Remediation of compact and degraded surface soil layers within natural habitats

MAFF Contract No: BD 1307
Final Scientific Report

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Final Scientific Report

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EXECUTIVE SUMMARY

The full potential of many wetland ESA and Countryside Stewardship schemes cannot be realised due to the presence of compacted and degraded soil conditions in the surface layers. These conditions, often present on clayey and peat soils, are unfavourable for both important plant communities and bird habitats, and they are often extremely difficult to alleviate.

The prime aims of this project were to:

1. Identify where possible improved remediation techniques for overcoming compaction and reversing degradation in the soil surface layers, which could be implemented directly in the field, without causing serious damage to existing important plant communities.
2. Substantiate through exploratory laboratory studies possible new approaches for the rewetting and improvement of degraded soils.
3. Provide guidance on future approaches to remediation, identifying any necessary future research needs.

Past experience has shown that improvement through mechanical fissuring measures alone on clay soils has proved unsuccessful and that these must be accompanied by soil-swelling and soil-structure improvement measures for success. Similarly on degraded peat soils, rewetting and swelling difficulties have seriously impeded improvement. In both situations subsequent field management techniques have a critical role to play in continuing the improvement process and preventing major reversals. An integrated approach was, therefore, required and taken in this project, considering not only the role of mechanical fissuring measures, but also natural soil wetting and drying processes, plant rooting and organism activity, desired field water regimes and how they could be achieved and surface management procedures capable of stabilising and sustaining the improved condition. Past information and experiences were reviewed, backed up by laboratory studies.

The laboratory studies concentrated on examining in more detail the swelling characteristics of a Newchurch Series clay and Turbary Moor Series peat soil to supplement existing information. Assessments were made of the following:

1. The rate and extent of volume change over a 3 month swelling period under unconfined and confined conditions
2. The influence of sample height and size on volume change
3. The influence of a range of drying periods on volume change on rewetting

The clay soil tested was sampled from Berney Marshes, Norfolk and the peat from Westhay Moor, Somerset. The clay samples were taken from two areas which had suffered different degrees of compaction damage and the peat samples from a grassed area previously arable cropped, and from an unploughed area now managed as a nature reserve. Undisturbed samples of these soils were placed on sand tables for rewetting under a moisture tension of 20mm and their volume and density changes with time measured over a 3 month period.

The swelling behaviour with time of both soils was similar, very rapid swelling initially, then falling to an almost zero or extremely slow rate after 3 months. Volume changes over the period were limited to between 10-15% in the clay and 6-10% in the peat, but swelling was reduced as the length of the water flow path through the larger compacted and degraded zones increased. Reworking the clay, as would occur during animal poaching, increased swelling further, although the increase was reduced if the soil was allowed to ‘age’ and stabilise after disturbance before rewetting. Poaching damage in the presence of surface water is equivalent to reworking without any ageing period, a serious situation for soil structure damage. Excessive drying of the degraded peat had minimal effect on its swelling recovery, but the effect on the undegraded peat was very serious, the samples failing to regain their original volume over the 3 month period.

The implications of this swelling behaviour for remediation measures are that it could take an extremely long time for recovery from compaction by continuous swelling alone in clay soils and in the case of degraded peats, complete recovery may not always be possible. Any significant drying within the swelling period will reverse improvement and hence good control over soil water regime will be essential to minimise this risk. Volume increases will also be more rapid if the compacted units are smaller in size, due to shorter water flow paths and increased surface area for water uptake.
The approach necessary for remediation on clay soils depends upon the extent of damage, whether it be largely compaction only or compaction plus serious structure breakdown. In the first situation, benefits from an initial swelling need to be followed by much longer term wetting and drying cycles, root action and organism activity, accompanied by careful grazing and cutting management. These processes separate the existing structural units from the compacted mass, regenerating a satisfactory soil structure. The initial swelling could be feasible without damaging existing plant communities, through intermittent winter flooding and careful water control later to avoid severe drying. Such an approach is, however, unlikely to be successful in the presence of serious structural damage. Repairing the damage first before attempting to establish the desired habitat, could prove a better alternative.

In the peat situation, due to a lack of information on potential recovery from severe desiccation, possibilities for remediation are unclear. Where improvements may be possible, very long wetting periods will be required. Possibilities exist for the establishment of mire or swamp communities to allow long term swelling, with conversion to wet grassland later. Alternatives, dependent upon the depth of effected peat, include mixing with undegraded peat to improve moisture retention and hence swelling, or burial to depths below the water table to extend wetting time.

All the remedial approaches as well as measures to prevent degradation require careful control over water regime and grazing and cutting management. Current ditch spacings are frequently inadequate to provide the necessary water control and need supplementation. This is achievable through additional ditches, or where these would be too frequent, control can be achieved through supplementary subsurface pipe or moling systems. The latter are also particularly useful as temporary systems, when more intensive control is required as part of the remediation process. Cylindrical compression moles are suitable for drainage and sub-irrigation use on the stable clay soils and a milling mole plough on peats. Preliminary trials with the milling mole plough have been particularly encouraging.

To improve the rate of water movement to and from ditches or subsurface conduits and increase surface water infiltration in compacted situations, techniques are required for generating fissures through the compacted layers without creating surface damage or excessive loosening. Suitably adjusted wing type subsoilers are well suited for this operation, but they need to be supplemented with ground-driven rotating slitting equipment, which generates many more surface slots to improve infiltration and reduce the size of the compacted units for more rapid wetting. The slitting technique has also considerable potential for improving water infiltration and storage in high rainfall upland areas, to reduce the risk of surface drying during dry periods.

Field trials are required to test and develop further the milled moling system in peat soils and to evaluate the remedial approaches suggested for clay soils under different wetland conditions. Further laboratory studies are also needed on peat soils, to identify those particular peat types and limits of degradation, which have the potential for satisfactory improvement.
1. **INTRODUCTION**

The occurrence of soil compaction and soil structure problems in the soil surface layers is seriously inhibiting the development and sustainability of existing and target wetland habitats in numerous conservation areas and ESA and Countryside Stewardship schemes. This soil damage has often been sustained in mineral soils through overcompaction by heavy traffic or cattle poaching and in peat soils by intensive drying following inappropriate water management. The damage within the soil manifests itself through characteristics such as reduced porosity, low infiltration rate, impeded capillary water movement, limited water availability, anoxic conditions, high penetration resistance and extreme resistance to rewetting. These undesirable features have very damaging effects on wetland plant communities and bird habitats.

Compaction damage particularly in mineral soils occurs largely through traffic and animal loadings under wet conditions. Animal poaching is particularly serious in initiating mineral soil structure breakdown, which leads to the creation of a massive rather than a crumb or granular structure. Poaching damage increases in the presence of surface water and with the intensity of stocking. These high moisture contents can arise through excessive rainfall, high water tables and/or low infiltration rates, the latter two being potentially controllable with good water management.

Current remediation measures are frequently failing to provide the required soil improvement, major problems being the difficulty of reducing soil surface densities and in stabilising any improvement. Mechanical measures alone are incapable of achieving density reduction and hence rewetting the surface layers adequately is necessary to induce soil swelling with a corresponding reduction in density. This rewetting has to be achievable without damaging the existing plant and invertebrate communities, a process not always achievable with the existing water control infrastructure. Improved soil conditions are more vulnerable to recompaction and further structural breakdown and hence improvements will not be sustainable unless accompanied by improved management measures.

2. **PROJECT AIMS AND OBJECTIVES.**

The prime aims of this project were to:

1. Identify where possible improved remediation techniques for overcoming compaction and reversing degradation in the soil surface layers, which could be implemented directly in the field, without causing serious damage to existing important plant communities.
2. Substantiate through exploratory laboratory studies possible new approaches for the rewetting and improvement of degraded soils.
3. Provide guidance on future approaches to remediation, identifying any necessary future research needs.

Specific objectives were the:

1. Assessment of the wetting and swelling characteristics of peat and mineral soils which had been subjected to excessive drying and compaction damage, identifying the critical factors controlling the potential rates and degrees of rewetting and swelling achievable.
2. Identification of the flooding tolerances of wet grassland plant communities and the abilities of plant species to re-structure and stabilise damaged soils following rewetting.
3. Identification of the most appropriate water management techniques for rewetting in specific field situations.
4. Identification of effective soil fissuring techniques to assist rooting and water infiltration and movement.

