Defra/Natural England project BD5001:
Characterisation of soil structural degradation under grassland and development of measures to ameliorate its impact on biodiversity and other soil functions

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1 Executive Summary

There are approximately 5 million hectares of managed grassland in England and Wales representing c.60% of the agricultural area (i.e. excluding rough grazing). Structural degradation in grassland soils can reduce the ability of grasslands to perform important ecosystem services, such as water regulation (including reducing flooding risk), food provision (crop production), climate regulation, nutrient cycling and support for biodiversity.

The main objective of the project was to better understand the nature of soil structural degradation in enclosed grasslands and to identify and evaluate physical (including mechanical) and biological measures that may be used to alleviate its negative impacts on soil functions, including biodiversity. The specific objectives were to evaluate methods (mechanical loosening and the introduction of deep-rooting herbs and legumes) which could be incorporated into agri-environment schemes in England and Wales, and to assess the impact of soil compaction and alleviation on a number of soil physico-chemical and bio-physical properties, greenhouse gas emissions, grassland productivity and biodiversity (with a focus on invertebrates and birds).

The survey of grassland soil condition in England and Wales, carried out as part of this project (BD5001), indicated that 2 - 3 million hectares of grassland in England and Wales were in ‘moderate’ physical condition and that 500,000 - 750,000 hectares were in ‘poor’ condition, thereby potentially compromising the delivery of important ecosystem services.

Results from the survey of grassland soil condition were used to identify four ‘high bulk density’ sites (three ‘medium’ textured and one ‘light sandy’) to investigate the effectiveness of (shallower and deeper) mechanical loosening and the introduction of deep-rooting herbs and legumes in alleviating soil compaction, and improving the ability of these grassland soils to provide vital ecosystem services. Replicated and randomised plot field experiments were used to investigate treatment effects and interactions between treatments over eight seasons (four years) on the following parameters:

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In addition, a split-field mechanical loosening study investigated the impact of mechanical loosening on bird foraging behaviour at the field scale.
Mechanical loosening gave rise to the most consistent (across all four sites) and prolonged effects on soil physical properties and notably substantially increased water infiltration rates (over a thirty month period). Deeper mechanical loosening had the greatest impact on water infiltration rates, resulting in 4- to 10-fold increases in water infiltration rate on the three 'medium' textured sites. This was due to the fracturing and lifting of the topsoil, creating large fissures, which connected the soil surface to the subsoil, and was associated with reduced soil penetration resistance and better (higher) visual evaluation scores. However, mechanical loosening reduced the number and biomass of earthworms at the Nafferton (medium soil) site in year one after loosening, with the effects of shallower loosening lasting into a second year and recovery in numbers thereafter in both the deeper and shallower loosened treatments. If this represents a typical response, there are implications for the viability of recommending mechanical loosening, since earthworms contribute to soil fertility and structure in agricultural grasslands.

Deeper mechanical loosening increased total root length \((P<0.001)\) below 10–20 cm depth, but had no effect on grass dry matter yields relative to the unloosened control \((P>0.05)\). Notably, mechanical loosening (or ‘sward lifting’) has an important role to play in reducing flooding risks and increasing slurry infiltration rates into grassland soils.

Deep-rooting herb and legumes
Power-harrowing, used to create establishment niches in the ryegrass sward for the deep-rooting herb and legume mix, decreased water infiltration rates in the first year, mainly due to a reduction in the size and continuity of macropores in the cultivated layer. There were no effects on water infiltration rates in years two and three, which indicates a degree of recovery from the cultivation effects. Addition of the seed mix improved plant species diversity and increased grass yields relative to the ryegrass control that received no nitrogen (N) fertiliser. There was also a measurable increase in microbial biomass N at one of the sites due to the seed mix. The introduction of forb and legume mixes could have an important role to play in supporting production and biodiversity in low input grazing livestock systems.

Bird foraging behaviour
At the Nafferton experimental site, neither mechanical loosening nor the introduction of the deep-rooting herb/legume mix had any effect \((P>0.05)\) on bird foraging behaviour or success. In the field-scale study at 15 sites comparing loosened and un-loosened split fields, foraging birds showed no preference for either half of the fields. These data indicate that grassland loosening/amelioration is not likely to be effective in improving the breeding success of foraging birds.

Conclusions
This study has provided valuable information about management of ‘high bulk density’, medium to light textured grassland soils to deliver key ecosystem services. Mechanical loosening is a practical option for increasing water infiltration rates and could have significant local impacts in reducing water runoff volumes and, importantly, flooding risks. The introduction of deep rooting herbs and legumes can play an important role in supporting productivity and biodiversity of low input grazing livestock systems. However, more information is needed on the impact of such options on heavy textured and poorly structured soils. Notably, these soils occupy large areas in high risk catchments where the structural condition of grassland soils plays a key role in the local delivery of vital ecosystem services, such as water regulation (i.e. flood risk mitigation), food provision, climate regulation and support for biodiversity.
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2 Introduction and background

There are approximately 5 million hectares of managed grassland in England and Wales representing c.60% of the agricultural area (i.e. excluding rough grazing). Grassland soils provide a number of provisioning and regulating services, including food production, climate change mitigation and flood regulation, and also perform an important habitat support role. However, the ecosystem services provided by grassland soils are ‘under pressure’ from livestock grazing and machinery use etc. Notably, a survey of grassland soil condition in England and Wales, carried out as part of this project (BD5001), indicated that 2 - 3 million hectares of grassland in England and Wales could be in ‘moderate’ physical condition and that 500,000 - 750,000 hectares may be in ‘poor’ condition, thereby potentially compromising the delivery of these ecosystem services (Newell Price et al., 2013).

Over the past twenty to thirty years, there have been a number of changes in grassland management that could have resulted in a greater degree of structural degradation in grassland soils. These have included a general increase in the size of agricultural machinery and greater use of contractors for grass harvesting and manure spreading (Hakansson & Reeder, 1994; Batey, 2009). In the 1980’s, wheel loads of 50 kN were considered to be high, but by 2001 the use of 90-120 kN wheel loads was common place (Van den Akker and Schjønning, 2004). There may also have been an increase in the use of extended grazing seasons and outwintering of livestock in some areas (c.55% of livestock farmers outwintered livestock in 2008 – Defra, 2008).

Increases in soil structural degradation may have threatened the ability of agri-environment schemes to achieve objectives (Defra project BD2304); particularly those related to biodiversity, including restoration of species-rich grasslands (Moore and Gowing, 2007; Roovers et al., 2004) and recovery of farmland bird populations (Gilroy et al., 2008; Wilson et al., 1999), but also those related to improving water quality and reducing soil erosion. In addition, there is growing evidence that soil structural degradation may have implications for flood management, water resources and air quality (e.g. Carroll et al., 2004). Clearly, any mitigation methods introduced to help alleviate compaction, and thereby improve the ability of soils to perform these numerous functions, will also need to ensure the conservation of archaeological features and artefacts.

Defra project BD2304 (“Scoping study to assess soil compaction affecting upland and lowland grassland in England and Wales”) provided a comprehensive review of likely causes and impacts of compaction in grassland soils, covering possible impacts on soil flora and fauna, plant communities, birds, water resources (and flood risk) and the diffuse pollution of water and air. The project also intimated that replicated field experiments would be needed to test the effectiveness of mitigation methods to improve soil structural condition and enhance the delivery of multiple ecosystem services. It was suggested that “products are on the market that offer solutions to soil compaction under grassland such as soil loosening and robust trials of these systems are needed…(so) that their impacts on biodiversity can be established. Considerations should also be given to the development of management practices that can manipulate soil fauna that will contribute to the reconditioning of compacted soils.”

There was therefore clearly a need to carry out research into the effectiveness of mitigation methods in improving soil structural condition in soils with ‘typical’ levels of structural degradation (i.e. reduction in porosity and increase in the size and angularity of soil structural units/peds). The key policy question to be addressed was whether or not mechanical or biological methods to remediate soil structural degradation could be effective in improving the ability of soils to meet agri-environment scheme objectives, such as supporting biodiversity, improving water quality and reducing surface runoff. The results are also relevant to Defra’s aim to ensure that all soils are managed sustainably by 2030 to safeguard their ability to provide essential ecosystem goods and services for future generations (Defra, 2011).

This report describes field experiments carried out at four ‘high’ bulk density (BD) sites in England and Wales to investigate the impact of mechanical loosening and the introduction of deep-rooting herbs and legumes on soil physical properties, dry matter (DM) yield, water...
infiltration rates, nitrous oxide emissions, soil microbial respiration and biomass, earthworms (number and biomass) and bird foraging. The key results are presented and discussed, including interactions between treatments and relationships between measured variables. The implications of the results for grassland management and the advice and possible incentives that could be provided to farmers to adopt or retain land management strategies are also discussed.
3 Project objectives and activities

The main objective in this project was to:

1. Better understand the nature of soil structural degradation in enclosed grasslands and to identify and evaluate physical (including mechanical) and biological measures that may be used to alleviate its negative impacts on soil functions, including biodiversity.

To achieve the overall project objective, there were a number of specific research objectives, viz:

i) Characterise soil structural degradation in grassland fields in England and Wales.

   Activity: Survey a total of 300 grassland fields across England and Wales covering both grazed fields and fields under a silage or hay regime. Characterise the fields according to the specific grassland type, management system and soil type and carry out soil penetrometer, shear vane and bulk density measurements; and visual soil assessments to determine the nature of soil compaction).

   Output: Characterisation of grassland soil compaction according to soil type, grassland type and management system across a wide range of sites in England and Wales; to better understand the nature and extent of soil structural degradation to determine appropriate action for policy makers and advisers.

ii) Identify measures which could be incorporated into agri-environment schemes in England and Wales.

   Activity: Carry out detailed literature searches to obtain a comprehensive list of candidate plant species to introduce to grasslands to alleviate compaction, and to explore the impacts of mechanical soil loosening in grasslands. Agree with Defra a short list of mitigation methods (both biological and mechanical) to apply to a selection of grassland fields that represent 'typical' grassland farming systems in England and Wales.

   Output: Recommendations for field studies to investigate the impact of soil compaction mitigation methods (both biological and mechanical) on soil productivity, biodiversity, water infiltration and nitrous oxide emissions.

iii) Evaluate methods (mechanical loosening and the introduction of deep-rooting herbs and legumes), which could be incorporated into agri-environment schemes in England and Wales.

   Assess the impact of soil compaction and treatments on:
   - soil structure/soil compaction
   - soil carbon storage
   - soil water infiltration rates
   - vegetation composition (ability to restore grassland plant communities)
   - vegetation palatability
   - invertebrates and soil biota (microbial communities)
   - bird foraging
   - biomass production
   - nitrous oxide emissions

   Activity: Implement soil compaction mitigation methods in randomised plots at four field experimental sites in England and Wales. Implement field studies to investigate the impact of compaction and alleviation of compaction on the parameters listed above.

   Output: An assessment of the practicability and effectiveness of biological and mechanical mitigation methods to alleviate compaction and improve soil functions, including an assessment of the ecological processes/mechanisms involved.
4 Methodology

4.1 Characterisation of soil condition under grassland

To meet the project objectives, ADAS carried out a survey of 300 grassland fields across England and Wales (between January and March 2010), covering both grazed fields and fields under a cutting (silage or hay) regime. Fields were characterised according to grassland type, management system and soil type. Soil penetrometer, shear vane and bulk density (BD) measurements, and visual soil assessments were carried out to evaluate soil structural conditions. Farm and field-level questionnaires were completed in an attempt to relate land management practices to soil conditions.

