Penetrability of the soil is defined as the force (kg) required to insert a No. 6 knitting needle (representing a bird's beak) into the soil. Vegetation height was measured with a drop disc.

All measurement stations were fenced to prevent cattle damaging the dipwells and soil moisture access tubes. The fencing meant that these areas were not subject to any trampling that might occur when the site was stocked, which may have an impact on water-table depths, soil moisture and evaporation. However, stocking generally took place from July to September and vegetation within the fenced areas was cut with a strimmer when the site was stocked to maintain the same vegetation height. Consequently, the impact was considered minor.

5.3 Summary meteorological results

Automatic weather station data along with Met Office Rainfall and Evaporation Calculation System (MORECS) data for each site are shown in Table 5.1. Soil temperature measurement commenced in Spring 2005 and the previously identified logistical problems at Berney mean that the data set is incomplete. Table 5.1 shows that between winter 2004 and winter 2006 rainfall at all sites was generally below average whilst spring 2006 and winter 2007 had above average rainfall. Temperatures over the study period were generally above average.

Table 5.1 Summary meteorological data for each site. The percentage deviation from long term seasonal averages are shown. Green shading indicates greater than average and yellow indicates less than average.

		Long Term Average		Percentage difference from long term average							
				2004		2005		2006		2007	
		Winter	Spring	Winter	Spring	Winter	Spring	Winter	Spring	Winter	
Berney	Rainfall	145 mm	133 mm	34.4	-16.4	-18.1	14.8	-24.1	18.6	25.9	
	Air Temperature	4.1 °C	8.0 °C			-3.7			46.3		
Otmoor	Rainfall	170 mm	159 mm	-23.1	-4.1	-54.1	-15.0	-33.6	20.4	34.2	
	Air Temperature	3.7 °C	8.2 °C			36.5	2.9	-1.8	5.3	-6.0	
Pawlett	Rainfall	236 mm	175 mm	9.9	-16.1	-33.6	-8.4	-32.9	10.5	28.0	
	Air Temperature	4.6 °C	8.4 °C			42.6	7.5	6.3	10.0	73.3	

5.4 Summary of water availability conditions

Pawlett

The grazing marsh at Pawlett receives around 725 mm of rain per year, but has a very small catchment draining to it because of its general location and configuration of ditches in the surrounding area. In addition, the soils are well structured and free-draining. The biggest challenge at the site is the limited availability of water to maintain ditch and grip levels, especially in low rainfall years. A main ditch surrounds the site and is equipped with a tilting weir, such that water levels could be maintained at any desired level. Historically, water has been imported to the site via a pipe under the River Parrett from the Cannington Brook. There was insufficient water during the project to maintain target water levels at all times, although an experimentally useful range of water levels was achieved.

Otmoor

Otmoor lies in a bowl shaped depression in the landscape with a catchment area (up the River Ray) of around 230 km² draining to it and rainfall of approximately 620 mm. Excess water from the site is pumped into a ring ditch that surrounds Otmoor. The ring ditch flows through agricultural land before rejoining the River Ray. The capacity of the ditch is low due to its shallow gradient and too much pumping resulted in inundation of the land downstream. There is an agreement that when the ditch is high, pumping stops, which most often occurs after heavy rainfall when water needs to be evacuated. During the project, the site was often too wet because pumping had not been permitted.

Berney

Although the Berney site has the lowest average annual rainfall (around 600 mm) of the three sites, it was overall the easiest to manage hydrologically. The soils are well structured and allow water to permeate horizontally quite readily. Water supply to maintain levels in the ditches surrounding the site was not a problem during the project due to the large catchment area and excess water could readily be evacuated.

5.5 Water table profiles and soil moisture

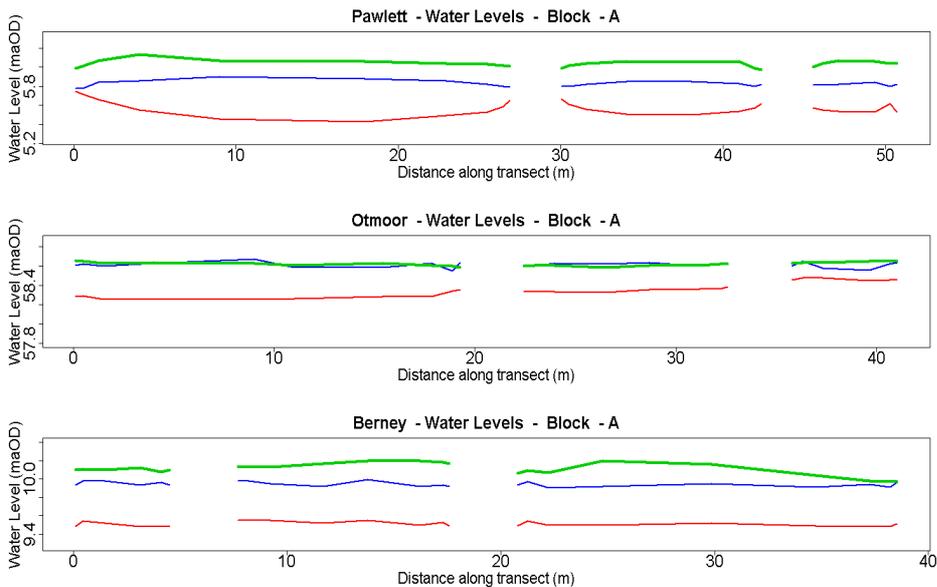


Figure 5.1 Example water table profiles for Pawlett, Otmoor and Berney, showing winter/draining (blue) and spring/irrigating (red) profiles, with ground surface (green).

Water table profiles

Fig. 5.1 shows the typical hydrological response to spring and winter conditions. The permeable soils at Pawlett give rise to a distinct dome or bowl shape depending on whether the grips are irrigating (*i.e.* high water level in the grip feeding water into the lower water table in the soil) or draining (high water level in the field draining into the grip). At Pawlett, the water-table elevation is therefore related to the distance from the grip. The impermeable soils at Otmoor give a much flatter water table profile and only in the 5m grip spacing is there evidence of the grips creating a water table gradient. This raises the question over whether the standard concept of a water table is so appropriate for such impermeable soils, where there is less distinction between the saturated and unsaturated zones. At Berney, the very permeable soils allow rapid lateral movement of water and thus there is little potential for a hydraulic gradient to develop.