3. **APPROACH AND METHODOLOGY**

An integrated approach was taken to assess the potential for improved remediation. Mechanical measures with the natural wetting and drying processes occurring in soils, the stabilising abilities of plant roots and soil organisms, and appropriate changes to water and grassland management have been investigated. Existing information from the literature, experimental results and practical field experience in soil and water management in both the agricultural
and natural habitat sectors was reviewed. This was supplemented with further exploratory laboratory studies on the swelling characteristics of a clay and peat soil. The laboratory studies were undertaken on undisturbed soil samples taken from damaged field situations. The results have been used to extend previous studies investigating the influence of factors such as initial soil density, soil unit size, exchangeable cation and degree of structural degradation on soil rewetting and swelling rates and final soil densities.

Large undisturbed peat samples were collected from Westhay Moor in Somerset. The soil type was of the Turbary Moor Series, classed as an earthy oligo-fibrous peat, a mixed Eriophorum/Sphagnum raised bog material. The topsoil, which was sampled, comprised of humified peat over an upper subsoil of humified peat with remains of cottongrass, becoming more fibrous with depth. Part of the site had been in arable cropping until several years ago and was now in grassland. The peat collected from these areas was in a degraded condition. Samples were also collected from a neighbouring field which had not been ploughed and which was managed as a nature reserve. These samples had not suffered serious degradation.

Large undisturbed samples of a Newchurch Series silty clay soil (3% sand, 53% silt, 44% clay) were collected from Berney Marshes in Norfolk. Two areas were selected for sampling, one showing more serious compaction damage than the other. Both areas lay within the RSPB Reserve.

The samples were subjected to a series of swelling tests to assess the following:

1. The rate and extent of volume change over a 3 month swelling period under unconfined and confined conditions
2. The influence of sample height and size on volume change
3. The influence of a range of drying periods on volume change on rewetting.

The range of samples prepared from the field samples are shown in Table 1

<table>
<thead>
<tr>
<th>Table 1 Soil samples tested</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>25 mm diameter, 10 mm height, unconfined</td>
</tr>
<tr>
<td>25 mm diameter 10 mm height, confined to vertical swelling</td>
</tr>
<tr>
<td>50 mm diameter, 20 mm height, unconfined</td>
</tr>
<tr>
<td>100 mm diameter, 40 mm height, unconfined</td>
</tr>
<tr>
<td>25 mm diameter, 10 mm height, unconfined, dried for one day</td>
</tr>
<tr>
<td>25 mm diameter, 10 mm height, unconfined, dried for one week</td>
</tr>
<tr>
<td>25 mm diameter, 10 mm height, unconfined, dried for one month</td>
</tr>
</tbody>
</table>

All samples were cut from the larger undisturbed samples using metal rings. These rings were removed from all except the “confined” samples to allow unconfined swelling both laterally and vertically. The remaining samples were restricted from swelling laterally by the rings.

The effect of possible “irreversible drying” in peats was investigated by air-drying some of the samples for one day, one week and one month before rewetting.

All samples were placed on a sand table maintained at 20mm tension. They were weighed initially, after 3 days and then weekly over a 3 month period. Volumes were measured by immersing the samples in a beaker of water and weighing the beaker with and without the sample immersed. Volumes were calculated on the basis of Archimedes principle and determined initially and then at 3-weekly intervals over a three-month period.
On completion of the experimental period, final moisture contents and dry bulk densities were determined and densities during the experiment calculated. Organic carbon contents and the sodium adsorption ratio were measured from bulked clay samples.

4. **RATIONALE FOR CONSIDERING NATURAL WETTING AND DRYING PROCESSES, AND ROOT AND ORGANISM ACTIVITY AS IMPORTANT COMPONENTS OF REMEDIATION MEASURES.**

The ideal surface conditions for plant and bird habitat are a soil comprising of a granular or crumb structure, with good root development and organism activity. Such conditions provide good aeration, drainage and water holding characteristics. The binding action of the roots increases the overall strength of the soil to help support external loads in the form of animals and machinery traffic. Whilst the overall strength is relatively high, the actual penetration resistance for birds is much lower, since the birds penetrate between the structural units. The soil penetration resistance will increase with drying and hence increasing soil moisture tension, but not at the same rate as within the stronger structural units, for the same tension change.

The soil compaction process forces the fine structural units closer together, eliminating most or all of the larger macro pores between, but with minimal change in the structural units themselves. Penetration then has to occur largely or completely through the structural units and the resistance will increase. When this compaction is accompanied by soil reworking, the structure itself changes towards a more platy and in the worst case a massive state, where no separate structural units are discernible. All macro pores are lost and probing must be through these larger and stronger structural units increasing penetration resistance further. In both the compaction and reworking situations, it is the properties of the particular structural units present which control penetration resistance. This compacted and damaged structural condition is also unfavourable for root and organism activity, thus it affects rooting and hence water availability, and invertebrate populations and hence bird food supply.

The shrinkage characteristics of massive/individual structural units are such that the units remain effectively saturated as drying and shrinkage (density increase) occurs. As this drying continues, the internal moisture tensions and cohesive bonding forces increase with corresponding increases in penetration resistance. This shrinkage reduces the internal pore size and hence hydraulic conductivity and the net effect of these changes is to change the response of internal moisture conditions to outside changes in moisture tension. Within a given wetting period, the extent of water uptake by a higher density unit in the presence of outside moisture at a much lower moisture tension may be limited. Highly shrunken units may not, therefore, swell completely in the time available, with the result that their internal moisture tension does not reach equilibrium with the outside tension. In these circumstances penetration resistances within the units will remain higher than would be expected on the basis of the outside moisture tension.

Whilst within a given soil the penetration resistance of its structural units is closely related to their density, this is not necessarily the situation between soils. Different soils can have the same penetration resistance at different structural unit densities, providing the moisture tensions within the units are similar (Spoor and Godwin,1979). It is not possible, therefore, to define a limiting density for acceptable penetration resistance applicable to all soils, each soil is unique in this respect.

A further problem with soil in a massive or compacted condition arises on drying. The volume of pores retaining water at relatively low tensions is much reduced compared with well structured soils. On drying, therefore, the increase in moisture tension is much greater for a given water loss in the damaged soil, thus creating a much greater increase in penetration resistance. More local water abstraction by root systems restricted by compaction also leads to the development of high moisture tensions more rapidly.

Whilst water uptake and accompanying swelling will be very useful in reducing penetration resistance, without improvements in structural condition towards a fine structural state, subsequent drying will tend to reverse the situation. Structural improvement can only occur through root and organism activity, and through wetting and drying cycles which induce internal stresses within the larger units causing size reduction. In the case of the compacted condition alone, such action will assist in separating the original structural units. Where the structure has been seriously damaged, the development of a fine structure again is much more difficult and may take a very considerable time.
Mechanical fissuring can reduce the size of larger compacted units creating macro-pores between, but this action has little or no effect on the soil condition within the units themselves. The direct effect of these operations on soil penetration resistance is, therefore, minimal. The major role of mechanical fissuring is, therefore, to improve conditions to assist the natural processes in rectifying the compaction and structural damage. In addition to reducing the finite size of the compacted units, the fissuring can also provide pathways for more rapid water movement at higher moisture contents for improved aeration and/or water supply depending on requirements.

The extent of density reduction through soil swelling will depend on the rate at which water can enter the compacted units, the time period available for water uptake and the strength of the internal soil bonding forces within the clay and organic fractions which resist swelling. Fissuring operations and the natural processes will only prove successful, when the water control measures on site are capable of providing the required water supply and water regimes for soil swelling, natural restructuring and avoidance of recompaaction by animals or traffic. This will have to be achievable without detriment to any important plant communities present on site.