The aim of the soil compaction survey was to establish the extent and severity of soil compaction in 300 fields in the main grassland areas of England and Wales and to investigate links between soil physical properties and management practices. The survey also aimed to represent the full range of soil compaction pressures on grassland farming systems from silage ground on high output dairy farms, to species-rich hay meadows on extensive beef and sheep farms, using a combination of both field and laboratory measurements.

The survey was stratified according to climate, farm type, grassland system and soil type, and was designed to represent the regional distribution of grassland cross-compliance soil types, thereby enabling a robust assessment of the extent of soil compaction over a wide range of grassland soils and farming systems. This stratified approach could potentially be used to assess the extent of soil structural degradation problems in grasslands.

Sites were identified using ADAS’ regional network of advisers and in consultation with Natural England, England Catchment Sensitive Farming Delivery Initiative (ECSFDI) catchment officers, Welsh agri-environment monitoring associates and contacts within the livestock industry (e.g. Dairy Co, Kingshay).

The survey was split into two stages:

- **Stage 1** involved a survey of soil conditions in 300 grassland fields, focussing on characterising compaction within the topsoil.
- **Stage 2** involved more detailed investigations of compaction and soil structure at 30 of the more compacted sites (above the 75th percentile as defined by surface soil BD) to provide a more detailed assessment of the extent and nature of soil structural degradation at these sites; and investigate relationships between different measurements of soil physical quality.

Sample stratification was based around agri-climate zones and was designed to reflect the proportion of dairy farms and beef/sheep farms in each zone. The sampling strategy covered three climate zones (average annual precipitation of > 900 mm; 700-900 mm; and < 700 mm – as used in Defra project WQ0106 to represent the range of climatic conditions in England and Wales) and reflected the proportions of managed grassland in each climatic zone.

Sites were restricted to grassland ≥ 5 years old (some of which may be regularly reseeded) and were selected to cover the main cross-compliance soil types; i.e. Heavy/Medium/Sandy-Light Silty/Chalk-limestone/Peaty. Soil types at the sites were defined by topsoil texture and, in the case of ‘Chalk-limestone’ and ‘Peaty’ soils, depth/parent material and soil organic matter (SOM) content respectively. This classification is distinct from RB209 soil types (Defra, 2010), which are defined by the depth and texture of the topsoil and subsoil or in the case of RB209 ‘organic’ and ‘peat’ soils, SOM content.

It was considered that variations in soil structural conditions were most likely to be determined by soil type, field use/history and ease of access from buildings and roads than geographical region. The strategy was designed to sample fields that were mainly cut (particularly for silage) to compare with fields that were mainly (or exclusively) grazed over the previous five years. The
aim was to select two fields on each farm with contrasting cutting and grazing management, with cutting/grazing information for the previous five years recorded. For some farms this meant that the *mainly cut* field was typically cut four times for silage and the *mainly grazed* field was only grazed. In other cases, there was less of a contrast and one field may have been cut twice then grazed, while the other was cut once then grazed. However, a distinction was always maintained such that on each farm the *mainly cut* field was always cut more frequently than the *mainly grazed* field. As part of the selection process we also established the age of the sward, whether the grass was in rotation with arable or forage crops, and whether the current sward was established following ploughing or reduced cultivation.

A more detailed explanation of the site selection strategy and the final sampling stratification is given in Appendix 1. The location of the 150 selected farms across England and Wales is shown in Figure 1.

4.1.1 Stage 1 - Field measurements in 300 grassland fields

In this first stage, the focus was on characterising compaction within the topsoil. Topsoil condition is critical to many soil functions, including water infiltration and storage, biomass production, soil carbon storage and nitrous oxide emissions, and biodiversity (see Appendix 1).

At each site, the main part of the field was sampled, excluding field margins and small areas, such as isolated wheel ruts or poached areas around feeders. For the purposes of soil biodiversity and the majority of soil functions it is the soil conditions in the greater proportion of the field that are important and not minor areas. Specific areas, such as gateways, ring feeders and drinking troughs can be foci for soil and diffuse pollution issues, but the overall impact of such areas depends on their proximity to receptors and their hydrological connection with other landscape features (Heathwaite et al., 2005). It was not the purpose of this study to address these ‘point source’ areas, but rather the ability of the majority of the grassland area to perform key environmental and production functions.

In each field, we carried out the following measurements to characterise the nature of soil structural conditions:

- Topsoil visual assessments (Landcare and Peerlkamp methods)
- Cone penetrometer tests (to 20 cm depth)
- Shear vane tests (0-5 cm)
- Soil bulk density (0-10 cm) measurements
- Gravimetric soil water content (0-10 cm)
- Soil organic carbon (both modified Walkley Black and loss on ignition methods) (0-7.5 cm)
- Total nitrogen (0-7.5 cm)
- Particle size distribution (i.e. sand, silt and clay contents) (0-7.5 cm)

Field measurements were carried out over winter when soils were ‘moist’ or close to field capacity, so measurements between fields were taken under comparable conditions. A cone penetrometer was used to quantify the range of (maximum) penetration resistance values at twenty randomly selected points across the main body of the field (i.e. not including isolated poached areas or tracks) to a depth of 20 cm. Then at the three points where the maximum, median and minimum penetration resistance values were measured, a soil bulk density (BD) sample was taken from the 0-10 cm layer and a structural assessment of the top 20 cm was carried out using the Visual Soil Assessment (VSA) method (Shepherd, 2000) and the Peerlkamp method (Peerlkamp, 1967).
Figure 1. Location of grassland compaction sites and distribution of cross-compliance soil types.
4.1.2 Stage 2 – 30 short-listed sites
The 30 sites for more detailed analysis were selected as outlined below:

- Soils that had BD values above the 75th percentile in each soil type group, covering both ‘mainly cut’ and ‘mainly grazed’ fields
- Soils with BD values equal to or greater than 1.1 g/cm³
- The number of ‘mainly cut’ and ‘mainly grazed’ sites was weighted in proportion to the number of grassland soils in each category with BD values equal to or greater than 1.1 g/cm³ (23% of ‘mainly grazed’ fields and 37% of ‘mainly cut’ fields had BD values greater than 1.1 g/cm³)
- The number of beef/sheep and dairy farms was weighted in proportion to the land areas covered by each enterprise type (i.e. c.60% of the farm types were beef/sheep and the remainder dairy)

Nineteen of the selected sites were ‘mainly cut’ fields and 11 ‘mainly grazed’ fields. Thirteen were on dairy farms and 17 on beef/sheep farms; two were ‘chalk/limestone’ soils, 6 ‘sandy/light silty’ soils, 11 ‘medium’ clay loam soils, 5 ‘heavy’ clay loam soils and 6 ‘heavy’ soils. Further details of the 30 selected sites are summarised in Appendix 1.

At the 30 short-listed sites, three soil profiles were described to 80 cm depth (assessing colour, mottling, structure, rooting, stoniness and earthworm channels) and soil BD at 0-10 cm, middle of the topsoil and top of the subsoil was measured. The above assessments provided a detailed assessment of the extent and nature of soil structural conditions at 30 of the more strongly ‘compacted’ sites. Soil profile descriptions were made at each site and chi-squared tests used to test for any differences in soil structural characteristics according to farm type, management type and age of sward. Generalised linear models (GLMs) were also used to investigate whether any soil and management variables were good predictors of BD or visual evaluation score (Appendix 1).

4.2 Field experiments - to evaluate mitigation method effectiveness

4.2.1 Site selection
The results from the grassland compaction survey were used to inform selection of four field experimental sites to test mechanical remediation of compaction and its interaction with the introduction of legumes and deep-rooting herbs (Figure 2). Apart from field experimental sites being ‘compacted’ (i.e. high in topsoil BD), other important considerations in site selection were access, the size and slope configuration of the field, uniformity of soil type and level of farmer interest (other considerations specific to the site are mentioned below). The four selected field experimental sites were:

- **Nafferton** - one of the most compacted sites (as defined by soil BD and structural discontinuity) in the north of England. Also, the site was well located for the bird foraging investigations to be carried out in 2011-12 (within a few miles of suitable bird housing).
- **Odstone** - one of the most compacted sites (as defined by soil BD) in central England. Also, compared with other possible sites in central England, the soil type was uniform across the experimental area.
- **Aberbran** - one of the most compacted sites (as defined by soil BD) in Wales. This site was chosen as the soil type and rainfall was typical of Wales and the site had deeper topsoil compaction (one of the factors considered during the selection process).
- **Bicton** - one of the most compacted sites (as defined by BD values and soil structural condition i.e. subangular blocky or massive below 10 cm) in the south west of England.
4.2.2 Experimental design

A large split-plot replicated field experimental design was used at all four sites using randomised blocks. The main block size was 24 x 16 m, with 6-12 m between blocks and 10-12 m headlands. Individual plot size was 8 x 16 m. All plots were established at the 4 sites, using a randomised block design with four replicates of each treatment. The field experiments were designed to investigate the effectiveness of mechanical (drawing upon the findings of the ‘Mechanical loosening’ Literature Review in Appendix 2) and biological (plant species) methods (drawing upon the findings of the ‘Plant species’ Literature Review in Appendix 3) in alleviating soil compaction and improving soil functions. There were nine treatments, as follows:

1. Untreated control - **uncultivated**
2. Shallower (c.20 cm) loosening - **uncultivated**
3. Deeper (c.35 cm) loosening – **uncultivated**
4. No loosening - **power-harrow, without species introduction**
5. Shallower (c.20 cm) loosening - **power-harrow, without species introduction**
6. Deeper (c.35 cm) – **power-harrow, without species introduction**
7. No loosening - **power-harrow + species mix**
8. Shallower (c.20 cm) loosening - **power-harrow + species mix**
9. Deeper (c.35 cm) loosening – **power-harrow + species mix**

The power-harrow treatment was designed to create at least 50% bare ground/gaps as suitable regeneration niches (RDS, 2009 – Technical Advice Note 29).

At each site, baseline botanical assessments were carried out in July 2010 and the rotavation, seeding and loosening operations (Table 1 and Plate 1) were carried out under suitable conditions between mid-August and early September 2010. Rotavation and mechanical loosening operations were carried out when the soil to be ‘cultivated’ was in a friable consistency state.
Table 1. Depths and dates of loosening at the four field experiment sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Nafferton</th>
<th>Odstone</th>
<th>Aberbran</th>
<th>Bicton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>02/09/10</td>
<td>19/09/10</td>
<td>13/09/10</td>
<td>08/09/10</td>
</tr>
<tr>
<td>Shallower loosening depth (cm)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Deeper loosening depth (cm)</td>
<td>35</td>
<td>30</td>
<td>35</td>
<td>30</td>
</tr>
</tbody>
</table>

Plate 1. Mechanical topsoil loosening at Aberbran on 13 September 2010.