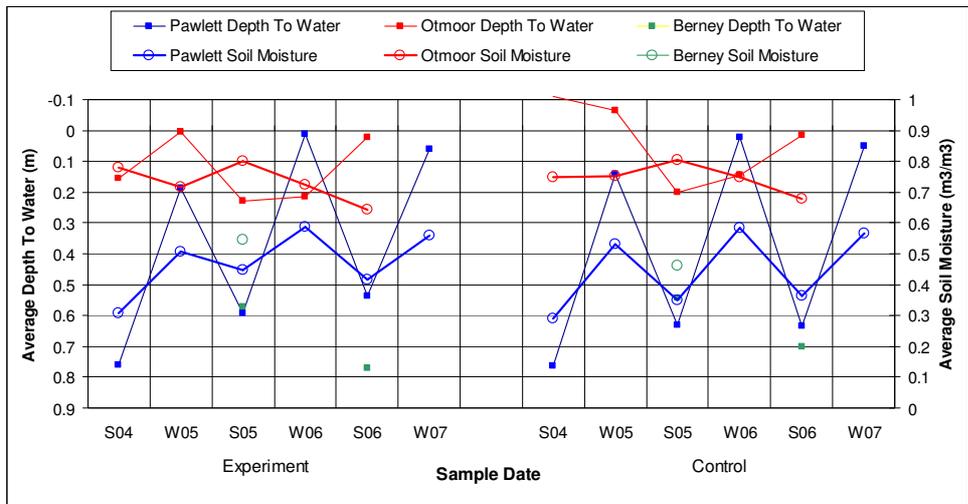


Figure 5.2 Mean depth to water-table in each invertebrate sample season at each site

Fig. 5.2 shows mean depth to water-table in each invertebrate sampling season. At Pawlett winter conditions were similar for the control and treatment area both before and after grip installation whereas in spring the treatment area was wetter. At Otmoor, the treatment was drier than the control in winter. In spring, the conditions in the treatment and control were similar with the exception of 2004, when the control area was flooded. At Berney, it is not possible to identify a trend between the control and treatment areas, but overall 2006 was drier than 2005.

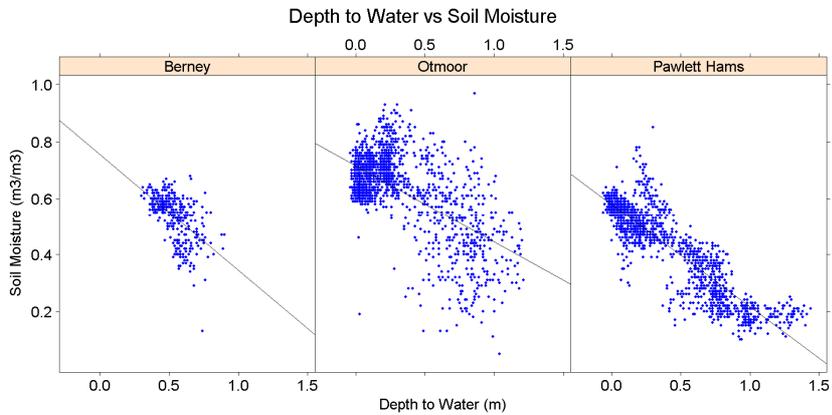


Figure 5.3 Relationships between soil moisture and depth to water table at each site. The straight line was produced by linear regression.

B 0.4 -0.5m O 0.6 -0.8 0.2-0.3

Soil moisture

Fig. 5.3 shows the relationship between soil moisture content at 10 cm depth and depth to water table for each site for the entire dataset. Otmoor has higher moisture content values than Pawlett for the same range of depths to water table. The soil moisture content of the soil is controlled by the water-table elevation and the rainfall and evaporation. The moisture content is also affected by the soil type and clay soils are better at retaining moisture as the water table drops than silty/sandy soils. In Fig. 5.3, the Pawlett data show less scatter than Otmoor, which is again due to the greater capacity of the soils at Otmoor to retain water. By contrast, the moisture content of the Pawlett soils is more closely related to the water-table elevation and the relationship between the two is therefore more clearly defined. Both sites show some saturation at the high and low ends of the data range, where the soil moisture content becomes insensitive to the depth to water (*i.e.* as the water table approaches the surface, the moisture content will be at or close to saturation, or when the water table drops below the depth at which it influences the near surface soil moisture). Fewer data were available for Berney (especially at the extremes), but they generally show that a similar pattern exists in the mid-range of the data set.

5.6 Variations in water table and soil moisture with grip characteristics

General Linear Model ANOVA, using Type III sums of squares, was used to analyse differences in hydrological variables in treatments and controls in response to the main effects (Date, Block, Spacing and Distance from grip) and interaction of effects (Date * Spacing, Date * Distance from grip, Distance from grip * Spacing). Before the ANOVA model was run, the degree to which the data sets follow a normal distribution was inspected. In most cases, there was limited departure from normal distribution. Some of the hydrological data were bimodal (*i.e.* strong differences between winter and spring/summer) for which no simple correction was available. Consequently the data were not transformed.

For each site, the summary of the ANOVA are presented (Tables 5.2 to 5.4) The most important relationships are shown in the text as whisker plots (Figs 5.4, 5.7, 5.8, 5.11 and 5.12) where: solid dot = median; box = 25th and 75th percentiles; dashed lines = 1.5 x interquartile range; open circles = outliers (> 1.5 x interquartile range). A simple statement was made describing the strongest relationships found by the ANOVA model.

Principal components analysis was undertaken on the data from each of the three sites; the results are shown in Figures 5.6, 5.10 and 5.14 for Otmoor, Pawlett and Berney respectively.

5.6.1 Otmoor

The pre-gripping data cover a period of 6 months whereas the post gripping data cover a period of 30 months. Pre-gripping, the control had a greater range of water levels than the experiment area. This was largely due to the hydrological management of the site. Once the grips were installed a revised water management regime was agreed with the site owners (RSPB) to allow experimental plot and control to act more naturally and thus be more consistent. This meant that the difference between the plots was due to the grips and not other factors.

The control had higher water-table levels than the treatment areas in winter and spring (particularly before installation of the new grips) as the grips were largely acting as drains; the control was often flooded during winter (sometimes to 150 mm) whilst in the treatment area, inundation was restricted by the grips to splash flooding (less than 10 mm).

Table 5.2. Otmoor. Summary of ANOVA test of effects and interactions of hydrological variables. Blocks A, B and C are treatments and Block D is control. ‘’ indicates $p < 0.01$ (highly significant relationship), ‘*’ indicates $p < 0.05$ (significant relationship) and ‘ns’ indicates no significant relationship.**

Variables	Date	Block	Spacing	Distance from grip
Depth to water	**Spring>Winter	*D>A,B,C	**D>5,10,20	**D>any other distances
Soil Moisture (5cm)	**Spring>Winter	*D>A,B,C	Ns	ns
Soil Moisture (10cm)	**Spring>Winter	ns	Ns	ns
Vegetation Height	**Spring>Winter	*B>C,D	Ns	ns
Soil Penetrability	**Winter>Spring	ns	Ns	ns

Variables	Date * Spacing	Date * Distance from grip	Distance from grip * Spacing
Depth to water	Winter: D>10,20,5**; 10>5* Spring: D>20, 5*	*Winter:D>any other distances Spring:ns	ns
Soil Moisture (5cm)	Ns	Ns	ns
Soil Moisture (10cm)	Ns	Ns	ns
Vegetation Height	Ns	Ns	ns
Soil Penetrability	Ns	Ns	ns