5. WETTING AND SWELLING CHARACTERISTICS OF CLAY AND PEA T SOILS.

The rate and degree of soil swelling on wetting, is an important component to assist in relieving compaction and reducing soil strength in any remediation process. Previous studies (Spoor et al., 1982, Spoor et al.,1985, Hann, 1994) have examined the swelling properties of a wide range of clay subsoils, identifying the major factors influencing their swelling characteristics. The organic matter contents of these subsoils, negligible in all cases except for a Fladbury Series clay, differ considerably from those of the topsoils under consideration in this project. The direct application of any results from this subsoil analysis to the topsoil situation, therefore, needs to be treated with caution, but one encouraging feature was that the Fladbury clay behaved in a similar way to the other soils. In the absence of comparative swelling data on topsoils from other sources, the results from these subsoil experiments are summarised and comparisons made with the behaviour of the Newchurch Series topsoil. Such a comparison allows an assessment to be made of the general applicability of the subsoil results to topsoils. The methods used to examine the swelling characteristics of the subsoils were very similar to those used within this project.

5.1 SWELLING CHARACTERISTICS OF CLAY SUBSOILS

The behaviour of 14 soils, identified in Table 2, were compared, these soils differed in terms of their clay mineralogy, dominant cation, clay content, density and parent deposit. Wallasea, Newchurch, Fladbury and Conway are particularly relevant to lowland wet grassland situations. The particular swelling characteristics examined included swelling rates and the extent of swelling within specific periods. These tests were carried out both on undisturbed peds and on disturbed samples which had been reworked to different degrees. The reworked samples were also subjected to different lengths of ageing period without moisture change before testing, during which period different bonds broken during reworking would have the opportunity to reform. Reworking tends to simulate poaching effects and ageing, the period between reworking and the commencement of reswelling. In a topsoil field situation, however, the ageing period could also be accompanied by soil drying.

Volume change with time

Fig 1 illustrates the nature of the volume change (swelling %) with time for undisturbed soil peds. The general form of this relationship was common to all the soils investigated. Soil volume increased very rapidly over the first 3-5 days of wetting, then slowed until finally either no further change occurred, or more usually, samples continued to swell at a very slow rate with time.

Swelling rates

Comparing the rates of swelling of undisturbed peds, the higher density soils tended to swell at lower rates than the low density soils. In Fig 1, the volume of the low density Fladbury reached 90% of its 28 day increase within a period of 3 days, whereas the high density Tedburn reached only 58%. Reworking the higher density soils tended to increase swelling rate, whereas the reverse tended to occur with the lower density soils. In all cases, swelling rates tended to decrease with the length of the ageing period (ageing periods were between 0 and 21 days).
Table 2 Soils selected for swelling activity tests

<table>
<thead>
<tr>
<th>Type of Deposit</th>
<th>Clay mineralogy</th>
<th>Clay content %</th>
<th>Density t m$^{-3}$</th>
<th>Calcareous/sodic presence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>High &gt;50</td>
<td>Med 35-50</td>
<td>Low &lt;35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Med 35-50</td>
<td>High &gt;1.5</td>
<td>Med 1.3-1.5</td>
</tr>
<tr>
<td>1. Alluvium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Denchworth</td>
<td>Smectitic</td>
<td>High</td>
<td>Med</td>
<td>---</td>
</tr>
<tr>
<td>Evesham</td>
<td>Smectitic</td>
<td>High</td>
<td>Low</td>
<td>Calc</td>
</tr>
<tr>
<td>Wallasea</td>
<td>Smectitic</td>
<td>Med</td>
<td>Low</td>
<td>Sodic</td>
</tr>
<tr>
<td>Newchurch</td>
<td>Smectitic</td>
<td>High</td>
<td>Med</td>
<td>Calc</td>
</tr>
<tr>
<td>Tedburn</td>
<td>Micaceous</td>
<td>Med</td>
<td>High</td>
<td>---</td>
</tr>
<tr>
<td>Teigngrace</td>
<td>Kaolinitic</td>
<td>Med</td>
<td>High</td>
<td>Sodic</td>
</tr>
<tr>
<td>Lacustrine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foggathorpe</td>
<td>Micaceous</td>
<td>High</td>
<td>Med</td>
<td>---</td>
</tr>
<tr>
<td>Crewe</td>
<td>Micaceous</td>
<td>High</td>
<td>High</td>
<td>---</td>
</tr>
<tr>
<td>River</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fladbury</td>
<td>Smectitic</td>
<td>High</td>
<td>Low</td>
<td>---</td>
</tr>
<tr>
<td>Conway</td>
<td>Micaceous</td>
<td>Low</td>
<td>Med</td>
<td>---</td>
</tr>
<tr>
<td>2. Non Alluvium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hanslope</td>
<td>Smectitic</td>
<td>Med</td>
<td>High</td>
<td>Calc</td>
</tr>
<tr>
<td>Clifton</td>
<td>Micaceous</td>
<td>Low</td>
<td>High</td>
<td>---</td>
</tr>
<tr>
<td>Salop</td>
<td>Mixed Micaceous</td>
<td>Low</td>
<td>High</td>
<td>---</td>
</tr>
<tr>
<td>Dale</td>
<td>Micaceous</td>
<td>High</td>
<td>Med</td>
<td>---</td>
</tr>
</tbody>
</table>

Figure 1 Soil swelling with time
(undisturbed soil peds)

Total swelling over a given time period.

Table 3 shows the density change and % change in volume over a 28 day swelling period of undisturbed peds in lowland wet grassland soils.
Table 3. Density and volume change over 28day swelling period.

<table>
<thead>
<tr>
<th>Soil Series</th>
<th>Density (t m$^{-3}$)</th>
<th>% Volume Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Final</td>
</tr>
<tr>
<td>Fladbury</td>
<td>1.01</td>
<td>1.05</td>
</tr>
<tr>
<td>Wallasea</td>
<td>1.38</td>
<td>1.01</td>
</tr>
<tr>
<td>Newchurch</td>
<td>1.46</td>
<td>1.38</td>
</tr>
<tr>
<td>Conway</td>
<td>1.47</td>
<td>1.45</td>
</tr>
</tbody>
</table>

The major soil characteristics influencing the extent of swelling over the 28day period were the type of dominant cation, the parent deposit and the clay mineral. There were no interactions between the factors, their effects being cumulative. The cation effects were greater than those of both the type of deposit and clay mineral. Clay content within these clayey soils did not have a significant influence. The presence of sodium, as in the Wallasea soil, generated the greatest swelling, the non calcareous clays were next followed by the calcareous clays. The marine clays swelled more than the river deposits, with lake deposits falling in between. As would be expected the smectitic clays showed the greatest swelling followed by the micaceous and finally the kaolinites.

Reworking the soils increased the amount of swelling considerably over the 28 day period. Table 4 indicates the percentage increase in swelling following different degrees of reworking compared with that of the undisturbed peds, and Table 5 indicates the final densities of the samples. The ageing period was zero.

Table 4. Increase in swelling due to reworking (%).

<table>
<thead>
<tr>
<th>Soil Series</th>
<th>Partial</th>
<th>Moderate</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fladbury</td>
<td>175</td>
<td>145</td>
<td>175</td>
</tr>
<tr>
<td>Wallasea</td>
<td>49</td>
<td>90</td>
<td>82</td>
</tr>
<tr>
<td>Newchurch</td>
<td>140</td>
<td>150</td>
<td>245</td>
</tr>
<tr>
<td>Conway</td>
<td>323</td>
<td>461</td>
<td>446</td>
</tr>
</tbody>
</table>

Table 5 Final densities following different degrees of reworking (t m$^{-3}$).

<table>
<thead>
<tr>
<th>Soil Series</th>
<th>Initial</th>
<th>Final ped</th>
<th>Degree of Reworking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Partial</td>
<td>Moderate</td>
</tr>
<tr>
<td>Fladbury</td>
<td>1.09</td>
<td>0.96</td>
<td>0.98</td>
</tr>
<tr>
<td>Wallasea</td>
<td>1.38</td>
<td>0.96</td>
<td>0.98</td>
</tr>
<tr>
<td>Newchurch</td>
<td>1.46</td>
<td>1.25</td>
<td>1.26</td>
</tr>
<tr>
<td>Conway</td>
<td>1.49</td>
<td>1.38</td>
<td>1.38</td>
</tr>
</tbody>
</table>

Reworking increased swelling in all cases, the calcareous clays responding most. Marine clays tended to be influenced more by the degree of reworking than the river deposits. Ageing reduced the degree of swelling in all cases, having the greatest effect on the calcareous soils, rather less on the marine and least on the riverine clays. Whilst total reductions in the degree of swelling tended to increase with increasing ageing time, the rates of increase tended to fall off rapidly with increasing time. 70-90% of the swelling reduction achieved from a 21 day ageing period was usually achieved following 7 days ageing.