The deep-rooting herb and legume mix was selected following a review of plant species for the alleviation of soil compaction in grasslands (see section 5.3 and Appendix 3) and discussions with the project Steering Group (Table 2). Nine candidate species were identified as having potential for alleviating soil compaction in agricultural grasslands (and available commercially), plus 2 further species that might be suitable on specific soil types. Another 8 species with suitable traits were rejected because they either had low establishment rates, low forage quality or would be unacceptable in an agricultural sward. The 9 candidate species identified in the BD5001 review (Tables 2 and 8) were selected and included as a mitigation method to be tested in the BD5001 field experiments. The other mitigation method tested was mechanical loosening using sward lifters (see section 5.2) at two specific depths. These experiments investigated the potential of the selected plant species to alleviate grassland soil compaction in isolation and in combination with mechanical loosening. One hypothesis is that the selected plant species could potentially exploit the mechanically loosened soil and thus increase the duration of the mechanical loosening effect and perhaps increase the soil’s resistance to re-compaction by establishing roots and mycorrhizal associations within and around loosened soil aggregates.
Baseline soil sampling and analysis was carried out on each replicate block at each site (Table 3). In the first nine months following over sowing, livestock grazing was carefully managed at each site when soils were ‘wet’ and liable to damage, to ensure that compaction did not occur as a result of livestock trampling.

Table 2. Deep-rooting herbs and legume mix.

<table>
<thead>
<tr>
<th>Latin name</th>
<th>Common name</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deep-rooting herbs and legumes</strong></td>
<td></td>
</tr>
<tr>
<td>Achillea millefolium</td>
<td>Yarrow</td>
</tr>
<tr>
<td>Centaurea nigra</td>
<td>Common Knapweed</td>
</tr>
<tr>
<td>Cichorium intybus</td>
<td>Chicory</td>
</tr>
<tr>
<td>Hypochaeris radicata</td>
<td>Catsear</td>
</tr>
<tr>
<td>Lotus corniculatus</td>
<td>Birdsfoot Trefoil</td>
</tr>
<tr>
<td>Plantago lanceolata</td>
<td>Ribwort Plantain</td>
</tr>
<tr>
<td>Sanguisorba minor subsp. muricata</td>
<td>Forage Burnet</td>
</tr>
<tr>
<td>Trifolium pratense var. pratense (wild)</td>
<td>Wild Red Clover</td>
</tr>
<tr>
<td>Trifolium pratense var. sativum (commercial)</td>
<td>Commercial Red Clover</td>
</tr>
<tr>
<td>Trifolium repens (small-leaved)</td>
<td>Small-leaved White Clover</td>
</tr>
<tr>
<td>Trifolium repens (large-leaved)</td>
<td>Large-leaved White Clover</td>
</tr>
<tr>
<td><strong>Grasses</strong></td>
<td></td>
</tr>
<tr>
<td>Agrostis capillaris</td>
<td>Common Bent</td>
</tr>
<tr>
<td>Anthoxanthum odoratum</td>
<td>Sweet Vernal-grass</td>
</tr>
<tr>
<td>Cynosurus cristatus</td>
<td>Crested Dog’s-tail</td>
</tr>
</tbody>
</table>

‘Normal’ farming practice was carried out across the experimental plots, although these were tailored to individual sites to optimise species establishment. For example, at each site in the spring following mechanical loosening, sheep were used in short (c.12-24 hours), single grazing periods to control sward height and avoid shading out of introduced species (Appendix 6).

Lime and major nutrients (apart from nitrogen) were applied on all study sites according to recommendations in the “Fertiliser Manual (RB209)” (Defra, 2010). Mollusc control was used to reduce seedling predation, but only after assessing the potential effects on soil invertebrate and bird foraging. To encourage the deep-rooting herb and legume mix, nitrogen fertiliser applications were limited in the first year (40 kg N/ha) and not applied thereafter, apart from on one side of treatments 1, 2 and 3 (original sward – 12 plots) to simulate standard farming practice in 2012 at Odstone, Aberbran and Bicton and again at Odstone in 2013 (Table 4).

The application of manufactured N fertiliser according to standard practice enabled investigation of the effects of loosening, deep-rooting herbs/legumes and manufactured fertiliser N use on biomass production and soil bio-physical properties. Furthermore, additional measurements on the split plots allowed us to test the hypothesis that deep-rooting herbs/legumes can provide greater improvements in soil bio-physical properties than either conventionally fertilised or unfertilised grassland.
Table 3. Baseline soil analysis results for the four experimental sites (0-7.5 cm sampling depth).

<table>
<thead>
<tr>
<th>Determinand</th>
<th>Units</th>
<th>Nafferton</th>
<th>Odstone</th>
<th>Aberbran</th>
<th>Bicton</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>Unit</td>
<td>5.9</td>
<td>6.9</td>
<td>5.6</td>
<td>5.7</td>
</tr>
<tr>
<td>Cross-compliance soil type</td>
<td>-</td>
<td>‘Medium’</td>
<td>‘Medium’</td>
<td>‘Medium’</td>
<td>‘Sandy and light silty’</td>
</tr>
<tr>
<td>Total Nitrogen (N)</td>
<td>% dm</td>
<td>0.29</td>
<td>0.25</td>
<td>0.21</td>
<td>0.17</td>
</tr>
<tr>
<td>Organic Carbon¹</td>
<td>% dm</td>
<td>2.9</td>
<td>2.3</td>
<td>2.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Organic Matter²</td>
<td>% dm</td>
<td>5.0</td>
<td>4.0</td>
<td>3.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Bulk density</td>
<td>g/kg</td>
<td>1.36</td>
<td>1.44</td>
<td>1.27</td>
<td>1.30</td>
</tr>
</tbody>
</table>

¹ via dichromate oxidation (Modified Walkley Black method)
² Organic carbon multiplied by 1.724 (MAFF, 1986)

Table 4. Manufactured fertiliser application rates in 2012 (Nitrogen was applied to half the plot on treatments 1, 2 and 3. Phosphate, potash and sulphur were applied to all plots).

<table>
<thead>
<tr>
<th></th>
<th>Nafferton¹</th>
<th>Odstone</th>
<th>Aberbran</th>
<th>Bicton</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kg/ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen prior to 1st cut</td>
<td>-</td>
<td>100</td>
<td>120</td>
<td>80</td>
</tr>
<tr>
<td>Nitrogen post 1st cut</td>
<td>150</td>
<td>40</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>Phosphate (P₂O₅)</td>
<td>-</td>
<td>40</td>
<td>70</td>
<td>15</td>
</tr>
<tr>
<td>Potash (K₂O)</td>
<td>-</td>
<td>80</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>Sulphur (SO₃)</td>
<td>-</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>

¹ field under organic production
4.2.3 Annual measurements
At all four field experimental sites, the following measurements were made on all plots on an annual basis (including an additional measurement of water infiltration rate in 2014 at the medium textured sites):

- Soil compaction - penetrometer, shear vane and bulk density measurements on each plot
- Grassland plant communities - presence and percentage cover of all plant species, vegetation structure
- Soil water infiltration rates

Above ground biomass yields were measured in 2011, 2012 and 2013 where a first cut of hay or silage were taken, to determine the effect of the soil loosening techniques and plant species on grassland productivity. Grass samples were also taken and analysed for D-value as a comparative measure of the palatability of introduced species for livestock.

Vegetation measurements were assessed annually before the first silage cut in May 2011, 2012 and 2013, from six fixed quadrats in each plot. Five measurements of vegetation height were taken per quadrat using a sward stick with a drop disk (drop disk diameter 12cm, weight 15.7g). Vegetation density was assessed by recording the lowest 10 cm mark on the sward stick that was visible above or through the vegetation. The percentage cover of all plant species rooted in the quadrat, and of bare ground, were assessed by eye.

The number of individual plants of the sown forb species was counted from the quadrats in the 12 plots per site subjected to Treatments 7, 8 and 9 (i.e. introduction of the deep-rooting herb and legume mix). *T. repens* was excluded because it was already present in the sward in some of the sites, and the two varieties of *T. pratense* were treated as a single species because they could not be separated accurately in the field. The size of three randomly selected individuals per quadrat of each forb species (if present) was measured. ‘Size’ was defined as the maximum width of spreading plants or height of upright plants, whichever was greater.

At each experimental site, conventional analysis of variance (ANOVA) comparisons were made between the contrasting replicated treatments. Additionally, the pooled data was analysed to assess the effects of treatments across all four sites (i.e. a cross-site analysis was undertaken). Relationships between treatments and sites were investigated further using *generalised linear mixed models* (GLMMs). This enabled us to enhance our interpretation of the data and in particular, interactions between the different treatments and soil physico-chemical and biophysical properties. Effects of site, year and treatment were assessed using the Laplace method for estimating parameters. Data for all sites was included in models for initial and saturated water infiltration rates, with site and replicate block nested within site, both specified as random effects. The GLMM models also included year and some included treatment as either a nine level factor (corresponding to the nine treatments) or as a three level factor (e.g. unloosened; shallower loosened; and deeper loosened).

**Plant community and sown species – data analysis**

Differences in the cover, counts and sizes of sown forbs among sites and loosening treatments (shallower, deeper and unloosened) were assessed using analysis of variance (ANOVA) models in Statistica v11 software (Statsoft, 2012). Cover data were transformed to arcsine √x and counts to log(x+1) (apart from total forb counts which were not transformed); size data were not transformed. To test for differences among sites and treatment effects across all sites in a given year, a mixed model ANOVA was carried out on plot means, including site and treatment as fixed factors and block as a random factor. To assess changes across all sites over the three year period from 2011 to 2013, a multivariate repeated-measures ANOVA model was specified, in which year was specified as the repeated measure. To test for treatment effects on individual species in a single site in a given year, a mixed model nested ANOVA was applied to individual
quadrat data, in which treatment was a fixed factor, and block and quadrat were random factors, the latter nested within block.

Differences in vegetation structure measurements (untransformed data), bare ground and the cover of a selection of plant species of agronomic importance were assessed across all nine treatments. Species analysed were the invasive species *Cirsium arvense* (Creeping thistle), *Poa annua* (Annual meadow-grass), *P. trivialis* (Rough meadow-grass) and *Rumex obtusifolius* (Broad-leaved dock). Cover of *Trifolium repens*, which was one of the sown species but also already present in the sward, was also analysed. A split-plot design ANOVA was applied, including site, loosening (main plot) and seeding (sub-plot) as fixed factors and block as a random factor nested within site.

Differences in the whole plant community among sites were assessed by applying a Principal Components Analysis (PCA) to log-transformed mean species cover data per plot from the 2011 and 2013 surveys. To determine the effects of loosening and seeding treatments on the plant community, partial Redundancy Analysis (pRDA) was applied to the log-transformed species cover data. In the pRDAs, site and block were specified as covariables, loosening as main plots and seeding as sub-plots. Significance testing was done by forward selection and 999 Monte Carlo permutations. PCAs and pRDAs were carried out using Canoco v4.5 software (ter Braak and Šmilauer, 2002).

### 4.2.4 Nitrous oxide measurements – 2010-12

Nitrous oxide emissions were measured from the unloosened control and the deeper loosening treatments (treatments 1 and 3) at Odstone and Aberbran, following the deeper loosening treatment in September 2010. In addition, N$_2$O measurements were carried out following the application of 40 kg N/ha in the form of manufactured nitrogen fertiliser to the experimental areas in February 2011. Additionally, measurements were made from an area not receiving the N source so that the effect of the N source could be differentiated from background emissions.

The nitrous oxide sampling schedule is outlined in Table 5 and was based on a validated measurement protocol used in other Defra-funded projects (e.g. AC0111 – Cracking Clays Air). Measurements were continued for 12 months in order to quantify the effect of compaction remediation and fertiliser N application on direct N$_2$O emissions from soils. The sampling comprised a total of 55 individual measurements, to meet scientific publication and IPCC reporting requirements.