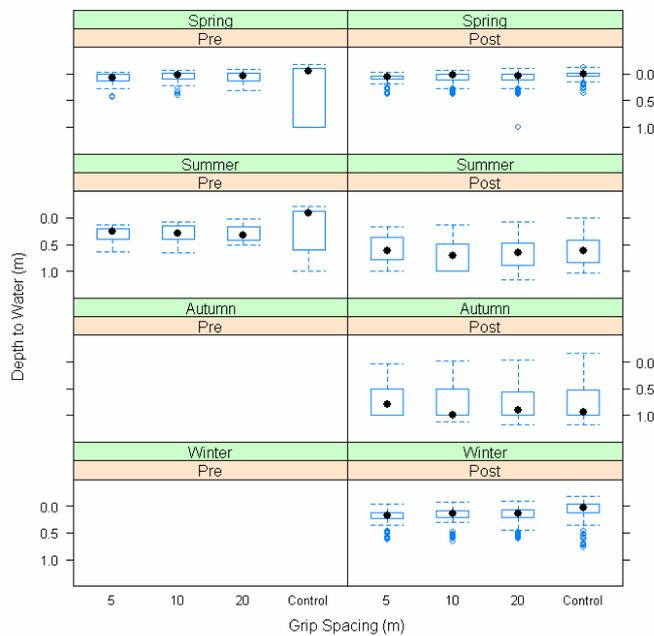


Fig.5.4 Depth to groundwater table for each grip spacing and control at Otmoor.

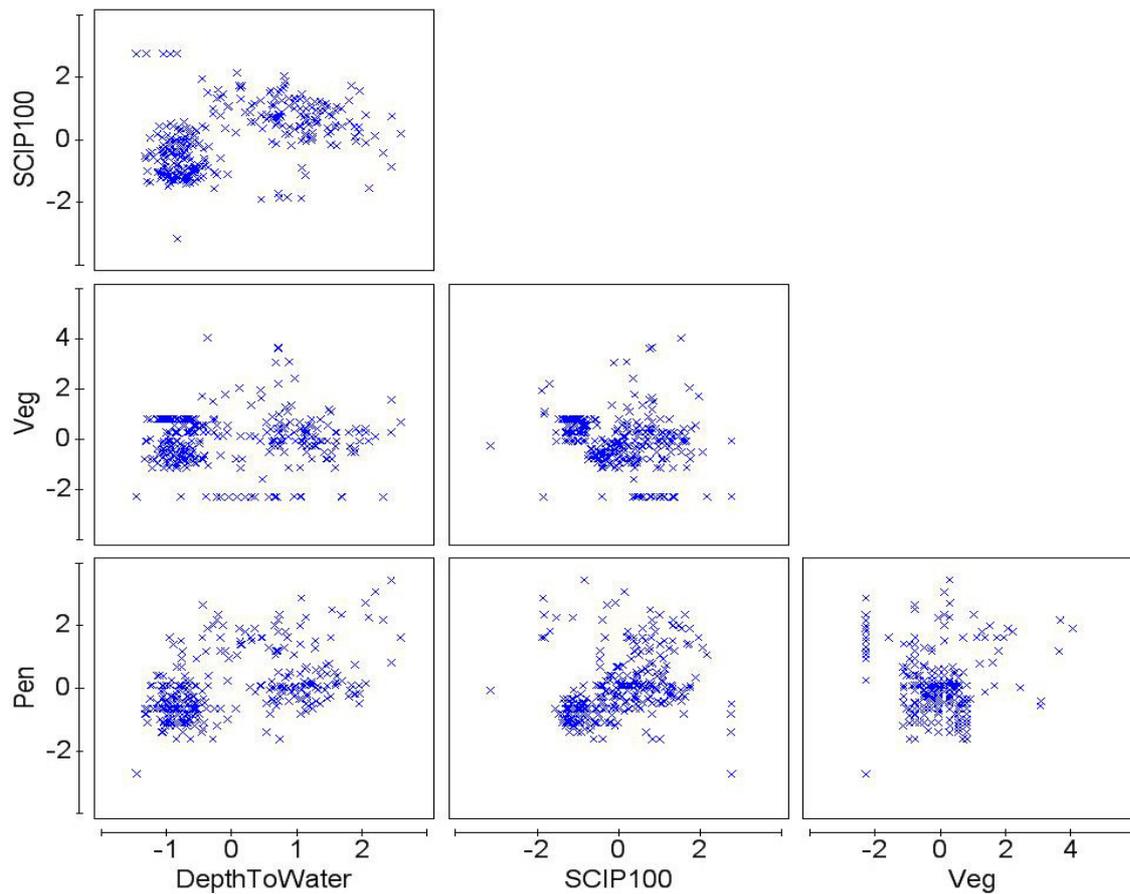
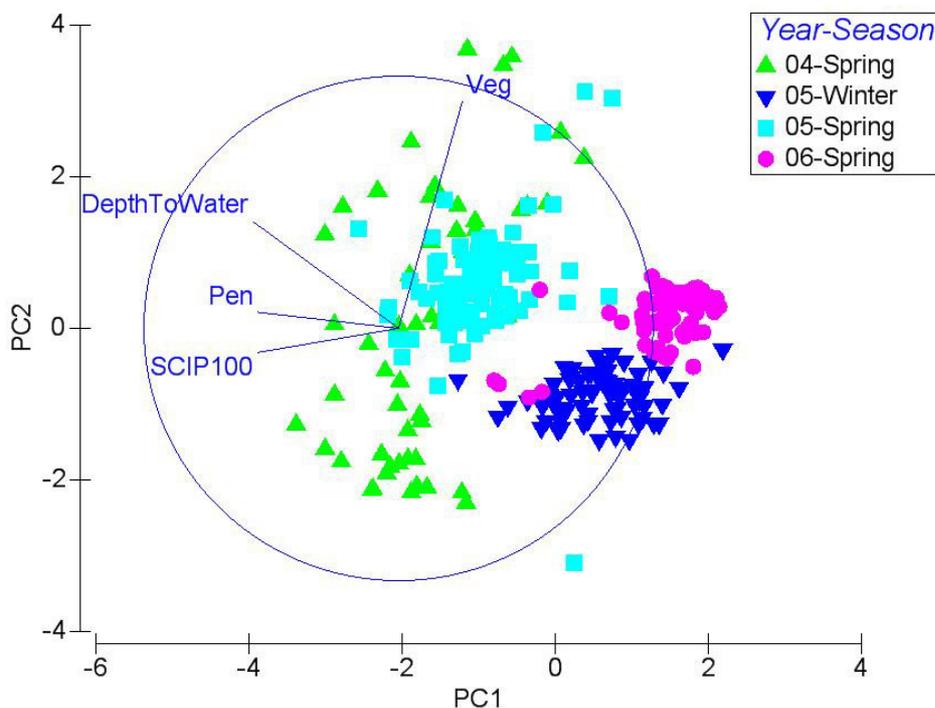


Figure 5.5. Biplots of environmental variables showing the pairwise variation between them at Otmoor site.