5.2 LABORATORY TEST RESULTS ON NEWCHURCH SERIES TOPSOIL

Volume change with time

The volume changes with time are illustrated for two representative samples in Fig 2. These followed a very similar pattern to those of the subsoils, rapid swelling initially, a reduction in the rate, then equilibrium or a very slow steady increase with time. Of the 55 samples tested, only 7 appeared to have reached an equilibrium state after 83 days swelling. The remaining 48 were continuing to swell at a steady rate, with a moisture uptake of between 0.0002 and 0.0004 ml.g$^{-1}$soil.day$^{-1}$. 

6
Figure 2. Swelling relationship over time for low and high density clay samples

Swelling rates.

Unlike the subsoils, no clear relationship was found in any of the treatments between the initial sample density and the average rate of swelling assessed between the 28 and 83 day period following the commencement of wetting.

Swelling behaviour

Table 6 indicates the density changes over the 83 day swelling period of the 25mm diameter samples of differing initial density. Swelling percentage tended to increase with increasing initial density, but the final densities of the higher density samples remained high. Assuming the higher density samples continued to swell at the same final 83 day rate, a further 6-9 months would be required for their moisture contents to increase by a further 10%, bringing their densities into the range 0.9-1.0 t. m$^{-3}$.

Table 6 Change in density over 83 day swelling period of samples of different initial density

<table>
<thead>
<tr>
<th>Density Range (t m$^{-3}$)</th>
<th>Number in group</th>
<th>Initial density (t m$^{-3}$)</th>
<th>Final density (t m$^{-3}$)</th>
<th>Decrease in density</th>
<th>Change in density (t m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7 - 0.8</td>
<td>4</td>
<td>0.75</td>
<td>0.65</td>
<td>14%</td>
<td>0.10</td>
</tr>
<tr>
<td>0.8 - 0.9</td>
<td>8</td>
<td>0.86</td>
<td>0.77</td>
<td>10%</td>
<td>0.09</td>
</tr>
<tr>
<td>0.9 - 1.0</td>
<td>11</td>
<td>0.95</td>
<td>0.83</td>
<td>12%</td>
<td>0.12</td>
</tr>
<tr>
<td>1.0 - 1.1</td>
<td>12</td>
<td>1.04</td>
<td>0.92</td>
<td>12%</td>
<td>0.12</td>
</tr>
<tr>
<td>1.1 - 1.2</td>
<td>3</td>
<td>1.15</td>
<td>1.02</td>
<td>12%</td>
<td>0.14</td>
</tr>
<tr>
<td>1.2 - 1.3</td>
<td>7</td>
<td>1.23</td>
<td>1.08</td>
<td>13%</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table 7 presents the aggregated results for the two sampling areas, one of which had been subjected to a higher degree of compaction than the other. The standard deviation values indicate very appreciable variations in density within the two areas, a situation not uncommon in areas compacted by animal loading.

Influence of sample height and size

Comparing the density changes of the 25, 50 and 100mm diameter unconfined swelling samples from the lower density area, indicated in Table 7, the percentage volume increase over the same swelling period decreased...
consistently with increasing sample diameter and height. The magnitude of the compacted units, particularly their thickness has, therefore, a significant influence on the degree of swelling likely to occur over a given wetting period. Although not statistically significant, the upper half of the sample tended to be at a slightly higher density after swelling than the lower half.

Table 7 Change in density over 83 day swelling period for high and low density areas.

<table>
<thead>
<tr>
<th>Soil condition</th>
<th>Initial density (t m$^{-3}$)</th>
<th>Standard deviation (n=15) or *(n=5)</th>
<th>Final density (t m$^{-3}$)</th>
<th>Standard deviation (n=15) or *(n=5)</th>
<th>Percentage increase in volume</th>
<th>Final Moisture Content (grav)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher density area, unconfined swelling (25mm dia. ht. 10mm)</td>
<td>1.14</td>
<td>0.112</td>
<td>0.99</td>
<td>0.111</td>
<td>15%</td>
<td>0.64</td>
</tr>
<tr>
<td>Lower density area, unconfined swelling (25mm dia. ht 10mm)</td>
<td>0.95</td>
<td>0.092</td>
<td>0.84</td>
<td>0.085</td>
<td>13%</td>
<td>0.82</td>
</tr>
<tr>
<td>Lower density area, confined swelling (25mm dia. height 10mm)</td>
<td>0.91</td>
<td>0.114</td>
<td>0.80</td>
<td>0.104</td>
<td>13%</td>
<td>0.75</td>
</tr>
<tr>
<td>Lower density area, unconfined swelling (50mm dia. ht 20mm)</td>
<td>0.94</td>
<td>0.140*</td>
<td>0.84</td>
<td>0.134*</td>
<td>11%</td>
<td>0.83</td>
</tr>
<tr>
<td>Lower density area, unconfined swelling (100mm dia. ht 40mm)</td>
<td>1.08</td>
<td>0.106*</td>
<td>0.98</td>
<td>0.114*</td>
<td>10%</td>
<td>0.66</td>
</tr>
</tbody>
</table>

In a previous test on the same soil (Bibi, 1998), but testing a large undisturbed sample 350mm diameter, 200mm deep with a compact layer thickness of 100mm, it took approximately 4 months for the surface of the sample to begin to swell, even though the moisture tension at the surface was only 10mm. The initial density of the compact layer was approximately 1.2 t m$^{-3}$. This illustrates the considerable time period required for water uptake and penetration in a one dimensional wetting situation through a very compact layer. Fissuring the compacted zone would have increased the surface area for water uptake and allowed lateral inflow from the fissures into the compacted mass, thus increasing the overall swelling rate.

5.3 LABORATORY TEST RESULTS ON PEAT SOIL

Little relevant information on the rewetting of degraded peats was found in the literature, a conclusion also reached following a detailed literature search by Armstrong (1996). The following discussion is, therefore, based upon the results of the limited laboratory experiments carried out within this project.

Volume change with time.

The volume increase on swelling with time follows a similar pattern to that of the clays, see Fig.3. Of the 65 samples tested, approximately 50% had effectively stabilised after the 3-month swelling period. The other 50% were continuing to swell at a very low rate, which if swelling continued, would result in a further 10% increase in their moisture content over approximately a one year period.

Swelling rates without any initial drying

No relationship was found between the initial sample density and its swelling rate within sample groups of similar degrees of degradation. Comparing swelling rates between the undegraded and the degraded samples, however, the samples which had not been degraded swelled significantly faster than the degraded, particularly during the first 3 days of wetting.

Amongst those samples continuing to swell after the 83 day period, the undamaged samples swelled at the highest rate (see long term rate of rewetting in Table 8).
Figure 3: Swelling relationship over time for undegraded peat, and peat dried before reswelling.

Extent of swelling

There was little difference in the % increase in volume in the 25mm diameter samples between the degraded and non-degraded samples over the 83 day period. The degraded peats had initial and final densities approximately twice those of the undegraded, yet the percentage increase in volume was similar in both groups. There was little evidence of structure improvement in the degraded peat following swelling. In the case of the non-degraded samples, the peat in a good physical condition. A much longer swelling test would be required before firm conclusions could be drawn concerning the swelling limits and possibilities for structural recovery of the degraded peats. These results suggest, however, that if further significant improvement was to be possible, it would be a long process.

Influence of sample size

There was a very marked decrease in the % volume change with time as the sample size and height of the degraded samples increased, the percentage falling from 6% to 0.3% (see Table 8). Sample height is likely to be the main influencing factor, through its control over the quantity and rate of capillary rise for rewetting. The results suggest the unsaturated hydraulic conductivity and/or the possible hydrophobic nature of the degraded peat, is insufficient to transmit water in satisfactory quantities for swelling, even through relatively short distances.

Influence of sample drying before rewetting on volume change

The effect of drying and the resulting density increase on the reswelling characteristics, was markedly different between the degraded and non-degraded peats. In the case of the degraded peat, with the exception of the most severely desiccated samples (1 month drying), all swelled to lower densities than their initial one and behaved in a similar manner to the undried samples. Whilst the 1 month dried samples did not quite reach their initial density, their potential swelling time was shorter than the others (56 days), and they were continuing to take up water at a fairly high rate of 0.001ml.g$^{-1}$.day$^{-1}$. It is probable, therefore, that they would certainly reach their initial density, if not beyond, if wetting continued. This particular sample of degraded peat, therefore, appears to have reached its limit of degradation from a reswelling point of view.