As the loosening was likely to stimulate microbial activity (and associated nitrous oxide production) and nitrous oxide emissions would be highest following N fertiliser application (Dobbie *et al.*, 1999; Firestone and Davidson, 1989), the sampling strategy was weighted with more intensive sampling during the (likely) period of elevated nitrous oxide fluxes (i.e. 4-6 weeks after fertiliser/manure N application and after soil loosening).

Direct N$_2$O emissions were measured using the static chamber technique, with 5 chambers per plot (giving a total of 15 replicate chambers per treatment; 60 chambers per site). Each chamber had dimensions of 40 cm x 40 cm square and was 25 cm tall, giving a soil surface area coverage of 0.16 m$^2$. The chambers were installed immediately after the deeper loosening treatment had been applied and were pushed into the soil up to a depth of 5 cm to ensure an airtight seal. The chambers were removed prior to the application of manufactured fertiliser N and reinstated in the same position before sampling. On each sampling occasion, after placing a lid on each chamber, headspace samples were taken after 40 minutes. Gas samples were analysed as soon as possible after collection by gas chromatography at ADAS Boxworth. The linear relationship was periodically checked during the experiment using a time series of samples. The N$_2$O flux was calculated based on the linear increase in N$_2$O concentration inside the chamber over the enclosure period from a measured ‘ambient’ concentration.
### Table 5. Sampling schedule for nitrous oxide measurements

<table>
<thead>
<tr>
<th>Weeks after deeper loosening treatment</th>
<th>Number of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>10</td>
</tr>
<tr>
<td>2-4</td>
<td>4</td>
</tr>
<tr>
<td>4-8</td>
<td>2</td>
</tr>
<tr>
<td>8-12</td>
<td>2</td>
</tr>
<tr>
<td>12-16</td>
<td>2</td>
</tr>
<tr>
<td>16-20</td>
<td>2</td>
</tr>
<tr>
<td>20-24</td>
<td>2 = 24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weeks after fertiliser N application</th>
<th>Number of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>10</td>
</tr>
<tr>
<td>2-4</td>
<td>4</td>
</tr>
<tr>
<td>4-8</td>
<td>2</td>
</tr>
<tr>
<td>8-12</td>
<td>2</td>
</tr>
<tr>
<td>12-16</td>
<td>2</td>
</tr>
<tr>
<td>16-20</td>
<td>2</td>
</tr>
<tr>
<td>20-24</td>
<td>2</td>
</tr>
<tr>
<td>24-28</td>
<td>1</td>
</tr>
<tr>
<td>28-32</td>
<td>1</td>
</tr>
<tr>
<td>32-36</td>
<td>1</td>
</tr>
<tr>
<td>36-40</td>
<td>1</td>
</tr>
<tr>
<td>40-44</td>
<td>1</td>
</tr>
<tr>
<td>44-48</td>
<td>1</td>
</tr>
<tr>
<td>48-52</td>
<td>1 = 31</td>
</tr>
</tbody>
</table>

**Total** 55

Water-filled pore space was estimated using measurements of bulk density and gravimetric water content and an assumed particle density of 2.65 g/cm³. Representative soil samples were taken (0-10 cm) from each plot for the determination of gravimetric moisture content on every N₂O measurement occasion. Topsoil dry BD measurements were taken on all treatments prior to soil loosening. The soil bulk density was then used to convert the soil gravimetric moisture content to water-filled pore space (WFPS) using equation 1; WFPS is expressed on a percentage basis and defined as the ratio of volumetric soil water content to total porosity (Meixner, 1994), and as in Thornton & Valente (1996):

\[
WFPS (\%) = \frac{\theta}{n} \times 100 \tag{1}
\]

where,

- **WFPS** = Water filled pore space
- **θ** = Volumetric water content
- **n** = porosity

and porosity is defined as:

\[
n = 1 - \frac{\gamma_d}{\gamma_s} \tag{2}
\]

where, **n** = porosity
\[ \gamma_d = \text{Dry bulk density} \]
\[ \gamma_s = \text{particle density (taken as 2.65 g/cm}^3\text{)} \]

and volumetric water content is defined as:
\[ \theta = m \cdot \gamma_d \quad (3) \]

where, \( m = \text{gravimetric water content} \)

4.2.5 Abundance and diversity of invertebrates – Nafferton 2011 and 2012

This study took place at Nafferton between October and November 2011 and September and October 2012, with additional earthworm samples collected in Spring 2014, and aimed to investigate the effects of mechanical and biological (plant species) methods for alleviating soil compaction and improving soil function on the abundance and diversity of earthworm species and tipulids. Work was carried out at this time of year to co-incide with the bird foraging work described in section 4.3.6. Only earthworms were successfully collected in this experiment, with Tipulids either not present or not identifiable in soil cores. This may have been due to the winter sampling regime, the time of year or low numbers on site. The remainder of the report concerns only earthworms.

Earthworm abundance and biomass were measured on the site, with each replicate of the nine treatments sampled in random order. Up to nine plots were tested per day, with surveys carried out between 8:00 and 14:00. Surveys were not carried out in adverse weather conditions (e.g. rain or high wind) or when the ground was covered in frost or snow.

Five 30 cm² metal quadrats were randomly placed within a treatment plot, and sunk into the ground to approximately 3cm depth. Within each quadrat, 2 litres of 0.33% mustard solution (see Gunn 1992) were applied to the topsoil. Following application, each quadrat was observed for 15 minutes. Earthworms that emerged within the quadrat were identified to species level (using The OPAL Soil and Earthworm Survey guide) and weighed using a small portable balance. After 15 minutes, a second application of 0.33% mustard solution was made and the identification and weighing process was repeated.

The total number and fresh weight (biomass) of all earthworms combined and individual species were recorded for each quadrat, as well as the time of day and temperature. Mean abundance and biomass per plot were calculated from the combined quadrat measurements. All earthworms were washed and released at the same plot after identification and weighing was completed. It took 60 days to complete the study (2011, 32 days; 2012, 18 days; and 2014, 10).

**Data analysis**

Statistical models were used to test the null hypotheses that the abundance and biomass of earthworms was not affected by mechanical loosening, cultivation or the introduction of deep-rooting herbs and legumes. All tests were performed using the program LMER in the lme4 package v.0.999375-42 (Bates et al. 2012) for R version 2.14.1 (R Development Core Team, 2011). Models were generalized linear mixed-effects models (GLMMs) fit using the Laplace method for estimating parameters.

Abundance and biomass were entered as the response variable in the models, with treatment (either unloosened treatments vs. shallow loosened treatments vs. deep loosened treatments, or untreated control vs. uncultivated loosening treatments vs. power-harrow without species mix vs. power-harrow with species mix) and year as fixed factors, plot as a random effect (to acknowledge the hierarchical design of the dataset) and to control for possible temporal and spatial effects, temperature, time of day, as continuous variables along with the interaction between treatment and year. Models had a Poisson error distribution. In addition, we included an individual-level random effect (1|observation) to control for overdispersion (Bates et al., 2012).
Models were run on three earthworm groups/ecotypes:

1. **All Earthworms species**
2. **Endogeic species** - small-bodied and make temporary burrows in the topsoil
3. **Anecic species** - larger-bodied (e.g. *Lumbricus terrestris*) and make deeper permanent vertical burrows

Note. No compost worms were found in the study and only very small numbers of one species of epigeic worm (*L. rubellus*). For this reason, the report focuses on differences in the biomass and abundance of endogeic and anecic earthworms.

The results of the earthworm sampling were also included as the response variable in models with a variety of soil physical and chemical parameters collected in other parts of the study as predictors. Predictors included were penetration resistance in the 0-30cm layer (N/cm²), shear vane strength (mean kPA), initial water infiltration rate (mm/hour), bulk density, dry yield (t/ha) and vegetation density.

### 4.2.6 Bird foraging – Nafferton 2011 and 2012

**Bird trials**

These took place at Nafferton between October and November 2011 and September and October 2012. Starlings were selected as a study species as they are a key UK grassland foraging species which has undergone serious declines in recent decades (Feare, 1989; Robinson *et al*., 2005). Starlings are also relatively straightforward to catch in autumn, forming large flocks post-breeding, and have been shown to perform well in feeding trials (Devereux *et al*., 2006). Starlings from a nearby population (55°05'03''N, 01°28'12''W) were captured under Natural England licence using whoosh nets (14 birds in 2011, 15 in 2012). They were housed indoors in 0.9 m x 0.7 m x 0.6 m cages at Newcastle University Field Station, Close House, Northumberland. Each cage housed a maximum of three birds and all groups were in auditory and visual contact with each other. The ambient temperature and lighting within the enclosure reflected external conditions. Birds received a diet of *ad libitum* turkey starter crumb and softbill pellets, and a 2.5 cm³ daily ration of mealworms (*Tenebrio molitor*) was provided after each day's trials were completed (Devereux *et al*., 2006; Rhymer *et al*., 2012). Water for drinking and bathing was available at all times. Starlings were aged and sexed using morphological traits e.g. throat feather length (Smith *et al*., 2005; Devereux *et al*., 2006) and colour ringed with a unique colour-coded combination for identification. They were released at the capture site following completion of all trials (time in captivity: 2011: 50 days, 2012: 36 days).

Each bird was randomly selected to be a focal bird (2011: 2 adult females, 5 first winter females, 5 adult males, 2 first winter males; 2012: 5 adult females, 4 first winter females, 2 adult males, 4 first winter males; Appendix 7). The randomized block design was used for measuring foraging behaviour, with each bird undergoing one replicate of each of the nine treatments in a random order. Each focal bird had the same two companions, selected at random, present for each trial to ensure that the focal bird’s foraging rate was not influenced by individual differences in its companion’s rates, because foraging rates are mediated by the rates of other flock members (Fernández-Juricic and Kacelink, 2004). To avoid pseudo-replication, the combination of companion birds was different for each focal bird. On average, each bird experienced eleven trials in total, nine as a focal and two as a companion.

Foraging trials were conducted in a purpose-built wire mesh bottomless cage that was divided into two sections (A and B) both measuring 0.5m x 0.5m x 0.5m (Plate 2). Before a trial began, the cage would be placed on the trial plot. Within section A, five measurements of penetration resistance, volumetric soil moisture content and grass length (cm) were made, one at the centre and at each corner. Penetration resistance was measured using a hand-held soil penetrometer.
(Model 16 – T0171, Controls Testing Equipment Ltd., UK) on a scale of 0 to 5 KgF, with five indicating the most force required to penetrate the soil. A JVC Everio digital camcorder on a tripod was placed 3m in front of the cage and used to record the trials.

Plate 2. Wire-mesh bottomless cage used for conducting foraging trials at Nafferton Farm, Northumberland, UK. The cage was divided into section A (left) and B (right). The focal bird was released into section A and the two companions were released into section B.