Figures 5.6. Principal component analysis summarizing the four environmental variables including depth to water, SCIP 100, penetration and vegetation at 626 study spots at Otmoor.

Key conclusions

- Water-table levels were higher in the winter and spring than in summer and autumn (Fig. 5.4), partly due to site management policy and partly to meteorological conditions during the project.
- The control had higher water-table levels than the treatment areas in winter and spring (particularly before installation of the new grips) as the grips were largely acting as drains; the control was often flooded during winter (sometimes to 150 mm) whilst in the treatment area, inundation was restricted by the grips to splash flooding (less than 10 mm).
- There was no significant hydrological difference between the treatment blocks, the spacings of monitoring stations or distances between grips.
- Penetrability was higher in winter than spring.
- Vegetation was taller during the spring than the winter, and slightly taller in block B, but there was no significant relationship between vegetation height and distance from grip.

5.6.2 Pawlett

Table 5.3. Pawlett. Summary of ANOVA test of effects and interactions of hydrological variables. Blocks A, B and C are treatments and Block D is control. ‘*’ indicates $p < 0.01$ (highly significant relationship), ‘*’ indicates $p < 0.05$ (significant relationship) and ‘ns’ indicates no significant relationship.**

Variables	Date	Block	Spacing	Dist-grips
Depth to water	**Winter>Spring	**A,B>D,C	*5,10,20>C	**1.1>2.5,5,10,D; 1.5>5,10,D; 2.5>D
Soil Moisture (5cm)	**Spring>Winter	ns	Ns	Ns
Soil Moisture (10cm)	**Winter>Spring	**B>A,C,D	Ns	**1.1>2.5,10,5,D; 1.5>5,D
Vegetation Height	**Spring>Winter	**	Ns	*D>1.1,1.5
Soil Penetrability	**Winter>Spring	**	**	*1.1>5

Variables	Date * Spacing	Date * Distgrips	Distgrips * Spacing
Depth to water	Ns	Winter:ns Spring:1.1>2.5,5,10,D; 1.5>5,10,D; 2.5>D**	ns
Soil Moisture (5cm)	Ns	ns	ns
Soil Moisture (10cm)	Ns	Winter:1.1>5,2.5* Spring: 1.1>1.5,2.5,5,10,D**; 1.5>2.5,5,10,D*	ns
Vegetation Height	Ns	Winter: D>1.1,1.5**; D>10,2.5,5* Spring: D>1.1,1.5**	ns
Soil Penetrability	Ns	ns	ns

Before the new grips were installed, water-table levels were lower in the treatment area (5, 10, 20 m spacings) than in the control (Fig. 5.7) due to control being slightly lower elevation. Major engineering works were undertaken on the site at the same time as the gripping to allow more control of water levels in different areas, including a tilting weir on the main feeder ditch. Following gripping, water-table levels were slightly higher in the treatment area because the grips were mainly irrigating the experimental plot.

Key conclusions

- Before the new grips were installed, water-table levels were lower in the treatment area (5, 10, 20 m spacings) than in the control (Fig. 5.7). Following gripping, water-table levels were higher in the treatment area; thus the grips were mainly irrigating.
- Water-table levels and soil moisture (SCIP 100 mm) showed a downward gradient away from the grips (highest at 1.1 m distance) in spring showing diminishing effect with

distance confirming the irrigation role of the grips (Fig. 5.8). The same effect was evident in water-table levels in winter, but was weaker for soil moisture.

- There was some variation between blocks, with soil moisture (SCIP 100 mm) highest in block B.
- Penetrability was higher in 1.1 than 5 m distance from grip.
- Vegetation was taller in the spring than in the winter but shorter near to the grips (1.1 and 1.5 m distance) than the control

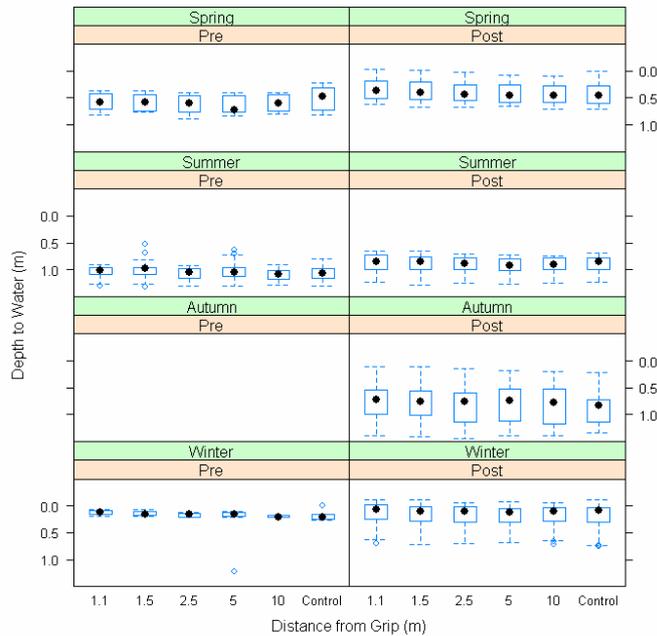


Figure 5.7 Variations in depth to water table with distance from grip and control at Pawlett.

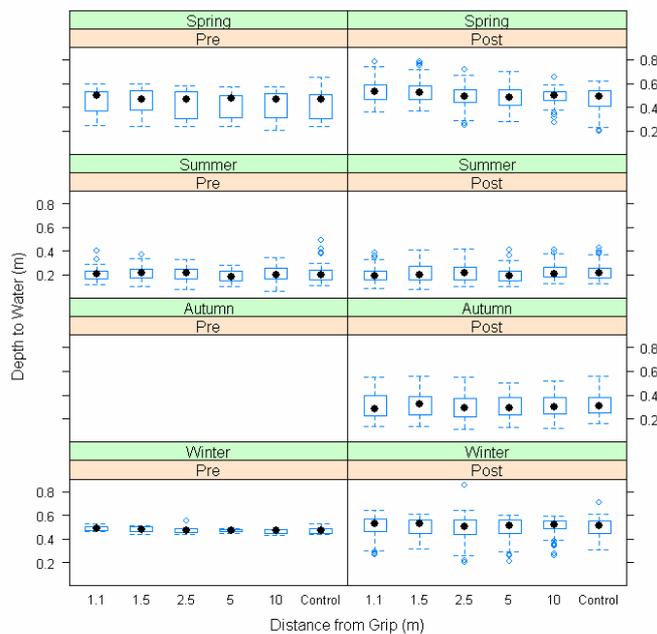


Figure 5.8 Variations in soil moisture with distance from grip and control at Pawlett.