Considering the non-degraded samples, the drying time and the shrinkage density reached had a very marked effect on swelling recovery. A one day drying period with a 40% increase in density had no influence on reswelling and the samples were continuing to swell at the end of the 83 days. One week and one month drying periods, with density increase of 180 and 470% respectively, very significantly reduced the extent of density recovery. Nevertheless the swelling recovery was very significant, with the samples continuing to swell at the end of the period. If this final swelling rate was maintained for a period of 9-10 months, the initial density would be regained.
<table>
<thead>
<tr>
<th></th>
<th>Initial density (t m(^{-3}))</th>
<th>Standard deviation (n=15) or *(n=5)</th>
<th>Final density (t m(^{-3}))</th>
<th>Standard deviation (n=15) or *(n=5)</th>
<th>Percentage increase in volume</th>
<th>Final Moisture Content (grav.) (g)</th>
<th>Long term rate of rewetting (ml g(^{-1}) day(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degraded, unconfined swelling (25mm dia., height 10mm)</td>
<td>0.36</td>
<td>0.041</td>
<td>0.34</td>
<td>0.037</td>
<td>6%</td>
<td>2.37</td>
<td>0.0005</td>
</tr>
<tr>
<td>Not degraded, unconfined swelling (25mm dia., height 10mm)</td>
<td>0.15</td>
<td>0.021</td>
<td>0.13</td>
<td>0.015</td>
<td>10%</td>
<td>7.20</td>
<td>0.0016</td>
</tr>
<tr>
<td>Degraded, confined swelling (25mm dia., height 10mm)</td>
<td>0.36</td>
<td>0.036</td>
<td>0.32</td>
<td>0.034</td>
<td>11%</td>
<td>2.28</td>
<td>0.0007</td>
</tr>
<tr>
<td>Degraded, unconfined swelling (50mm dia., height 20mm)</td>
<td>0.31</td>
<td>0.039*</td>
<td>0.29</td>
<td>0.014*</td>
<td>4%</td>
<td>2.78</td>
<td>0.0004</td>
</tr>
<tr>
<td>Degraded, unconfined swelling (100mm dia., height 40mm)</td>
<td>0.30</td>
<td>0.019*</td>
<td>0.30</td>
<td>0.017*</td>
<td>0.3%</td>
<td>2.71</td>
<td>0.0007</td>
</tr>
<tr>
<td>Degraded, unconfined swelling, dried for 1 day (25mm diameter)</td>
<td>0.44 (0.35 before drying)</td>
<td>0.075*</td>
<td>0.32</td>
<td>0.047*</td>
<td>35%</td>
<td>2.54 (1.81 before drying)</td>
<td>0.0007</td>
</tr>
<tr>
<td>Degraded, unconfined swelling, dried for 1 week (25mm diameter)</td>
<td>0.61 (0.35 before drying)</td>
<td>0.073*</td>
<td>0.33</td>
<td>0.019*</td>
<td>86%</td>
<td>2.40 (2.02 before drying)</td>
<td>0.0005</td>
</tr>
<tr>
<td>Degraded, unconfined swelling, dried for 1 month (25mm diameter)</td>
<td>0.83 (0.36 before drying)</td>
<td>0.019*</td>
<td>0.35</td>
<td>0.017*</td>
<td>139%</td>
<td>2.28 (1.69 before drying)</td>
<td>0.0010</td>
</tr>
<tr>
<td>Not degraded, unconfined swelling, dried for 1 day (25mm diameter)</td>
<td>0.20 (0.14 before drying)</td>
<td>0.023*</td>
<td>0.13</td>
<td>0.012*</td>
<td>47%</td>
<td>6.90 (6.11 before drying)</td>
<td>0.0017</td>
</tr>
<tr>
<td>Not degraded, unconfined swelling, dried for 1 week (25mm diameter)</td>
<td>0.42 (0.15 before drying)</td>
<td>0.084*</td>
<td>0.20</td>
<td>0.013*</td>
<td>92%</td>
<td>4.21 (5.52 before drying)</td>
<td>0.0035</td>
</tr>
<tr>
<td>Not degraded, unconfined swelling, dried for 1 month (25mm diameter)</td>
<td>0.85 (0.15 before drying)</td>
<td>0.026*</td>
<td>0.23</td>
<td>0.018*</td>
<td>277%</td>
<td>3.75 (5.26 before drying)</td>
<td>0.0051</td>
</tr>
</tbody>
</table>
Density/moisture content relationship

Fig 4 shows a plot of the density/moisture content relationship for both the degraded and undegraded 25mm samples. The relationship is similar in form to many shrinkage curves, the undegraded showing very appreciable “structural” shrinkage, where the volume/density change is much less than the volume of water removed or added, indicating air entering or leaving the system. The degraded section is closer to “normal” shrinkage where volume change is very similar to the moisture removed or added, with little or no air entering the system on drying.

Figure 4: Relationship between density and gravimetric moisture content for degraded and undegraded peat samples

It is of particular interest that the undegraded samples which were dried and rewetted fall on the same curve in their partially swollen state (see Figure 4). This suggests that at that stage of their wetting, no significant change in their structural state had resulted from drying. Whilst this one experiment does not allow a generalisation of this observation, the indications are that this swelling/shrinkage curve could prove to be a particularly useful indicator of both the degree of denaturing and whether structural change has taken place on drying. If structural change had not occurred, it would be expected the swelling curve would closely follow the drying one, if it had, the curve would deviate. The offset open circles in Fig 4 indicate that the initial sample conditions were unsaturated, being at lower moisture contents at a given bulk density.

5.4 DISCUSSION AND CONCLUSIONS ON SWELLING BEHAVIOUR

5.4.1 Clay soils

Applicability of subsoil swelling results to topsoil situations.

The swelling behaviour with time of the topsoil samples was very similar in form, although different in magnitude, to the subsoil clays. Table 9 allows a comparison to be made between the Newchurch subsoil and topsoil properties which were sampled from different sites.

Table 9. Properties of Newchurch Series topsoil and subsoil

<table>
<thead>
<tr>
<th>Location</th>
<th>Texture</th>
<th>Organic matter %</th>
<th>Sodium adsorption ratio</th>
<th>Initial density t m⁻³</th>
<th>Final density t m⁻³</th>
<th>Density change %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsoil</td>
<td>Silty clay</td>
<td>Trace</td>
<td>0.6</td>
<td>1.46</td>
<td>1.38</td>
<td>6</td>
</tr>
<tr>
<td>Topsoil</td>
<td>Silty clay</td>
<td>14</td>
<td>5.7</td>
<td>1.14</td>
<td>0.99</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
<td>9.4</td>
<td>0.95</td>
<td>0.84</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
<td>9.4</td>
<td>0.95</td>
<td>0.84</td>
<td>12</td>
</tr>
</tbody>
</table>
The main difference between the two sets of samples was in their organic matter and exchangeable sodium levels, both being considerably higher in the topsoils. Overall, the subsoil % density change was only half that of the topsoil, although the subsoil swelling period was shorter at 28 days rather than 83. Whilst the time difference would have some effect, the main difference can be attributed to the higher levels of organic matter and sodium in the topsoil. The 12% density change within the partly sodic Newchurch topsoil, compares with a 27% change in a low organic matter Wallasea Series clay subsoil with similar sodium level. The reduced topsoil swelling was most likely due to the much higher organic matter content producing a stabilising effect. A further difference between the topsoils and subsoils was in the influence of density on swelling rate. Swelling rates were reduced with increasing density in the subsoils, but there was no interaction in the top soils. Whilst differences do exist in terms of the magnitude of changes and slight changes in swelling rate between the topsoils and subsoils, their overall behaviour is similar. In view of this the broad conclusions relating to the factors controlling swelling behaviour derived in the wider and more detailed subsoil experiments, should be applicable to topsoil situations.