Up to nine focal birds were tested (in a random order) per day, with trials carried out between 8:00 and 14:00. Observations were not made in adverse weather such as rain or windy conditions or when the ground was covered in frost or snow. On average, each bird was used in a trial once every 5 (~± 0.27) days in 2011 and every 3 (~± 0.18) days in 2012, the number of rest days ranged between 1 and 15. No bird experienced more than one trial as a focal bird per day. Individual birds were transported to the field site in cotton bags. The focal bird was released into section A and the two companions were released into section B. The birds were left to forage for 10 min and the trials lasted 10 min from the first probe by the focal bird. The behaviour of the focal bird was recorded by the digital video camera. If the focal bird failed to forage in the 10 min following release into the cage the trial was abandoned. Birds were returned to their indoor cages after completing a trial. Birds did not complete all nine trials if they began to show stereotypical behaviour (e.g. somersaulting), when released into the outdoor cage. Birds which displayed this behaviour were immediately excluded from any further trials and released at the original capture site before the end of the study period.

252 trials were completed over the course of two years (2011 and 2012). Twenty-one birds completed all nine trials, seven completed eight trials and one completed seven (see Appendix 7 for details).

Data analysis
Foraging behaviour data was extracted from the digital video recordings using an event recorder (42 hours of digital video recordings in total from 252 trials). Each recording was analysed frame by frame and a number of variables were recorded: video date, video duration, number of “roots” (see Table 6 for definitions) and the number of roots that resulted in prey captured. The time of day, temperature, mean penetration resistance, mean grass length and identity of prey items (where possible) were also recorded. Random data were cross-checked and the recording of foraging variables was found to be consistent in all cases.
Table 6. Description of the foraging variables used in this study

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe</td>
<td>Initial investigative stab into the soil</td>
</tr>
<tr>
<td>Rooting behaviour</td>
<td>Secondary stab into the soil followed by opening of the bill. The number of roots gives an indication of search intensity (^b)</td>
</tr>
<tr>
<td>Prey capture</td>
<td>Secondary stab that results in prey capture</td>
</tr>
</tbody>
</table>

\(^a\) Tinbergen 1981  
\(^b\) Devereux 2006

Statistical models were built in order to test the null hypotheses that Starling foraging behaviour (root rate per minute, number and percentage of successful roots; models A, B and C respectively) was not affected by mechanical loosening, cultivation or the introduction of deep-rooting herbs and legumes.

All tests were performed using the program LMER in the lme4 package v.0.999375-42 (Bates \textit{et al}., 2012) for R version 2.14.1 (R Development Core Team, 2011). Models were generalized linear mixed-effects models (GLMMs) fit using the Laplace method for estimating parameters. Individual bird identity ‘Bird ID’ and plot were modelled as random effects to acknowledge the hierarchical design of the dataset and to control for possible temporal and spatial effects. Type of treatment (either unloosened treatments vs. shallow loosened treatments vs. deep loosened treatments or untreated control vs. uncultivated loosening treatments vs. power-harrow without species mix vs. power-harrow with species mix) and year were included as fixed factors.

Penetration resistance, grass length, temperature, Julian date and time of day were also included in the model along with an individual-level random effect to control for over dispersion (Bates \textit{et al}., 2012). Squared terms were dropped from the models if on their own they did not explain a significant amount of deviance. Root rate and number of successful roots were modelled using a Poisson error structure and log link function, while the percentage of roots that resulted in prey capture was analysed using a binomial error structure and a logit link function.

To check the robustness of the models, and whether the variables were interchangeable, GLMMs were run with penetration resistance, mean grass length, Julian date, temperature and time of day independently (referred to as ‘penetration resistance without Julian date’, ‘Julian date without penetration resistance’, ‘Julian date without grass length’, ‘Julian date without time of day’, ‘Julian date without temperature’ and ‘temperature without grass’).

4.2.7 Final year measurements

In the final year, the following additional measurements were made at all four sites. All soil samples, apart from visual soil evaluations and sampling for below ground dry matter and root characteristics, were taken to 7.5 cm depth:

- Soil microbial respiration - a measure of soil microbial activity - size - by the Potassium Hydroxide absorption method; ADAS Standard Operating Procedure (SOP) SOILS/083
- Soil microbial biomass C and N - a measure of the size of the soil microbial community - by fumigation incubation
- Soil respiration quotient – a measure of microbial activity per unit of biomass size
- Soil biomass quotient – a measure of soil biomass size per unit of soil organic carbon
- Visual soil evaluations (3 per plot) using the Landcare VSA method (Shepherd, 2000)
- Visual soil evaluations (3 per plot) using the Peerlkamp method (Peerlkamp, 1967), including scoring of discrete layers
• Soil pH (measured in a soil/water suspension)
• Extractable phosphorus (Olsen's P), extractable potassium and extractable magnesium (Ammonium nitrate extract) – following procedures described in The Analysis of Agricultural Materials (MAFF, 1986)
• Total soil organic carbon - dichromate oxidation and loss on ignition
• Total nitrogen (Kjeldahl digestion)
• Below ground dry matter and root characteristics – using root washing and root scanning techniques

In November 2013, root samples were taken at Odstone and Nafferton (where the seed mix species established most successfully) from the unloosened and deeper loosened treatments, with and without species mix added (i.e. treatments 1, 3, 7 and 9). At Odstone, 10 cores per plot were taken from the 0-10 cm layer (to the base of a ‘compacted’ layer) and from 10-30 cm. At Nafferton, 10 cores per plot were taken from 0-20 cm (to the top of a ‘compaction’ pan) and from 20-30 cm. Cores (1.3 cm diameter) were bulked for each layer per plot. Roots were extracted from the soil samples using a DELTA-T root washer with filters of 550 Micron. Root samples were then scanned using the winRHIZO root analysis package (Regent Instruments Ltd., Quebec City, Canada) and root measurements (total length, mean diameter and surface area) calculated. The volume of soil associated with each sample was calculated and used to calculate root length density (RLD; cm of root per cm$^3$ soil).

The root samples were dried in an oven at 80°C for 48 h (or until there was no further weight loss) and the sample dry weights were recorded. These were used with the root lengths to calculate the specific root length. The specific root length (SRL) is a measure of the length of root per unit of root biomass, expressed as metres per gram. Plants with a high SRL build more root length for a given amount of root biomass. A high SRL can be the result of low tissue density or a low root diameter.

Treatment effects on root measurements were analysed separately for each sampling depth and each site using a split-plot ANOVA with loosening (main plot) and seeding (sub-plot) as fixed factors and block as a random factor. In all cases, data from quadrats in Treatments 1-3 that had been fertilised in 2012 and 2013 were omitted.

4.3 Bird foraging field-scale experiments

The behaviour of wild birds at the field scale in relation to loosened and un-loosened grassland areas was studied at fifteen sites across England and Wales (Figure 3). Cost, time and practicality constraints meant that it was not feasible to carry out and replicate a variety of treatments on a large scale. Mechanical loosening (i.e. sward lifting) was therefore used to investigate the effects of alleviating soil compaction on bird foraging at the field scale. Fifteen fields were selected for a split field assessment with one half of the field loosened and the other half left without treatment in autumn 2011. These sites were a mixture of permanent and rotational pasture. They varied in size (1.6 - 7.3 ha), topography and soil type (Table 7). Bird response was determined on the fifteen split fields by counting birds regularly on each field through the latter part of winter 2011-12 and early part of the 2012 breeding season. Fields were located across the main grassland regions of England and Wales (Figure 3).

4.3.1 Soil loosening procedure

Half the area in each field was loosened mechanically using a dedicated “sward lifter” between September and November 2011 (see Appendix 2). The timing of the procedure was dependent on the soil conditions at each individual site – loosening cannot be carried out if the soil is too dry or too wet as the sward itself will be damaged (Plates 3-4). Timing decisions were made by assessing soil moisture and consistency in the field. The loosening was carried out mainly by independent contractors, or in two cases, by the landowners themselves. The depth to which loosening was carried out varied between sites and was determined from an assessment of the
depth of compaction in each field. The depth of mechanical loosening varied from 25 to 30 cm (see Table 7). Loosening was carried out in the autumn in order that the sward recovered sufficiently for birds not to exhibit a bias towards loosened and unloosened areas of the field because of surface disruption - many birds are known to exhibit a preference for bare or disturbed soil (Whittingham and Markland, 2002).

![Figure 3. Map of field site locations in England and Wales.](image)

4.3.2 Bird surveys
Site surveys began in February 2012 and continued until May 2012. With the exception of the Cornwall site (which was not surveyed in February) and the Staffordshire site (not surveyed in May), each site was surveyed twice per month: eight times in total. The surveys were carried out using a standard winter bird survey protocol (Wilson et al., 1996). Visits were carried out between 1 h after dawn and 1 h before dusk to avoid periods when birds were arriving or leaving roost sites. Periods of very wet or windy weather were avoided due to the negative effect of such conditions on bird activity. The fields were surveyed with binoculars on arrival to the site, and the location of any birds noted. A visit comprised the observer walking across the field to within 5 m of every part, ensuring all birds were flushed. The field was flushed in a random pattern, with all birds sighted on each part of the field recorded to species level. Care was taken not to double-count birds by noting where previously flushed birds had landed. Depending on the size of the field, this survey took between 10 and 30 minutes.
Table 7. Details of the 15 field sites.

<table>
<thead>
<tr>
<th>Farm code</th>
<th>Region</th>
<th>Farm type</th>
<th>Field area (ha)</th>
<th>Loosening date</th>
<th>Loosening depth</th>
<th>Mean bulk density</th>
<th>Textural Sub-class</th>
<th>Peaty/org. min./min.</th>
<th>Soil org. matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG</td>
<td>NE England (Co. Durham)</td>
<td>beef/sheep</td>
<td>2.4</td>
<td>06/10/2011</td>
<td>25 cm</td>
<td>1.3</td>
<td>Heavy clay loam</td>
<td>Min.</td>
<td>5.9</td>
</tr>
<tr>
<td>SR</td>
<td>NE England (Co. Durham)</td>
<td>dairy</td>
<td>1.6</td>
<td>06/10/2011</td>
<td>25 cm</td>
<td>1.2</td>
<td>Med. clay loam</td>
<td>Min.</td>
<td>6.9</td>
</tr>
<tr>
<td>GB</td>
<td>NW England (Lancashire)</td>
<td>dairy</td>
<td>3.2</td>
<td>07/10/2011</td>
<td>25 cm</td>
<td>1.4</td>
<td>Heavy clay loam</td>
<td>Min.</td>
<td>4.2</td>
</tr>
<tr>
<td>SS</td>
<td>West Midlands</td>
<td>dairy</td>
<td>3.2</td>
<td>13/10/2011</td>
<td>28 cm</td>
<td>1.2</td>
<td>Med. clay loam</td>
<td>Min.</td>
<td>5.3</td>
</tr>
<tr>
<td>AR</td>
<td>N Wales (Flintshire)</td>
<td>dairy</td>
<td>4.1</td>
<td>29/09/2011</td>
<td>25 cm</td>
<td>1.3</td>
<td>Med. clay loam</td>
<td>Min.</td>
<td>5.2</td>
</tr>
<tr>
<td>GR</td>
<td>N Wales (Denbighshire)</td>
<td>dairy</td>
<td>1.6</td>
<td>29/09/2011</td>
<td>25 cm</td>
<td>1.3</td>
<td>Heavy clay loam</td>
<td>Min.</td>
<td>6.7</td>
</tr>
<tr>
<td>GK</td>
<td>N Wales (Wrexham)</td>
<td>beef/sheep</td>
<td>2.8</td>
<td>09/11/2011</td>
<td>30 cm</td>
<td>1.5</td>
<td>Sandy loam</td>
<td>Min.</td>
<td>4.4</td>
</tr>
<tr>
<td>BJ</td>
<td>Mid Wales (Powys)</td>
<td>beef/sheep</td>
<td>4.8</td>
<td>30/09/2011</td>
<td>25 cm</td>
<td>1.2</td>
<td>Med. clay loam</td>
<td>Org. min.</td>
<td>8.5</td>
</tr>
<tr>
<td>MB</td>
<td>Mid Wales (Powys)</td>
<td>dairy</td>
<td>7.3</td>
<td>09/11/2011</td>
<td>30 cm</td>
<td>1.3</td>
<td>Heavy clay loam</td>
<td>Min.</td>
<td>5.6</td>
</tr>
<tr>
<td>PP</td>
<td>West Midlands</td>
<td>beef/sheep</td>
<td>2.0</td>
<td>09/11/2011</td>
<td>30 cm</td>
<td>1.5</td>
<td>Sandy loam</td>
<td>Min.</td>
<td>2.7</td>
</tr>
<tr>
<td>RA</td>
<td>S. Wales (Monmouthshire)</td>
<td>beef/sheep</td>
<td>3.2</td>
<td>24/10/2011</td>
<td>30 cm</td>
<td>1.4</td>
<td>Heavy silty clay loam</td>
<td>Min.</td>
<td>6.8</td>
</tr>
<tr>
<td>BP</td>
<td>S. Wales (Monmouthshire)</td>
<td>dairy</td>
<td>1.6</td>
<td>05/10/2011</td>
<td>25 cm</td>
<td>1.2</td>
<td>Silty Clay</td>
<td>Min.</td>
<td>4.7</td>
</tr>
<tr>
<td>DH</td>
<td>SW England (Somerset)</td>
<td>dairy</td>
<td>3.0</td>
<td>22/09/2011</td>
<td>29 cm</td>
<td>1.4</td>
<td>Med. clay loam</td>
<td>Min.</td>
<td>4.9</td>
</tr>
<tr>
<td>PS</td>
<td>SW England (Devon)</td>
<td>beef/sheep</td>
<td>3.7</td>
<td>20/09/2011</td>
<td>27 cm</td>
<td>1.2</td>
<td>Heavy clay loam</td>
<td>Min.</td>
<td>6.5</td>
</tr>
<tr>
<td>MH</td>
<td>SW England (Cornwall)</td>
<td>beef/sheep</td>
<td>0.8</td>
<td>15/09/2011</td>
<td>30 cm</td>
<td>nd</td>
<td>Clay loam</td>
<td>nd</td>
<td>nd</td>
</tr>
</tbody>
</table>
Plate 3. Detail of the cutting discs, loosening legs and roller.