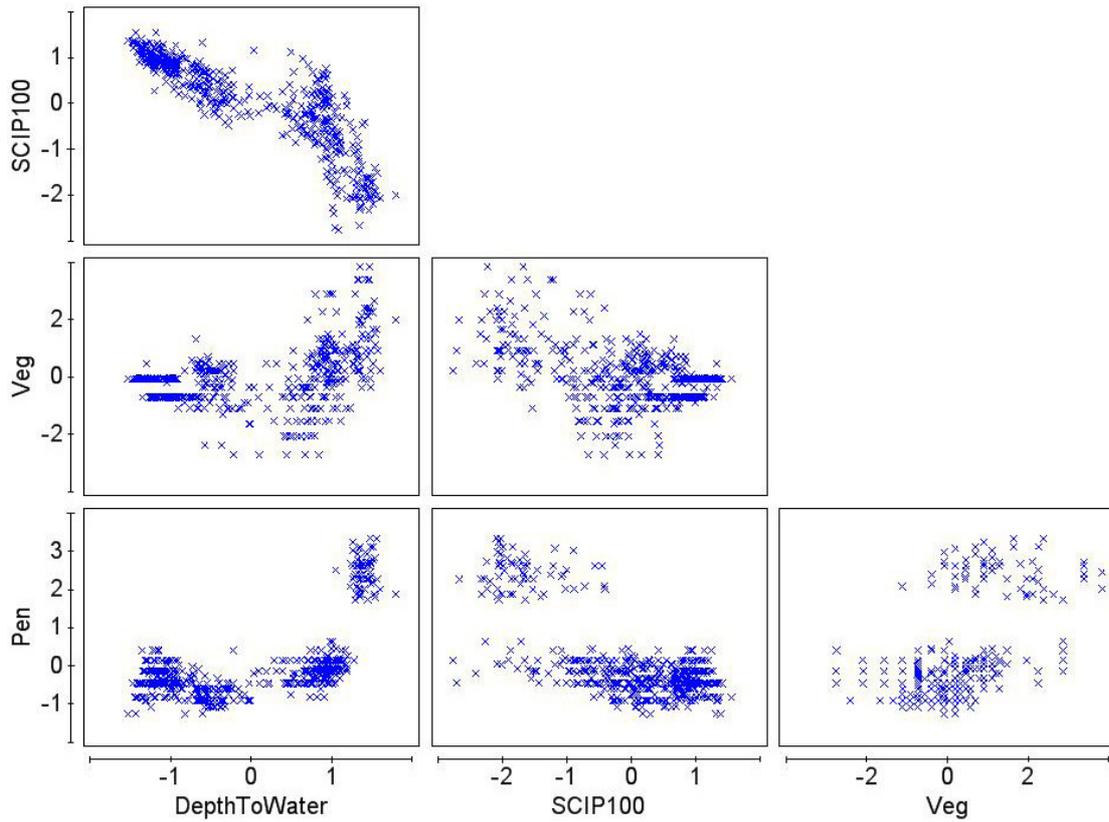


Figure 5.9. Biplots of environmental variables showing the pairwise variation between them at Pawlett.

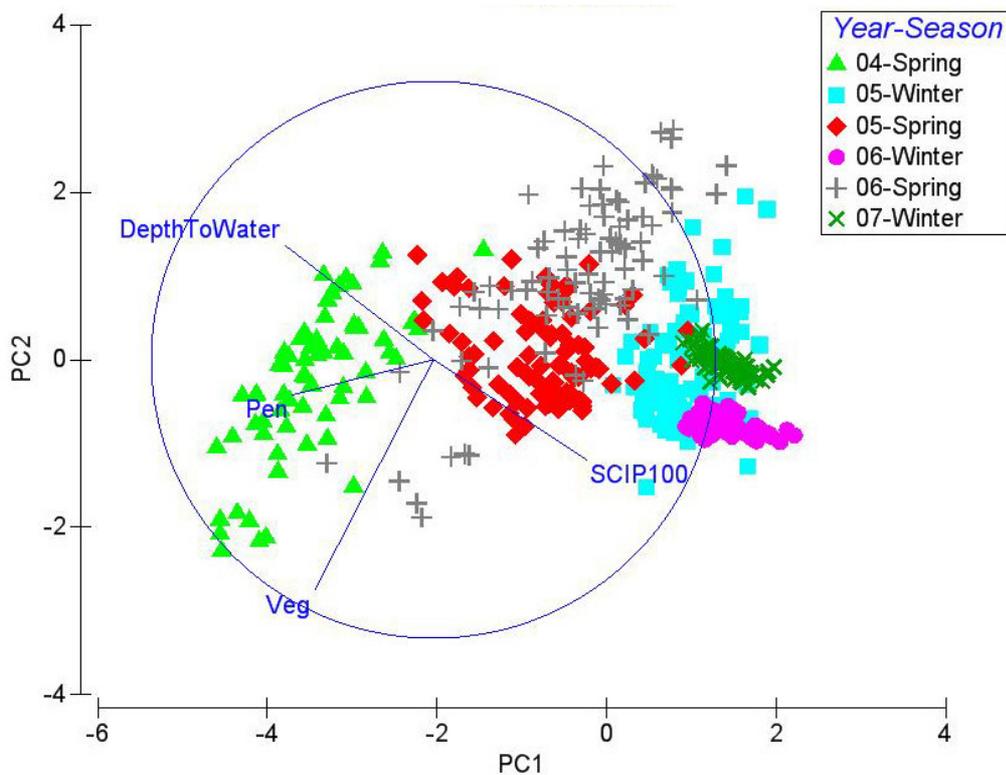


Figure 5.10 PCA summarizing the four environmental variables including depth to water, SCIP 100, penetration and vegetation at 626 study spots at Pawlett.

5.6.3 Berney

Table 5.4. Berney. Summary of ANOVA test of effects and interactions of hydrological variables. Blocks A, B and C are treatments and Block D is control. ‘*’ indicates $p < 0.01$ (highly significant relationship), ‘*’ indicates $p < 0.05$ (significant relationship) and ‘ns’ indicates no significant relationship.**

Variables	Date	Block	Spacing	Distance from grip
Depth to water	**Spring>Winter	**D>C,A,B *C>B	**5<D,10,20	**D>1.1,15,2.5 **10>1.1,1.5,2.5
Soil Moisture (5cm)	**Winter>Spring	ns	ns	**10>1.1,1.5,2.5,5
Soil Moisture (10cm)	**Winter>Spring	ns	*5>D; *20>D	*1.1>D
Vegetation Height	**Spring>Winter	ns	ns	Ns
Soil Penetrability	**Spring>Winter	ns	**5<10,20,D	*10,5>1.1,1.5,2.5 D:ns

Variables	Date * Spacing	Date * Distance from grip	Distance from grip * Spacing
Depth to water	ns	ns	*1.1m: 10>20,5
Soil Moisture (5cm)	ns	ns	ns
Soil Moisture (10cm)	ns	Winter:ns Spring:D<1.1,1.5,2.5	ns
Vegetation Height	**Winter:5>10,20; D>10,20 *Spring:10>20,5;D>10	ns	ns
Soil Penetrability	**Winter:10>20,5,D **Spring:5<10,20,D	**Winter:D>1.1,1.5,2.5 **Spring:D,5,10>1.1,1.5,2.5	ns

The well-structured soils of Berney allowed good lateral permeability of water.