Soil characteristics influencing the swelling behaviour of topsoil clays

Based upon the subsoil test results, the main soil factors likely to influence the extent of soil swelling on wetting are as follows: nature of the exchangeable cations, clay mineralogy, type of deposit, the degree of disturbance and subsequent ageing period and organic matter content. With the exceptions of ageing and organic matter content, there is little or no interaction between the factors and hence their effects are cumulative. The likely effects are as follows:

- Nature of cations: swelling increases with increasing sodium and decreases with increasing calcium.
- Clay mineralogy: greatest swelling occurs with the smectitic clays, least with the kaolinites, clays of mixed and micaceous mineralogy being intermediate.
- Type of deposit: undisturbed marine clays tend to swell more than riverine and lacustrine clays.
- Disturbance: disturbance increases the amount of swelling in all situations, but particularly so in the calcareous soils and smectites, which also swell more as the degree of disturbance increases. Marine clays also respond to the degree of disturbance whereas riverine and lacustrine clays are largely insensitive. Glacial till soils are least affected by disturbance.
- Ageing: all soils respond to ageing after disturbance, and in general the longer the ageing period, the greater the reduction in swelling. The rate at which the resistance to swelling develops with ageing is very high with short ageing periods and then diminishes as ageing time increases. Resistance develops as a result of the re-formation of broken bonding forces; this can take some months in the case of calcium bonds.
- Organic matter content: organic bonds tend to reduce the swelling potential in all situations, although it may take some time for some types of organic bond to reform following soil disturbance.

Conclusions from topsoil swelling tests

The following conclusions can be drawn from the topsoil swelling tests:

- Volume increases of between 10-15% occurred over a 83 day period following the rewetting of moist clay samples. The percentage change in density was fairly insensitive to the initial sample density.
- The major change in density, 80-90%, occurred during the first 1-2 weeks of wetting, although most samples were still continuing to swell at a very low rate after the 3 month period. A further 6-9 months would have been required to increase moisture uptake by a further 10% at the final very low rate of swelling. This long-term swelling did not reduce the densities of the compacted samples to levels where penetration resistances would have been low.
- The size and height of the sample (thickness of the compacted layer) had a major influence on the percentage volume increase. Where the wetting is one-dimensional, i.e. from the bottom upwards, the greater the compact layer thickness the lower the percentage volume increase in a given time. Additional lateral water uptake from vertical fissures would increase the volume change.

Implications of results for remediation procedures and future avoidance of compaction

Based upon the results of both the subsoil and topsoil studies, the following implications for both remediation procedures and the avoidance of future damage can be drawn:
• Exceptionally long swelling periods would be necessary to produce major changes in soil density and in many compact situations, the changes would be insufficient to reduce the strength and penetration resistance of the soil structural units to the required levels.
• Large unfissured compacted areas are only wettable in a vertical plane. The presence of vertical fissures through them allows additional lateral wetting in the presence of high water tables.
• Animal poaching in the presence of surface water will cause considerable additional swelling due to the soil reworking effect with effectively zero ageing time. This density reduction and weakening of the soil, will increase the susceptibility of the soil to increased structural damage from further treading.
• Poaching on wet soils in the absence of free water will induce less swelling. An ageing period following reworking will allow some regain in soil strength to minimise further damage.

5.4.2 Peat soil

Conclusions from exploratory laboratory tests

The following conclusions can be drawn from the laboratory tests:

• Volume/density changes of between 6-10% occurred when rewetting moist peat samples over a 83 day period. At the end of this period, approximately 50% of the samples had reached almost an effective equilibrium state, the remaining 50% were continuing to swell at a very slow rate. A further 6-9 months swelling would have been required for these latter samples, for a further 10% water uptake if the swelling rate had remained the same.
• Undegraded samples swell much more rapidly in the early stages than degraded samples. 80-90% of their 83 day volume was achieved within the first 1-2 days of swelling compared with 1-2 weeks for the same gain with the degraded samples. Their swelling rates at the end of the 83 day period also tended to be more than 10 times faster than the degraded.
• The overall percentage volume change of undisturbed small 25mm samples tends to be similar for both undegraded and degraded samples, even though the density of the undegraded is considerably less (50%) than that of the degraded.
• Increases in sample height (thickness) of degraded samples reduces the percentage volume increase, the upper half of the sample tending to swell less than the lower. This could be due to the poor wettability and/or the very low unsaturated hydraulic conductivity resulting from denaturing.
• The length of a drying period and the resulting increase in density have a major influence on the ability of undegraded peats to regain their initial density within a reasonable time on rewetting. Short drying periods with a 40% increase in sample density had no longer term effect, the samples more than regaining their initial density over the 83 day period. Increasing the drying time to one week and one month, however, initiating 180 and 470% increases in density, prevented the samples returning to their initial density within the 83 days, a further 9-10 months swelling at the 83 day rate being required for this.
• Degraded samples appear to have the ability to reswell to their initial density within at the most a 2-3 month period, even after considerable drying which increased their density by 470%.

Implications of results for remediation procedures and future avoidance of degradation

Based on the results of the exploratory tests, the following implications can be drawn with respect to reversing or preventing the denaturing process:

• The ability of a degraded peat to reswell towards its pristine state is very limited and swelling rates become exceptionally slow after the first few weeks of rewetting.
• Once severely degraded, further excessive drying has only a minimal impact on peat rewetting characteristics; the original degraded density being achievable on rewetting.
• Substantial drying and shrinkage of undegraded peat severely reduces its ability to reswell to its original density. Shorter limited drying periods, however, have minimal or zero effect on complete recovery.
• Degradation reduces the capillary rise characteristics considerably, requiring much higher water table levels for rewetting the surface layers.
6. WATER CONTROL TOLERANCE LIMITS AND FIELD WATER CONTROL MEASURES

6.1 WATER CONTROL TOLERANCE LIMITS

On wet-grassland sites with existing botanical interest, it would be necessary to consider the tolerance of the vegetation to raised water levels before embarking on a scheme to restore soil structure. In many cases it would be possible to halt and to reverse the deterioration processes without destroying the nature conservation interest of the sward. This would involve sensitive management of water levels in spring to avoid soil anoxia during the active growing season. The absolute tolerance of grass species and communities to waterlogging varies. These tolerances have been defined for most of the relevant species by previous MAFF-sponsored research (Project BD0209; Gowing et al., 1997b). The tolerances of plant communities are currently being determined by a continuation of that study (Project BD1310.) Quantitative information produced by such research would be able to guide the management of water at a specific site, in order that botanical diversity could be conserved.

All wet-grassland communities are tolerant of intermittent inundation during the winter, so there is an opportunity to re-wet soils during that season. Such a wetting period may be sufficient for initial rewetting in situations where only moderate compaction has occurred. The date at which the upper profile drains and the root-zone becomes re-oxygenated is a critical determinant of community composition. The mean date for soil aeration can vary from early March for some grassland types to late May for others. There is of course annual variation about these means and this tolerance could be exploited during a soil-remediation process. The ability to manage a site as grassland either by cutting or grazing the sward is an additional constraint on high water tables in the growing season. The soil must be sufficiently dry to support access by machinery or stock without sustaining further damage.

When considering soils which have suffered substantial deterioration and which can only be expected to re-wet very slowly, a 5-month period of intermittent inundation, maintaining a soil moisture deficit close to zero may prove insufficient for remediation. In such cases any existing wet-grassland flora may have to be lost if remediation of the soil is considered of higher priority. It should be noted here that soils, which are so damaged as to have lost their ability to re-wet and retain moisture, are rather unlikely to hold grassland species of conservation interest anyway. In these cases, it may be appropriate to establish a different vegetation community, such as a mire or a swamp, for the period of remediation. Such communities are tolerant of very-prolonged or even permanent inundation and thereby the scheme would be able to maximise the opportunity for rewetting. Managing surface water in this way may, however, be constrained by the requirements of adjacent land and flood-defence considerations. These wetland communities could be re-converted to wet grassland and brought back into regular management after the period of remediation.

6.2 FIELD WATER CONTROL MEASURES

Compaction and peat denaturing problems are closely associated with inadequate control over field water regime conditions, conditions being too wet, too dry or too variable for damage free grazing and machinery operations or peat conservation.