Plate 4. A field site showing half the field loosened (right) and half unloosened (left).
4.3.3 Data analysis

Bird data were analysed using Generalised Linear Mixed Models (GLMMs) in R (version 2.9.1). Different models were built with each “species group” – all species, all grassland species (where woodpigeons, finches and pheasants were removed), thrushes only and corvids only (Table 8). As there were only three instances of waders reported, this could not be included as a separate group in the analysis, although they are included in the “all species” and “all grassland species” group. Presence/absence data were used, rather than absolute bird number because, as flocking species, bird number can be subject to autocorrelation. Data were therefore modelled with a binomial error structure and a logit link function. Presence or absence of a species at a site on a visit was declared as the response variable, loosening treatment a factor and site a random effect.
5 BD5001 Work Package 1 & 2 summaries

The following three sections summarise outputs from a survey of grassland soil structural condition in England and Wales (BD5001 WP1) and literature reviews on mechanical loosening and plant species for the remediation of soil compaction (WP2).

5.1 Characterisation of soil condition under grassland – main results

The results of a survey of 300 grassland fields is reported and discussed in detail in Appendix 1. The main findings from the study were:

- Based on Landcare Visual Soil Assessment (VSA) and Peerlkamp Soil Structure (‘St’) scores, and current interpretation of these scores, approximately 10% of fields were assessed to be in poor condition and around 60% in moderate condition.
- Compared to fields with ‘improved’ swards, the fields with ‘semi-improved’ or ‘species-rich’ swards had a higher percentage of soils in good condition, but also a higher percentage of fields in poor condition, indicating that poor soil structural condition is not necessarily a limitation to plant species diversity.
- Based on BD ‘trigger values’ (Merrington, 2006), 16% of the soils would be considered ‘compacted’.
- There was a small, but significant difference ($P<0.01$) in BD values between the ‘mainly cut’ (mean = 1.02 g/cm$^3$) and ‘mainly grazed’ (mean = 0.95 g/cm$^3$) fields, indicating that management for cutting may give rise to lower soil porosity in the surface layer.
- Grassland type (improved; semi-improved or species rich) had an effect on BD ($P<0.001$) when investigated as a single factor; BD was highest in improved grasslands (mean = 1.02 g/cm$^3$) and lowest in semi-improved and species rich grasslands (mean = 0.88 g/cm$^3$), indicating that improved grasslands generally have lower soil porosity in near surface layers.
- There was a negative relationship between ‘St’ scores and mid topsoil BD at the 30 sites ($P<0.01$; $r^2 = 25$%), indicating that the measurement of BD in the middle of the topsoil provides a reasonable indication of soil structural conditions, as determined by visual soil assessment.

5.2 Review of mechanical loosening – main findings

The BD5001 review of mechanical loosening summarised UK and overseas results from experimental studies into the use of aerators and sward lifters to alleviate compaction in grassland soils (see Appendix 2 for more detail). Results from UK studies were variable, with both yield increases and decreases measured. However, results indicate that mechanical soil loosening can be effective in improving soil structure and increasing grass yields where soil compaction has been positively identified and mechanical alleviation is effectively carried out. Where no compaction was identified at the outset of field trials/experiments, it appears that soil loosening improved soil physical properties (i.e. reduced penetration resistance), but resulted in a reduction in grass yield due to sward and root damage (e.g. Frost, 1988a). It is probably the case that where compaction cannot be identified through visual assessment (i.e. compaction assessed as a distinct coarsening and angularity of structures at some level in the topsoil), soil loosening is unlikely to have a positive effect on grass yield and the resulting sward and root damage is more likely to result in yield penalties (relative to the situation when mechanical loosening has not been carried out).

Nevertheless, the review found that grassland loosening devices have the potential to alleviate compaction at varying depths, if used in appropriate conditions, although reductions in compaction are not necessarily translated into increased grass yields, and improvements in soil physical properties can be short-lived (i.e. up to 12 months in duration). The short-lived nature of the loosening effect was thought to be due to a combination of re-settling of soil aggregates
and pressure exerted by machinery and livestock once they are returned to the land. Technical notes reviewed in the document recommended that recently loosened soil is very sensitive to re-compaction and that it is important to allow the newly loosened structure to be stabilised by root activity and natural soil processes. The reviewed technical notes also stated that if late growth needs to be utilised following autumn loosening it is advisable to graze with sheep rather than cattle, and spring growth should be cut and conserved rather than grazed. If loosening is carried out in late August/early September this strategy allows c.10 months for the loosened soil to stabilise before ‘normal’ practices are resumed.

Overseas studies from New Zealand and North America confirm the UK and ROI findings; that mechanical loosening of compacted grassland soils can have a beneficial effect in improving soil physical properties and in some cases increasing grass yields. However, the studies also confirmed that results vary and that depending on a number of factors, soil physical properties and grass yields can be unaffected, slightly improved, or slightly impacted by soil loosening or aeration. Mechanical loosening when soils were in a plastic state or when there were no clear signs of compaction or later in the spring tended to result in reductions in grass yield (Appendix 2). The duration of beneficial mechanical treatment effects (where changes were observed) varied from a few weeks to 2 or 3 years.

5.3 Review of plant species for remediation of soil compaction – main findings

The aim of this BD5001 review was to identify plant species that may have potential to remediate soil compaction in grasslands and would also have some practical application in the field. The literature was reviewed (full details are in Appendix 3). The specific objectives were to identify:

1. Plant species and traits shown to have remedial effects in compacted soils,
2. UK grassland species that could have potential to remediate soil compaction and
3. Ease of establishment, persistence and agronomic value of the candidate species.

There were relatively few relevant studies from grasslands in the UK, most studies having been carried out elsewhere under various climatic conditions and using commercial crop species within arable rotations. Lucerne (Medicago sativa) was the most widely studied species and featured most prominently in the literature. However, these studies pointed to a number of consistent traits associated with alleviating soil compaction. Members of the family Fabaceae are frequently reported as being capable of tolerating compaction and improving soil structure. Possible mechanisms for this are linked to Rhizobium bacteria in root nodules and arbuscular mycorrhizal associations. A deep rooting system capable of deep penetration and radial expansion, especially a large tap root, is also a recurrent feature. In general, dicotyledonous species tend to have more strongly penetrating root systems than grasses. Long-lived perennials are also more likely to develop larger root systems than annuals.

Successful establishment of plant species into an existing grassland sward has been linked to ruderality, percentage germination of seeds and autumn germination. Generalist species, especially those associated with fertile soils, are more persistent in restoration experiments than habitat specialists and species associated with infertile soils. Persistence in a sward is also related to species tolerance or avoidance of repeated defoliation caused by grazing or cutting.

The nutritive value and digestibility of grassland species is also of relevance if they are to be introduced into agricultural grassland swards to help remediate soil structure. Nutritive value of forage plants are determined by digestibility, protein content and concentration of essential minerals. Digestibility declines with maturity, the rate varying among species. Stage of growth and ability to absorb nutrients will affect a species’ protein and mineral concentrations. Forbs (including ‘weed’ species) are recognised for their mineral content and palatability but have declined in intensive grassland systems. Fabaceae are valued for their nitrogen-fixing properties and some also have high feeding value.
<table>
<thead>
<tr>
<th>Species</th>
<th>Remedial characteristics</th>
<th>Establishment &amp; persistence</th>
<th>Agronomic value</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Trifolium pratense</em> (Red Clover)</td>
<td>Tap-rooted legume, mycorrhizal associations.</td>
<td>Possibly not long-term persistent in sward and native varieties might be slow to establish.</td>
<td>High.</td>
</tr>
<tr>
<td><em>Lotus corniculatus</em> (Bird’s-foot trefoil)</td>
<td>Tap-rooted legume, high mycorrhizal associations.</td>
<td>Establishes better than most other native forbs.</td>
<td>High.</td>
</tr>
<tr>
<td><em>Achillea millefolium</em> (Yarrow)</td>
<td>Mycorrhizal associations but no tap root.</td>
<td>Establishes and persists well but might not disperse well in productive swards.</td>
<td>Tolerates grazing; superior mineral source to grasses and average for forbs.</td>
</tr>
<tr>
<td><em>Hypochaeris radicata</em> (Cat’s-ear)</td>
<td>Tap-rooted, mycorrhizal associations.</td>
<td>Less easy to establish than other species and needs to disperse seeds to persist.</td>
<td>Reasonably good source of minerals and selectively grazed.</td>
</tr>
<tr>
<td><em>Trifolium repens</em> (White Clover)</td>
<td>Superior to <em>Lolium perenne</em> although shallower rooting depth than other forbs identified.</td>
<td>Establishes and persists well.</td>
<td>High.</td>
</tr>
<tr>
<td><em>Cichorium intybus</em> (Chicory)</td>
<td>Deep tap root but probably does not occur naturally in grasslands.</td>
<td>Establishes well and competes well with legumes.</td>
<td>High mineral content; can increase productivity and forage quality.</td>
</tr>
<tr>
<td><em>Centaurea nigra</em> (Black Knapweed)</td>
<td>Tap-rooted, mycorrhizal associations but no data on rooting depth found.</td>
<td>Moderate establishment and persistence.</td>
<td>Probably low.</td>
</tr>
<tr>
<td><em>Plantago lanceolata</em> (Ribwort Plantain)</td>
<td>Tap-rooted but shallower rooting depth than other forbs identified.</td>
<td>Establishes and persists well.</td>
<td>Medium feed value.</td>
</tr>
<tr>
<td><em>Sanguisorba minor ssp. nuricata</em> (Forage Burnet)</td>
<td>Probably deep tap-rooted with mycorrhizal associations.</td>
<td>Establishes well, tolerates grazing.</td>
<td>Good quality forage.</td>
</tr>
</tbody>
</table>
Livestock usually learn to select the more digestible species from a sward and mostly avoid plants with spines. Plants with a low growth habit will often escape being grazed. Plants containing undesirable chemicals and highly invasive or competitive weeds are considered to be actively detrimental to agricultural production. The 9 candidate species identified in the BD5001 review (Tables 2 and 8) were selected and included as a mitigation method to be tested in the BD5001 field experiments.
6 Field experiment results

6.1 Field experiments - to evaluate mitigation method effectiveness

The following sections describe the effects of mechanical loosening, power-harrowing, the application of manufactured N fertiliser and the establishment of deep rooting herbs and legumes on soil bio-physical and physico-chemical properties; soil structural condition; plant communities; invertebrate number and diversity; bird foraging behaviour; water infiltration rates and nitrous oxide emissions.