Key conclusions

- Differences between the treatment area and the control were not pronounced
- Water-table levels were generally higher near to the grips suggesting an irrigation function (Fig. 5.11). This trend was consistent with a slight downward gradient in soil moisture (100 mm) away from the grips - highest at the 1.1 m distance (Fig. 5.12).
- In the autumn, there is some evidence for a drainage effect as water table levels were higher in the control.
- The highest water-table levels and soil moisture in the treatment area were in the 5 m spacing, where grips are closest together.
- In summer, penetrability was highest in the 5 m spacing.
- Vegetation was taller during the spring than the winter, with a tendency to be taller in the narrow spaced grips than the wider spaced grips; vegetation in the wider spaced grips was shorter than in the control.

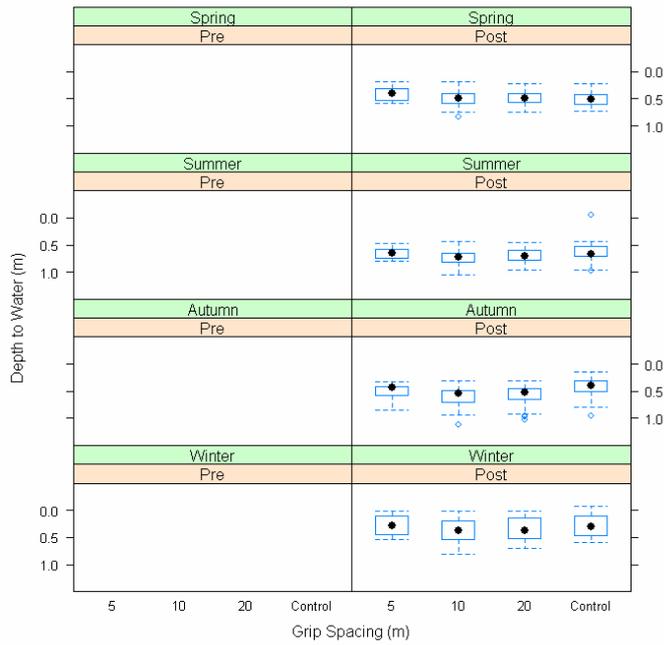


Figure 5.11 Variations in depth to water table with spacing and control at Berney

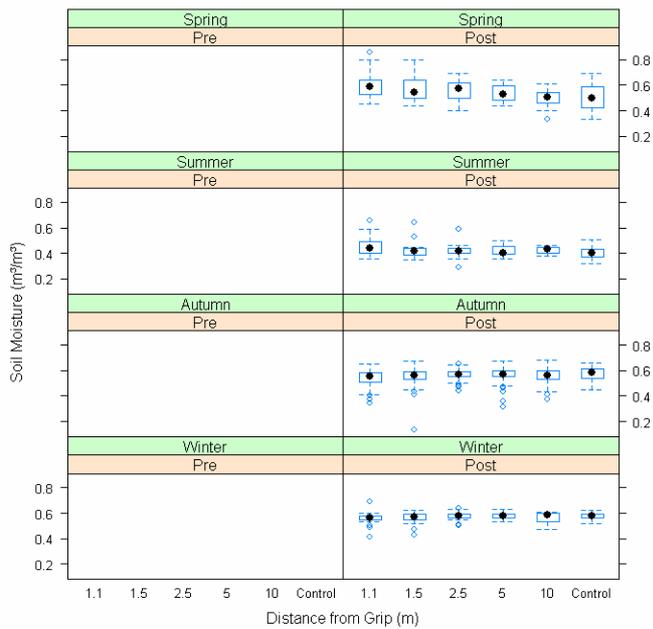


Figure 5.12 Variations in soil moisture (100 mm) with distance from grip and control at Berney

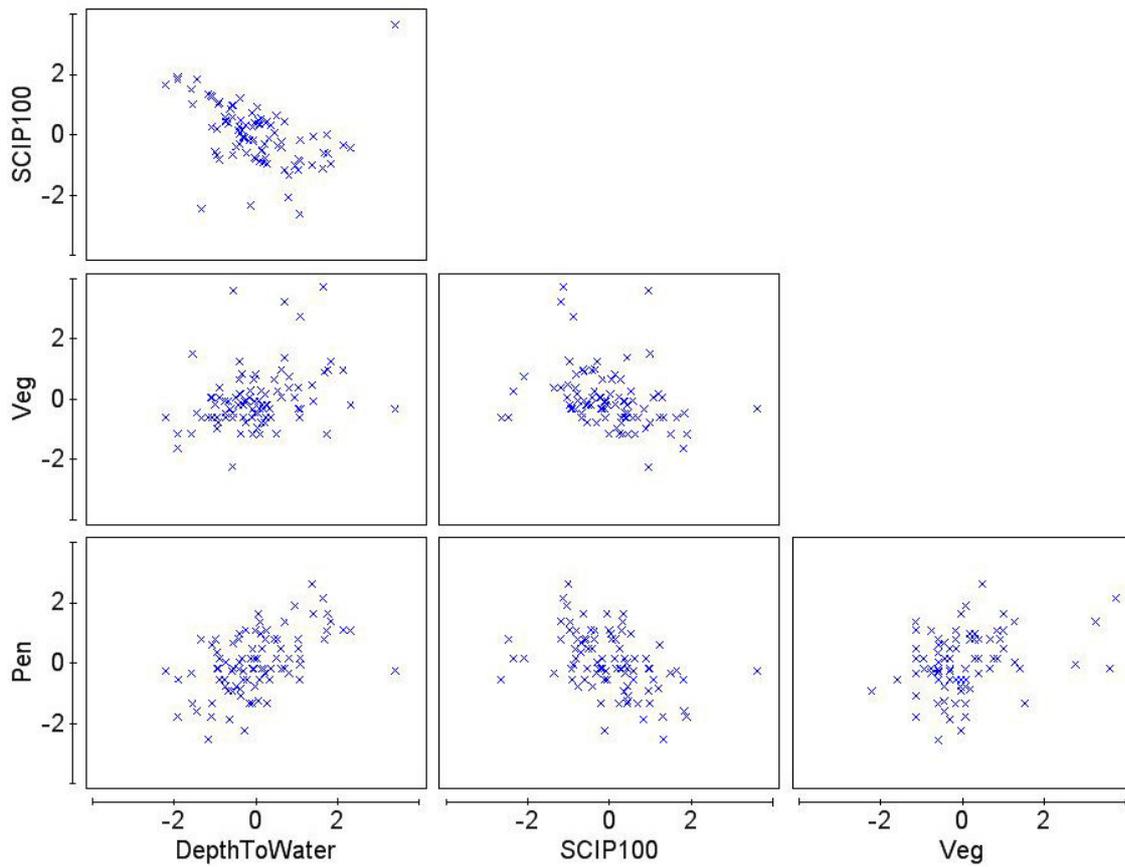


Figure 5.13. Biplots of environmental variables showing the pairwise variation between them at Berney site.