Field situations experiencing these problems fall broadly into two groups:

1. Lowland relatively flat areas, subjected to groundwater table control through open ditches and/or pipe systems. They may be subject to some surface flooding in winter and early spring and suffer significant potential soil moisture deficits during late spring and summer. They occur on both mineral and peat soils. Examples are situations within the Norfolk Broads and Somerset Levels.
2. Upland areas, often on sloping sites, subjected to perched water tables and surface water, in higher rainfall areas with relatively low potential soil moisture deficits. Examples are found in the Peak District and occurrence can be on both peat and mineral soils.

Lowland areas

Many observations, measurements and predictions clearly indicate that many existing ditch systems are too widely spaced with existing ditch water levels, to provide adequate water table drawdown in early spring and to maintain
high enough field water tables in late spring and summer to prevent excessive profile drying. (Spoor, et. al., 1996; Gowing, et.al.1997a; Gilbert, et al. 1997; Spoor et al. 1999) The problems in these situations are particularly severe within the central 60-70% of the field area between the ditches. The early spring problem, which results in wetter conditions for grazing, is often compounded on some nature reserves through the maintenance of very high ditch and field water tables right into the commencement of the growing season. In some areas also, surface drainage through surface grips or gutters is either absent or has been abandoned and hence surface water removal has to be through the soil profile to the ditches, which is a much slower process than by surface discharge.

The risk of compaction and degradation problems developing, whilst still maintaining satisfactory water regimes for the desired habitats, can be much reduced by matching ditch spacings to achievable ditch water levels, thus providing the required degree of water table control. Recommendations for the desired water regimes frequently only specify ditch water level requirements, neglecting spacing needs, which of course will vary depending upon the climatic conditions and the hydrological properties of the soil and site. The result unfortunately, is often unsatisfactory water regimes across considerable sections of fields, habitat requirements not being fully met and the area more prone to damage. Closer spacings would solve the problem.

Spacing adjustments can also compensate to some degree, for the inability to maintain high ditch water levels in situations where higher field water tables are desired. Closer spacing allows the maintenance of higher field water tables and more uniform water table depths between ditches with the same ditch water level. It also allows more rapid water table drawdown to meet aeration needs, or rise in the case of sub-irrigation.

In the less permeable clayey soils and peats, ditch spacing requirements for satisfactory water control may be too close to be practical from a surface management point of view. In these situations field experiments have shown that supplementing a wider spaced ditch system with intermediate subsurface pipes or moles can provide the same control as additional ditches, without interfering with surface management. (Hooker.1991, Walker.1995). Pipe systems would have to be avoided in situations prone to iron ochre formation due to blockage problems (Rands and Dennis,1991). Molding systems which can be replaced regularly at low cost if they become blocked or collapse, would still, however, be feasible.

From the previous discussions on wetting and swelling characteristics, the proximity of the water table to the damaged area and the ability of the water control system to provide sufficient water to avoid significant drying, are of considerable importance in remediation work. Spacing requirements in these situations may differ from those required after reclamation and frequently closer spacings would be needed during the remediation work. This requirement can readily be met in the form of a temporary moling system in both the clay and peat soils (Spoor,1995).

Upland areas

Particular problems arise in upland situations through surface compaction and poaching damage restricting water infiltration. Field investigations have identified situations where the top 50-75mm of the soil profile is extremely wet, sometimes accompanied by standing surface water, yet below, the soil is relatively dry. (Spoor.1999). The result is that even during relatively short drying periods, the surface layer dries out very rapidly, partly as a result of the lack of readily available stored water below to assist in keeping the surface moist through capillary rise. Improving water infiltration rates in these situations is, therefore, an important requirement

Pipe and mole water control systems

Ditch, pipe and mole water control systems have been compared on the peat soils of the Nene Washes, West Sedgemoor and King’s Sedgemoor, to assess their relative suitability and efficiency in maintaining desired field water regimes.( Hooker.1991, Walker.1995). The results showed that all were satisfactory, but that pipes and moles were rather less efficient than ditches in the drawdown situation. The rather poorer drainage performance was due to increased water entry resistance losses as a result of smaller inflow areas. This deficiency could be readily compensated for, however, by using slightly closer spacings.

Two types of moling equipment were compared, the traditional cylindrical type agricultural mole plough, developed for use on clay soils , which forms channel by compression and a peat mole plough. The peat mole plough mills out a rectangular channel at depth, the cut peat being lifted to the surface. This machine was developed for use on the North German Plain and has been used very successfully for complete water control and
peat conservation in grassland. The life of the milled mole channels is dependent particularly upon the density of the peat, the higher its density the longer the life, 5-20 years being common in the German situation (Scholz, 1986).

The exploratory trials with the milled moles proved very successful and they proved much superior to the cylindrical moles in terms of performance. They have the added advantage over cylindrical moles and pipes, that no peat drying is required before installation. Performance is most satisfactory in wet peat and ditches must be full, to allow water to be drawn into the cavity to lubricate the milling cutter as installation proceeds. This milled type mole offers considerable potential for improved water management at very low cost on peat soils.

The use of cylindrical mole channels for drainage in clay soils has been well proven in agricultural situations and exploratory trials on the Newchurch Series clay soils on Berney Marshes are showing promise as sub-irrigation carriers. Success in the sub-irrigation context with flooded mole channels will depend upon the water stability of the soil structural aggregates. This needs to be reasonably high, as is the case in the Berney Marshes soil.

These moling techniques, providing they are supported by further trials and development, should prove particularly valuable in providing temporary close spaced systems for remediation work and the peat mole plough in particular has considerable potential for effective water control and peat conservation in the long term.

7. SOIL FISSURING TECHNIQUES

In compacted conditions on mineral soils, both vertical and horizontal water movement is often restricted due to the loss of conducting macro-pores. New fissures need to be introduced throughout the profile in such situations and particularly through the compacted layers, to improve hydraulic conductivity and infiltration rates.

These fissures must be introduced with minimal damage to the plant communities and without undue soil loosening, otherwise the treated soil will be particularly susceptible to further poaching and recompaction damage.

Whilst fissures can be most readily produced under drier soil conditions, grassland damage is likely to be considerable and profile drying has other undesirable effects. Fissuring equipment must, therefore, be capable of generating fissures under moist conditions, leaving a level surface profile after the operation.

The most suitable types of equipment for meeting these requirements are low lift winged subsoilers, commonly used for alleviating problems in agricultural grassland (Spoor and Godwin, 1979). The action of these tools is to lift the soil mass and as it flows up and over the wings, it is placed in tension and vertical fissures are generated. The degree of soil lift and bending required to produce these fissures depends on working depth and soil condition, particularly moisture content. Too little lift fails to generate any fissures, whilst too much creates excessive soil disturbance and rearrangement. The ideal implement is, therefore, one with adjustable wings, where wing lift height can be adjusted to suit the prevailing conditions to initiate the soil fissures. Surface damage can be minimised by fitting flat discs immediately ahead of the tool legs, these create shallow slits ahead of the legs thus avoiding grass tearing. Leg spacings need to be at approximately 1.5 times working depth, to ensure the whole soil mass lifts uniformly, thus leaving a final level surface.

The soil fissures generated in these operations are usually spaced at approximately 150-250mm intervals and the soil between is left largely undisturbed. Whilst this is satisfactory from a bearing strength point of view, the compacted areas need reducing further in size, to allow more rapid and uniform swelling during the re-wetting process. A promising implement to achieve this is the ground driven rotating blade type slitter, developed for sports field use. This tool produces intermittently spaced vertical slits through the surface layers, reducing the size of the compacted units as well as improving water infiltration. The implement functions most satisfactorily under moist conditions and it should be adjusted so that the slitting depth extends through the most severely compacted zone.
8. FUTURE APPROACHES TO REMEDIATION.

The following recommendations are based upon reviewing the current situation, field experiences and the results and implications of the laboratory and other field studies reported in section 5.4.1. The clay soil and peat situations are assessed separately.

8.1 CLAY SOILS

8.1.1 Principles underlying any remediation process

*Initial soil swelling*

In any wetting process under conditions of low hydraulic conductivity such as in compacted soils, the length of the water flow path through the damaged area influences the rewetting rate. The shorter the flow path the greater the opportunity for water uptake. Reducing the size of the units within the compacted mass will, therefore, allow free water to reach more surfaces for water uptake.