Given the high number of variables measured across four sites and on up to four separate occasions (measurements were made in every year between autumn 2010 and spring 2014) results are summarised below in tabular form (Tables 9 and 10) with sites in columns, treatments in sub-columns and variables in rows and each cell containing a symbol for each year showing significant increase compared to control (arrow up), significant decrease (arrow down), no change (sideways arrows) or not measured (hyphen).

6.2 Treatment effects on soil physical properties

Shear vane measurements (0-5 cm depth) and penetrometer measurements in two layers (to depth of shallower and deeper loosening respectively; Table 9) indicated that both mechanical loosening (shallower and deeper) and the introduction of deep-rooting herbs and legumes had effects on soil strength \( (P<0.05) \). Mechanical loosening consistently reduced soil strength and cultivations to introduce the seed mix increased soil strength, although effects were not detected at all depths or at all sites in all years. In each section, effects across all sites are presented before notable results at individual sites are described.

6.2.1 Penetration resistance

Effects of mechanical loosening were detected at all sites in autumn 2010, 2011 (one year after loosening) and 2012 (two years after loosening) (Figures 4 and 5). However, by autumn 2013 (three years post loosening) there was no overall effect of mechanical loosening on maximum penetration resistance (MPR) when assessed across all sites \( (P>0.05) \).

![Figure 4. Effect of mechanical loosening on maximum penetration resistance (N/cm²) in the 0-15 cm layer across all sites and years [Error bars give the standard error of the mean]](image-url)
Table 9. Summary of results of deeper and shallower mechanical loosening. Arrows indicate the nature of significant differences ($P<0.05$) in measured soil variables when compared to the unloosened and uncultivated control. The symbols represent a significant decrease (↓), increase (↑), no change (↔) and not measured (-).

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Table 10. Summary of results of power-harrowing, with (“Seed mix”) and without (“No mix”) the introduction of deep rooting herbs and legumes. Arrows indicate the nature of significant differences ($P<0.05$) in measured soil variables when compared to the unloosened and uncultivated control. The various symbols represent a significant decrease (↓), increase (↑), no change (↔) and not measured (-).

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In autumn 2010 and 2011, mechanical loosening (both shallower and deeper) reduced MPR in the 0-15 cm layer ($P<0.001$: Figure 4), but by autumn 2012 only shallower loosening had this effect ($P<0.01$) when assessed across all sites.

**Figure 5. Effect of mechanical loosening on maximum penetration resistance (N cm$^{-2}$) in the 15-30 cm layer across all sites and years [Error bars give the standard error of the mean]**

In autumn 2010, deeper loosening reduced MPR in the 15-30 cm layer relative to both shallower loosening and the unloosened control (Figure 5; $P<0.001$). In 2011, only deeper loosening reduced MPR in this layer relative to the control ($P<0.01$) and in 2012 both shallower and deeper loosening had this effect ($P>0.01$). In autumn 2013, reductions in MPR due to mechanical loosening were only detected at Nafferton, in the 0-15 cm layer for shallower loosening ($P<0.05$) and in the 15-30 cm layer for shallower and deeper loosening ($P<0.001$).

**Figure 6. Effect of cultivation and introduction of the species mix on maximum penetration resistance (N/cm$^2$) in the 0-15 cm layer across all sites and years [Error bars give the standard error of the mean]**
Cultivation and the introduction of the seed mix had no effect on MPR in the season of treatment (autumn 2010), but by autumn 2011, cultivation treatment resulted in an increase in MPR in the 0-15 cm layer ($P<0.01$; Figure 6). However, there were no effects of cultivation or the seed mix on MPR in subsequent years, when assessed across all sites ($P>0.05$).

At Odstone, the seed mix increased MPR in the 0-15 cm layer in autumn 2011 ($P<0.001$) and autumn 2012 ($P<0.05$), although there were indications that the power-harrowing treatment contributed to this effect (Figure 7). However, at Bicton in 2012, MPR to 30 cm depth was greater in the species mix plots than in the N fertilised (80 kg N/ha) or unfertilised plots ($P<0.01$). The seed mix also appeared to increase the depth of MPR in the 0-30 cm layer ($P<0.01$) compared to the original sward, indicating that the seed mix had an effect on soil physical properties below the depth of harrowing at this site.

![Figure 7. Effect of power-harrowing and seed mix establishment on maximum penetration resistance (N/cm²) in the 0-15 cm layer at Odstone in autumn 2011 (one year after mechanical loosening).](image)

[Error bars give the standard error of the mean]

At Odstone in 2013, mechanical loosening and the seed mix had no effect on MPR to 30 cm depth. However, the addition of manufactured N fertiliser (250 kg N/ha in 2012 and 2013 compared with zero N) had reduced MPR to 30 cm depth ($P<0.05$) and reduced the mean depth of MPR in the 0-15 cm layer ($P<0.05$).

6.2.2 Shear strength

As with penetration resistance, soil surface shear strength varies with soil moisture and consistence. It is therefore the relative values between treatments that are important rather than the actual values recorded at any particular time or site. When assessed across all sites, mechanical loosening had the effect of reducing soil surface shear strength (Figure 8). In autumn 2010 and 2011 shear strength was lowest on the shallower loosened plots ($P<0.001$ 2010; $P<0.05$ 2011), while in autumn 2012 (two years post loosening) shear strength was lowest on the deeper loosen plots ($P<0.05$). By autumn 2013 there was no effect of mechanical loosening on shear strength when assessed across all sites ($P>0.05$)
The effect of cultivation on soil surface shear strength, with or without introduction of the species mix, changed between the season post-cultivation and subsequent years (Figure 9). Cultivation reduced shear strength in autumn 2010 (two months post-cultivation; \(P<0.001\)), but in 2011 \((P=0.01)\) and 2013 \((P<0.05)\) increased shear strength at the soil surface. The initial effect of cultivation was to reduce shear strength and cohesion, while in subsequent years, cultivation had the effect of increasing soil shear strength, possibly due to the development of a surface crust and roots as seed mix and other plant species were established.

Figure 8. Effect of mechanical loosening on soil surface shear strength (kPa) across all sites and years [Error bars give the standard error of the mean]

Figure 9. Effect of cultivation and introduction of the species mix on soil surface shear strength (kPa) across all sites and years [Error bars give the standard error of the mean]
The effects of mechanical loosening and power-harrowing on soil surface shear strength were most apparent at Nafferton, Odstone and Bicton. In 2010 at Nafferton and Odstone, mechanical loosening reduced soil shear strength (0-5 cm) with shallower loosening reducing it more than deeper loosening ($P<0.001$). However, at Odstone, by 2011, the pattern had reversed with soil shear strength on the unloosened and shallower loosened plots greater than on the deeper loosened plots ($P<0.001$). This effect persisted in 2012, when the same pattern was also measured at Bicton ($P<0.05$). In 2013, only Odstone had differences in shear strength between treatments with deeper loosened plots again having lower strength than shallower loosened plots ($P<0.01$).

Power-harrowing reduced soil shear strength at Nafferton ($P<0.01$) and Bicton ($P<0.001$) in 2010. However, in 2011 at Odstone, shear strength was greater on the (power-harrowed) seed mix plots than on the (unloosened and uncultivated) control ($P<0.05$). Over the longer term, power-harrowing, and possibly also root development of seed mix and ruderal plant species, therefore increased shear strength in the 0-5 cm soil layer and effects persisted for up to three years after cultivation.

6.2.3 Bulk density

Bulk density (BD) is considered to be the most robust indicator of physical soil quality (e.g. Merrington et al., 2006), mainly because it provides a good indication of total soil porosity; and yet when data from all sites were analysed together, differences in BD (0-10 cm depth) between treatments were only detected in 2010, two to three months post-treatment (Figures 10 and 11). In 2010, 0-10 cm BD was lower in the shallower loosened plots than in the unloosened control ($P<0.05$; Figure 10). Deeper loosening had no effect on 0-10 cm BD ($P>0.05$). In the following years, mechanical loosening (shallower or deeper) had no effect on 0-10 cm BD (Figure 10). Furthermore, mechanical loosening had no effect on mid topsoil BD (measured in autumn 2013 only; three years post-loosening, as specified in the work schedule).

![Figure 10. Effect of mechanical loosening on 0-10 cm bulk density (g cm$^{-3}$) across all sites and years [Error bars give the standard error of the mean]](image-url)
The across site data indicates that power-harrowing reduced 0-10 cm BD in autumn 2010 (two to three months post-cultivation; \(P<0.05\)), but had no effect in subsequent years \((P>0.05; \text{Figure 11})\). Furthermore, power-harrowing and the introduction of seed mix species had no effect on 0-10 cm and mid topsoil BD three years post-treatment \((P>0.05)\).

At the single sites, differences in 0-10 cm BD (measured every autumn from 2010 to 2013) were only detected between treatments at Nafferton and Bicton in the autumn following mechanical loosening. At Nafferton in autumn 2010, 0-10 cm BD was lower on the shallower loosened plots (1.26 g/cm\(^3\)) than on the deeper loosened (1.34 g/cm\(^3\)) or unloosened plots (1.40 g/cm\(^3\); \(P<0.001\)). In the same season at Bicton, 0-10 cm BD was higher on the uncultivated plots (1.25 g/cm\(^3\)) than on the power-harrowed without seed mix (1.17 g/cm\(^3\)) or power-harrowed with seed mix plots (1.14 g/cm\(^3\); \(P<0.01\)).

In this field experiment, therefore, no persistent changes in BD were detected as a result of mechanical loosening and power-harrowing treatments. Overall, there were indications that mechanical loosening, power harrowing, the introduction of deep-rooting herbs and colonisation by ruderal species can affect soil physical properties.