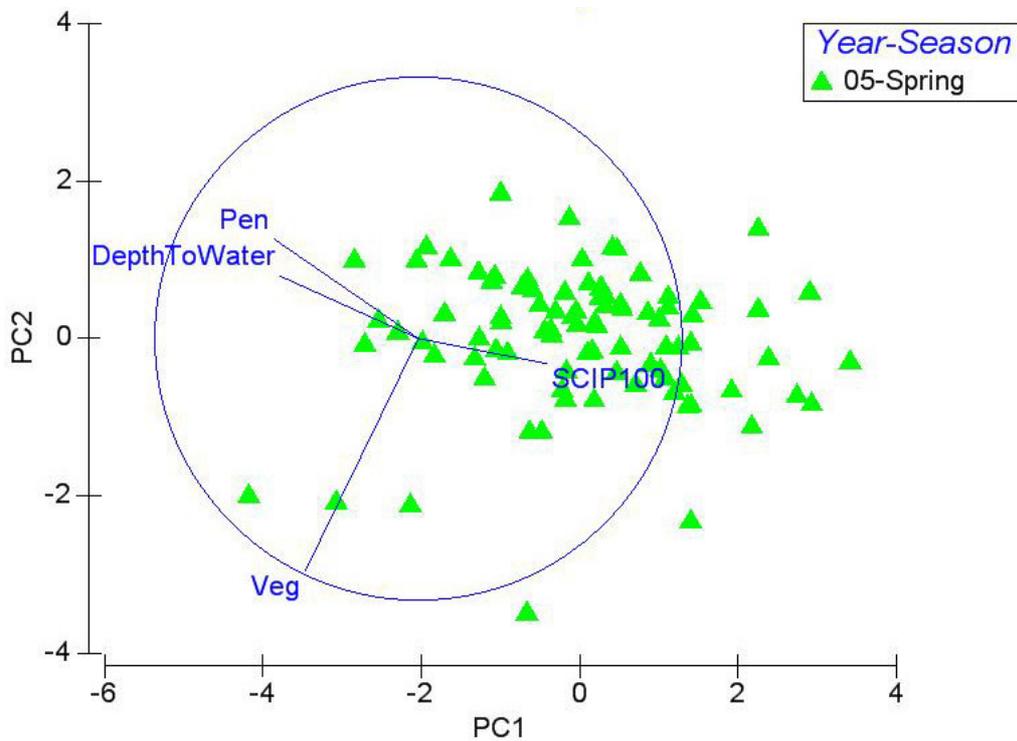


Figure 5.14 . Principal component analysis summarizing the four environmental variables including depth to water, SCIP 100, penetration and vegetation at 626 study spots at Berney.

5.7 Field soil penetrability

Fig. 5.15 shows penetrability as a function of soil moisture. It can be seen that as the soil moisture content increases, the soil strength tends to decrease and the force required to insert a bird beak decreases. These results are consistent with those from the falling cone (Section 4, Fig. 4.7). It is noteworthy that there is greater variation at Otmoor than Pawlett or Berney due to the less structured nature of the soil.

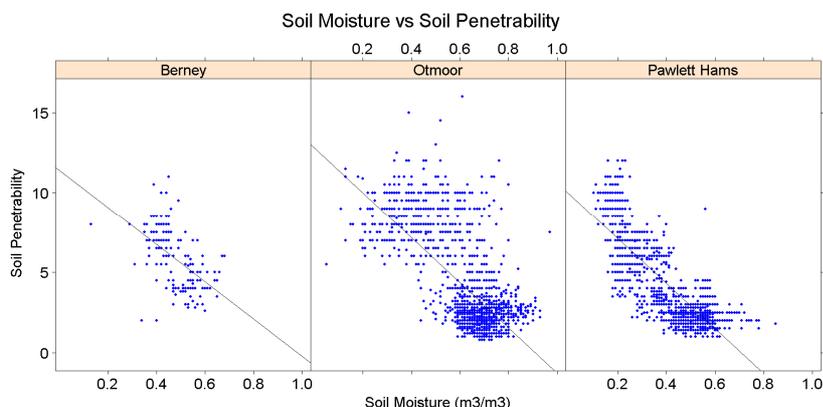


Figure 5.15 Relationships between soil moisture and soil penetrability (force kg required to penetrate a needle). The linear regression is shown by the straight line.

5.8 Grip margin analysis

It was recognised that the grip margins provide a different habitat, generally less vegetation and exposed soil, than the large vegetated land areas between the grips. These margins are characterised by period inundation, when the grips are full of water and then drying as the water level recedes. To examine this habitat, measurements were made of the distance from the station 10 cm from the grip edge to the water, i.e. the width of the muddy grip margin. Time series were produced to describe how the area of margin varies during the key times (winter, breeding season).

5.8.1 Otmoor

Figure 5.16 shows that at Otmoor, the grips were full for most of the winter and spring, producing a high moisture status ($0.7 - 0.8 \text{ m}^3/\text{m}^3$) and little grip margin. Water level declined during the early summer (Table 5.5), with grips being dry by August (denoted by width of 2.0) until the autumn. At this time the soil moisture drops to around $0.5 \text{ m}^3/\text{m}^3$. Overall, as expected, there is an inverse relationship between amount of grip edge and soil moisture. The grips at Otmoor typically start to dry out 1 month later than those at Pawlett.

Table 5.5. Grip drying periods at Otmoor and Pawlett

Drying cycle	2005		2006	
	Start	End	Start	End
Otmoor	01/06/2005	27/07/2005	01/06/2006	06/07/2006
Pawlett	09/05/2005	16/06/2005	06/04/2006	16/06/2006

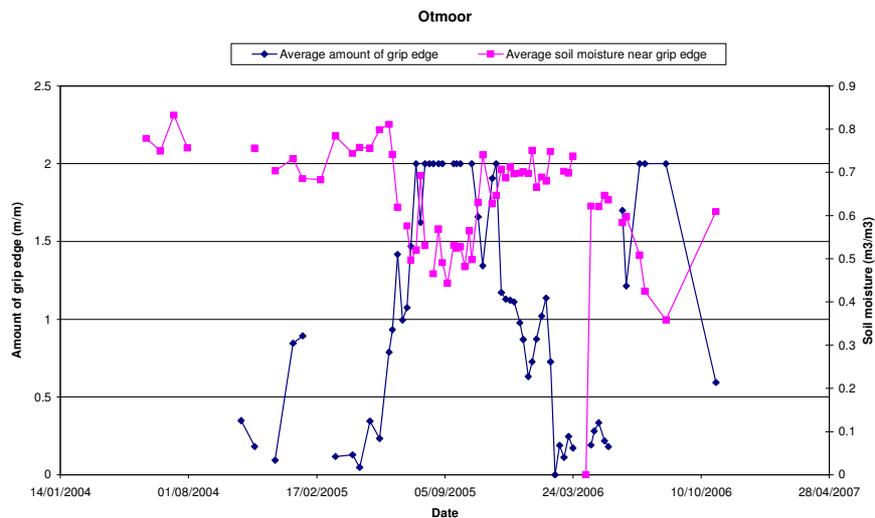


Figure 5.16 Time series of width of grip margin and soil moisture at grip edge at Otmoor

5.8.2 Pawlett

Figure 5.17 shows that at Pawlett, the grips were rarely completely full due to an overall lack of water, thus some grip margin was maintained, but dried rapidly. Soil moisture at the grip edge reached a maximum of $0.5 - 0.6 \text{ m}^3/\text{m}^3$ during the spring. Water levels declined during the early summer (Table 5.5), with grips being dry in July (denoted by width of 2.0) until the late autumn. At this time the soil moisture drops to around $0.2 - 0.3 \text{ m}^3/\text{m}^3$. Overall, as expected, there is an inverse relationship between amount of grip edge and soil moisture. The grips at Pawlett typically dry out 1 month earlier than those at Otmoor.