Exceptionally long swelling periods would be required to reduce soil densities in many severely compacted situations and even if this were physically possible, it would be impractical from a time point of view. This initial swelling although worthwhile is, therefore, only a first stage in the improvement process and additional measures are required to progress the improvement to its end point. Soil aggregate swelling hopefully continues with time, even though at a very slow rate.

*Natural processes*

The additional measures required following the initial swelling, are the natural processes of wetting and drying and rooting and organism activity. It is critical during the improvement period and afterwards that there is no major reversal through severe drying to induce excessive shrinkage again.

The rate of improvement is now dependent upon the prevailing soil and weather conditions and whether the situation is one where compaction damage is severe but with minimal structural damage, or where serious structural damage has also occurred. The restoration will be much faster in the former case than in the latter.

To maximise the benefit from the natural processes, a favourable water regime is required with appropriate but not excessive air filled porosities in the surface layers. Excessive aeration encourages unwanted drying and a reversal in the improvement process. Rapid wetting and drying / swelling and shrinkage cycles will open up planes of weakness between the aggregates, transforming the soil into a more open condition, even though the soil aggregates themselves may still remain relatively strong. These cycles can occur at the higher moisture contents as a result of normal changes in weather patterns and consequential root water extraction and natural rewetting. Good water regime control and water availability are necessities to allow the diurnal / weekly moisture variations to occur without excessive drying during dry periods.

An active grass cover is also essential, not only to promote rapid root development and water abstraction, but also to protect the surface, thus preventing the extremes of surface drying which can occur on bare soil surfaces. Whilst different species or plant communities may prove more efficient in stabilising soil structure than others, no information on this aspect was found in the literature. The final timescale for improvement will depend upon the severity of the initial compaction, the accuracy of water regime control and subsequent surface management.

*Subsequent surface management*

Particular attention needs to be given to grazing management in terms of stocking density, animal type, the timing of grazing in terms of soil moisture status and the avoidance of grazing in the presence of surface water. Unsatisfactory grazing can rapidly reverse any improvement. If grazing damage is likely to occur, substituting grass cutting, either for hay or silage, using low pressure tyred equipment is a good alternative in the early years, until improved rooting increases the soil bearing strength to support animals.
Remediation based upon the above measures could be an exceptionally long process where structure regeneration is also required. A possible faster alternative would be to improve conditions before re-establishing grassland. Cultivation treatments together with additions of organic materials, lime or fertiliser where necessary, to encourage rooting and organism activity, would be appropriate. Any resulting increase in fertility which may be unsatisfactory for subsequent habitats could be reduced once soil conditions have improved. Such an increase in fertility would not necessarily be a problem for bird habitat.

Field observation (Gowing et al, 1997b) has shown very clearly that a very well structured soil of high porosity and high hydraulic conductivity is essential for species-rich flood-plain wet grassland. If such a habitat is the ultimate target, no swelling/fissuring/natural wetting and drying cycle measures are capable of providing such a soil condition. The soil condition must, therefore, be rectified through cultivation and associated measures, before any attempt is made to establish these communities.

8.1.2 Mechanical treatment requirements

In lowland compacted groundwater situations, soil fissuring will be required to depths below the compacted zone to aid more rapid water movement from supply ditches or pipes to the damaged areas. This fissuring must be achieved with minimal overall soil loosening, otherwise a significant loss in bearing capacity will result, making the area even more susceptible to poaching damage and re-compaction.

Where the compacted zone tends to be continuous and extensive laterally, surface slitting operations will be required to reduce the overall dimensions of the compacted units. The working depth of the slitting tines should be such as to penetrate through the main compacted layer. This operation is also necessary to improve water infiltration rates, to reduce the risk of short term surface water ponding.

Where excessively wide spaced ditches relative to the control ditch water levels, have been significant contributors towards the development of the problems, additional ditches or pipes will need to be installed. Spacings still may be too wide for the more precise water control needed during the restoration programme and in this situation, the installation of temporary mole drains for use as both drainage and sub-irrigation conduits will be necessary. Provision also needs to be made for the rapid control of surface water when necessary, with the installation, if not already present, of controllable outlet/inlet surface grips/gutters.

In high rainfall upland situations, slitting operations constitute the primary need to increase the area of wetting surfaces in the compact zone and to improve the water infiltration characteristics to ensure the wetting up of the sub-surface layers, thus reducing the risk of surface water ponding. Slitting operations should penetrate through the compacted layer. A deeper fissuring operation may also be beneficial in situations where water movement is restricted at depth and with suitably spaced tines, it can reduce the extent of local surface depressions, thus reducing local surface water ponding.

8.2 PEAT SOILS

The extent to which severely denatured peats can be restored is still not particularly clear, it will depend on the peat type and there are likely to be situations, particularly when the peats are becoming drummy in nature, when it becomes impossible. Based upon the conclusions and implications drawn in section 5.4.2, where possibilities for restoration do exist and degradation has been serious, the time scale for success is likely to be very great. One clear requirement, however, is that remedial measures need to be directed towards maximising the opportunity time for water uptake at low or zero moisture tensions, together with the avoidance of significant drying.

Possible ways of achieving this long term wetting include the following:

- Long term flooding with the possible encouragement of mire communities. These areas could be re-converted back to wet grassland once the desired improvement had been achieved.
- In situations where the volume of denatured peat is not excessive, mixing with undamaged peat would help restore some of the lost capillary rise properties within the mass. Such an improvement would enable the degraded material to be wetted with time with lower water tables.
Where larger volumes are involved, deeper burial to a zone which is likely to be continually below the water table would maximise the opportunity for recovery. Before, however, mixing or burial is contemplated, some firm assurance would be required that reversing the denaturing process was possible for that particular type of peat.

The most important conclusion coming from both field experience and the laboratory results, is that every effort must be directed towards preventing any further deterioration of peats which still retain their desirable properties. Careful water management is needed to achieve this, and to avoid excessive drying and shrinkage, and minimise oxidation.

8.2.1 Mechanical treatment requirements

In situations where current ditch spacings with associated ditch water levels are too wide to maintain the desired field water table levels, additional ditch or subsurface conduit systems will be necessary to provide the desired degree of control. The subsurface conduits could be in the form of pipes or milled mole channels.

In upland high rainfall areas where water infiltration rates have declined, slitting techniques will assist in improving infiltration. This increased infiltration will increase the water storage in the upper layers of the profile, which acts as a buffer against surface layer drying during shorter dry periods.

9. FUTURE RESEARCH NEEDS

9.1 REMEDIATION MEASURES FOR CLAY SOILS

The approaches necessary for the remediation of compaction problems on clay soils are now clearly defined for both lowland and upland situations. The future research requirement is, therefore, to test and develop these approaches on a field scale for extended use. Particular aspects to be considered include soil fissuring and slitting procedures and the provision of temporary water control measures to provide the desired remediation water regimes. A key component of the work must also be the identification of appropriate subsequent management measures to continue the improvement process, avoid reversals and stabilise the resulting condition.

Appropriate contrasting soils for the lowland trials would be the calcareous marine alluvium Newchurch Series and the non-calcareous river alluvium Fladbury Series, soils both very common in ESA situations. The non-alluvial micaceous Dale Series soil, common in the Staffordshire and Derbyshire Peak area and low being targeted for additional wetting support, would be appropriate for the upland investigations.

9.2 REMEDIATION MEASURES FOR DEGRADED PEAT SOILS

Approaches for the remediation and recovery of degraded peat soils are much less well defined than for the clays and the extent to which improvement may even be possible is still uncertain. Research priority, therefore, needs to be given to further laboratory studies on different peat types, suffering from different degrees of degradation, to assess possibilities and approaches for recovery. The swelling tests need to continue over a much longer time period than was possible within this study. Use of the density/moisture content relationships identified within this project (section 5.3), coupled with changes in moisture release characteristics, should prove satisfactory indicators, with the required sensitivity, to enable the important remediation parameters to be quantified.

Close control over field water tables will be essential in any remediation process, just as it is now for the avoidance of deterioration and the conservation of current peat sites. As water control on many of these sites, including the "bumpy fields" (Spoor and Burton, 1997), is inadequate due to too widely spaced ditch systems, field trials are required to assess the potential of the milled mole technique to satisfactorily support the ditch systems. These water management trials should be installed on a range of peat soils, differing in their density at moling depth, to identify situations where they would prove successful and to determine their expected life.

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REFERENCES