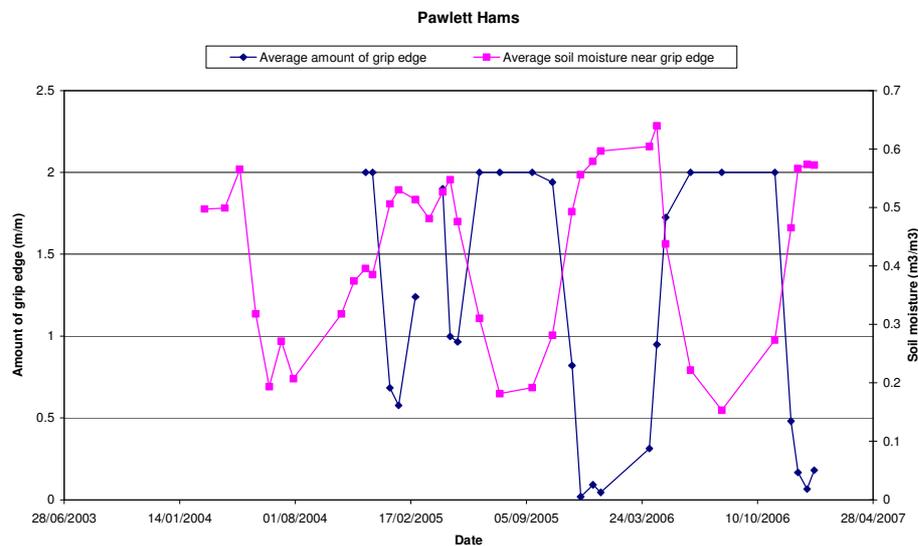


Figure 5.17 Time series of width of grip margin and soil moisture at grip edge at Pawlett

5.8.3 Berney

Fewer data were available from Berney than for Otmoor and Pawlett and patterns of grip margin width are not clear. Figure 5.18 shows that soil moisture did not vary greatly, staying around $0.5-0.6 \text{ m}^3/\text{m}^3$.

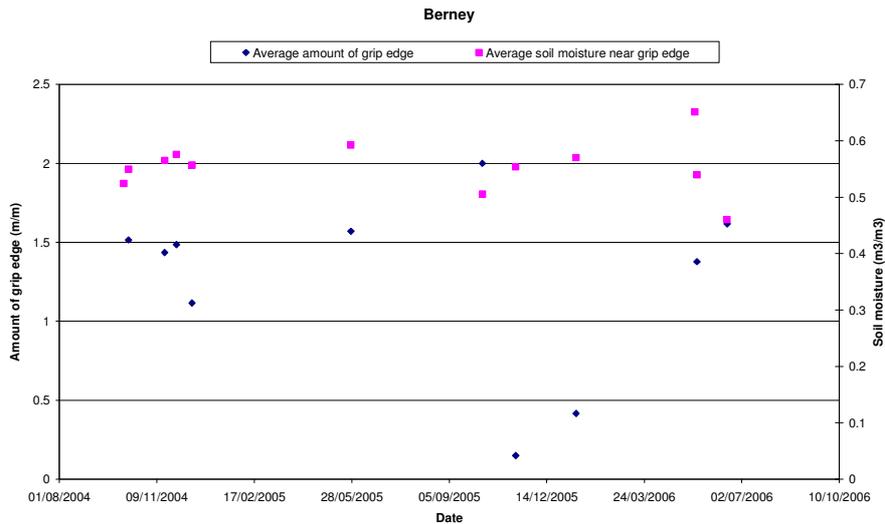


Figure 5.17 Time series of width of grip margin and soil moisture at grip edge at Berney

Figure 5.18 shows a scatter plot of grip margin width against soil moisture at 0.1 m. Otmoor and Pawlett show similar gradients with generally moister conditions at Otmoor. This Figure confirms the broadly constant soil moisture at Berney, 0.5-0.6 m³/m³, and more limited range of margin widths as water was generally held in the grips for longer.

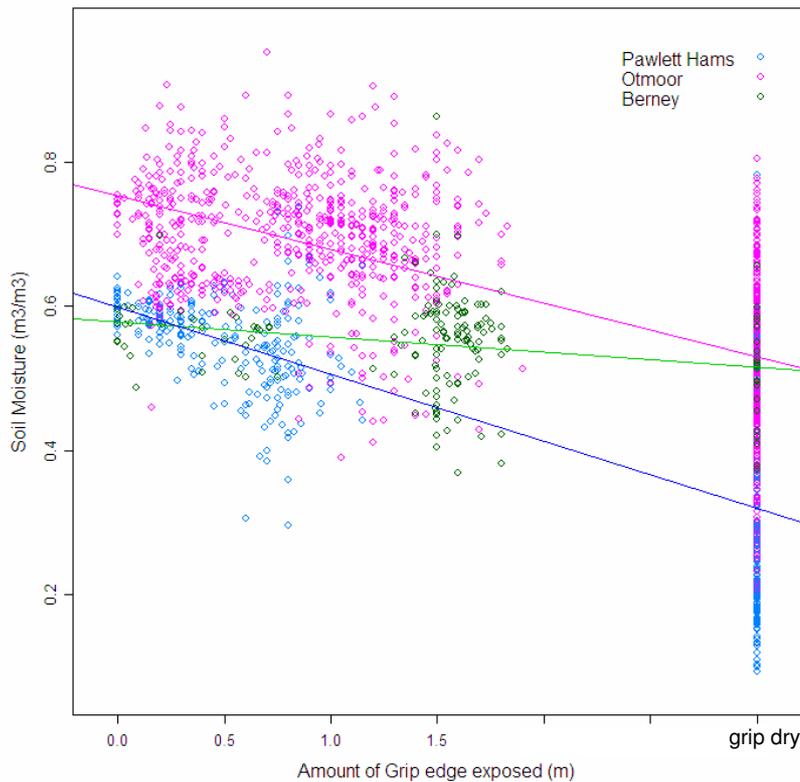


Figure 5.18 Grid margin width versus soil moisture at Otmoor, Pawlett and Berney.