6.3 Visual soil evaluation – autumn 2013 only

Analysis of data across all sites (using ANOVA) indicated that deeper loosening resulted in a small but significant increase in visual soil assessment (VSA) scores compared with the unloosened control \((P<0.01; \text{Figure 12})\); indicating better structure where soil had been mechanically loosened.
Figure 12. Effect of treatment on VSA score across all sites in autumn 2013 (three years after mechanical loosening).
[Error bars give the standard error of the mean]

The results were dominated by findings at Odstone, where mechanical loosening resulted in better (higher) visual soil assessment (VSA) scores than on the unloosened control ($P<0.05$). This indicated that three years after treatments had been applied, soils were in better condition where mechanical loosening had been carried out (Figures 12 & 13). Indeed, at Odstone, mechanical loosening resulted in soil condition improving from ‘moderate’ (VSA Ranking Score 10-20) to ‘good’ (VSA Ranking Score > 20).

Figure 13. Effect of treatment on VSA score at Odstone in autumn 2013 (three years after mechanical loosening).
[Error bars give the standard error of the mean]
There was also evidence at Odstone (but not across all sites) that deeper loosening increased Peerlkamp (St) score in the upper discrete layer compared with the unloosened control. The mean St score for the upper discrete layer in deeper plots was 6.7 compared with 6.0 in unloosened plots ($P<0.05$; Figure 14). This provides an indication that deeper loosening at Odstone effected some apparent soil structural improvement three years post loosening.

![Figure 14. Effect of mechanical loosening on St Score in the upper discrete layer at Odstone in 2013. [Error bars give the standard error of the mean]](image)

6.4 Treatment effects on soil chemical properties – autumn 2013 only

The following sections report on the results from the measurement of soil chemical and biological properties on each plot and at each site in autumn 2013. Analysis of data across all four sites indicated that there were differences between sites for all variables ($P<0.001$ for all variables apart from microbial biomass; $P<0.01$) apart from C:N ratio, but no differences due to treatment.

6.4.1 Soil pH

Analysis of data across all four sites indicated that there were no differences in soil pH between treatments. The only treatment effect on soil pH was due to the use of manufactured N fertiliser at Odstone, where mean soil pH was 6.6 on manufactured N fertiliser plots (500 kg N/ha in two years) compared with 6.8 on the unfertilised control ($P<0.05$).

6.4.2 Extractable P, K and Mg

Analysis of data across all four sites indicated that there were no differences in extractable P between treatments. However, single site analysis indicated that mechanical loosening resulted in a small increase in soil extractable phosphorus (P) at Nafferton (7 mg/l cf. 9 mg/l; $P<0.01$), Odstone (23 mg/l cf. 15 mg/l; $P<0.01$; Figure 15) and Aberbran (24 mg/l cf. 21 mg/l; $P<0.05$). At Nafferton and Aberbran, the shallower loosening treatment resulted in slightly higher soil extractable P, while at Odstone soil extractable P was higher on the deeper loosening treatment (Figure 15). At Aberbran, shallower loosening also resulted in a small increase in soil extractable K compared with the unloosened and deeper loosened treatments (88 mg/l cf. 72 mg/l; $P<0.001$).
Figure 15. Effect of mechanical loosening on soil extractable P at Odstone in autumn 2013; three years after mechanical loosening. [Error bars give the standard error of the mean]

At Odstone, the use of manufactured N fertiliser increased soil extractable Mg from 173 mg/litre (Index 3) on the unfertilised control to 204 mg/litre (Index 4) on the fertiliser N plots ($P<0.05$).

6.4.3 Organic matter

Analysis of data across all four sites indicated that there were no differences in organic matter between treatments. However, single site analysis indicated that at Aberbran, shallower loosening resulted in a small increase in soil organic matter, as measured by loss on ignition (6.0% organic matter), compared with the unloosened treatment (5.6% organic matter; $P<0.05$).

At Odstone, the use of manufactured N fertiliser (500 kg N/ha in two years) increased soil organic carbon (SOC; Walkley Black dichromate oxidation method) from 2.7% on the unfertilised control to 2.9% on the manufactured N fertiliser plots ($P<0.01$; Figure 16).

Figure 16. Effect of the addition of 500 kg N/ha of manufactured fertiliser over two years on soil organic carbon at Odstone. [Error bars give the standard error of the mean]
However, there was no difference in SOC content between the N fertiliser plots and the seed mix plots $P>0.05$) indicating similar levels of root activity and below ground net primary production.

6.5 Treatment effects on grassland plant communities

6.5.1 Establishment and persistence of sown forbs

In 2011, the first year after applying the loosening and seeding treatments, there were highly significant differences between the four sites in the total cover and counts of sown forb species ( 
This was despite the target of 50% bare ground being achieved by the cultivations at all sites. The greatest cover (23–52%) and counts (17–24 plants 0.25m²) were at Bicton and least at Aberbran (1–7% and 1–6 plants respectively). There were also significant treatment effects, both cover and counts being up to 50% higher in the unloosened than in the shallower or deeper loosened plots. However, in the case of plant counts, the treatment differences were attributable to the Bicton and Odstone sites only (site x treatment interaction $F_{6,18}=3.3$, $P<0.05$).

Sown forb species with the highest counts in 2011 were *C. intybus*, *P. lanceolata* and *A. millefolium* at Bicton, and *C. intybus* and *T. pratense* at Odstone (Table 12). Species that established least well in the first year were *L. corniculatus* at Odstone and Aberbran, *S. minor muricata* at Odstone and Nafferton, and *H. radicata* also at Odstone. Significantly higher counts of several species were detected in unloosened plots, compared to either shallower or deeper loosened plots. These were *C. intybus* at Aberbran, Bicton and Odstone, and *A. millefolium*, *H. radicata* and *P. lanceolata*, all at Bicton. An exception to this pattern was *C. nigra* at Nafferton, which had lowest counts in the shallow loosened plots.

In 2011 there were also significant differences among sites in the size of individual plants of all sown forb species, with the exception of *L. corniculatus* (Figure 17). Where differences were detected, the plants tended to be larger at Odstone and Bicton than at Aberbran and Nafferton.

Changes in total cover and total counts of sown forbs varied among sites during the three-year period of the experiment (year x site interactions for cover $F_{6,64}=64.7$, $P<0.001$; counts $F_{6,64}=14.0$, $P<0.001$). Cover and counts declined at Aberbran to very low levels by 2013 (1% cover and <1 plant 0.25m²). In contrast, counts increased at Bicton and Nafferton, although cover at Bicton (52%) and Odstone (65%) tended to be highest in 2012 (Table 12).
Significant site x year interactions for counts of all sown forb species indicated that directional changes were either not consistent among sites, or the rates of change differed from 2011 to 2013 (Table 14). For example, *P. lanceolata* counts declined at Aberbran but increased at Nafferton and Odstone (Figure 19). In contrast, *C. intybus* counts declined strongly at Bicton, but less so at the other sites (Figure 19). Both *L. corniculatus* and *S. minor* ssp. *muricata* declined at all sites, although neither had established well initially. In contrast, *A. millefolium* counts increased at all sites except Aberbran, where all species had declined to very low levels by 2013. Recruitment of new individuals after the first year would be suggested by a concurrent increase in counts and decline in mean size. This appeared to be the case for *A. millefolium* and *C. nigra* at Bicton and *P. lanceolata* at Odstone. Mean size of *C. intybus* and *P. lanceolata* plants declined from 2011 to 2013 at Aberbran, Bicton and Odstone but otherwise the different trends among sites in the size of the remaining species probably reflected variation in growing conditions at the time of survey.
Figure 17. Mean size (cm) of individual sown forb plants across all three loosening treatments in 2011 (means and 95% confidence intervals). A = Aberbran, B = Bicton, N = Nafferton, O = Odstone.
The significant differences between loosening treatments in the total mean cover and counts of sown forbs was still evident by 2013, with unloosened plots still tending to have the highest values and shallower loosened the lowest (Table 12). This was consistent across sites, there being no significant site x treatment interactions in either 2012 or 2013. By 2013 however, the only individual species still showing a treatment effect were at Odstone, where counts of *C. intybus* in the unloosened treatment were greater than shallower or deeper loosening ($F_{2,15}=9.1, P<0.01$), and of *H. radicata* were lowest in the shallower loosened plots ($F_{2,15}=5.4, P<0.05$). At Bicton, both *L. corniculatus* and *P. lanceolata* showed the same general trends but the treatment effects were just outside the limits of statistical significance ($F_{2,15}=3.3, P=0.06$ and $F_{2,15}=3.4, P=0.06$ respectively).

As in 2011, there were no significant effects of loosening treatment on individual plant sizes of any of the sown forb species in 2012 or 2013. In 2013, the size of individual plants of *C. nigra*, *C. intybus*, *P. lanceolata* and *T. pratense*, still varied significantly among sites, but these now tended to be smaller at Aberbran (9.3, 14.4, 7.4 and 7.5 cm for each species respectively) than at the other sites (16.4–21.5, 16.4–20.4, 16.5–20.0 and 12.3–14.8 respectively).
Table 12. Total cover (%) and counts (mean number of plants 0.25m\(^2\)) of sown forb species in 2011, 2012 and 2013 with \(F\) values from the mixed model ANOVAs including all sites and the three loosening treatments. Untransformed data (mean per plot ± standard errors) shown for clarity. * \(P<0.05\), *** \(P<0.001\).

| Variable | Year | Aberbran | Bicton | Nafferton | Odstone | Site \(F_{3,18}\) | Unloosened | Shallow | Deep | Treatment \(F_{2,16}\) |
|----------|------|----------|--------|-----------|---------|----------------|-------------|---------|------|----------------|---|
| Cover    | 2011 | 6.6 ± 0.77 | 32.8 ± 3.16 | 4.3 ± 0.63 | 15.3 ± 1.60 | 72.4*** | 18.3 ± 4.09 | 12.1 ± 2.59 | 13.9 ± 2.79 | 6.9* |
|          | 2012 | 2.6 ± 0.75 | 52.2 ± 3.90 | 23.0 ± 3.63 | 65.0 ± 3.17 | 141.8*** | 42.6 ± 7.82 | 30.2 ± 5.90 | 34.3 ± 6.27 | 6.1* |
|          | 2013 | 1.0 ± 0.35 | 23.2 ± 1.98 | 21.6 ± 2.67 | 14.1 ± 0.89 | 42.8*** | 17.9 ± 3.15 | 12.2 ± 2.15 | 14.8 ± 2.52 | 7.6* |
| Counts   | 2011 | 6.2 ± 0.75 | 17.2 ± 1.5  | 3.6 ± 0.48 | 11.5 ± 1.80 | 34.7*** | 12.4 ± 2.34 | 8.2 ± 1.21  | 8.3 ± 1.12  | 7.88* |
|          | 2012 | 1.8 ± 0.49 | 21.6 ± 1.43 | 10.2 ± 2.18 | 19.7 ± 1.32 | 39.0*** | 16.5 ± 2.69 | 10.9 ± 2.10 | 12.7 ± 2.18 | 5.2* |
|          | 2013 | 0.5 ± 0.16 | 23.8 ± 2.62 | 19.4 ± 3.40 | 13.1 ± 0.78 | 19.3*** | 18.0 ± 3.55 | 11.6 ± 2.28 | 13.1 ± 2.56 | 6.1* |
Table 13. Counts (plants 0.25m$^2$) of individual sown forb species in each site in 2011, by loosening treatment with $F$ values from mixed model nested ANOVAs (mean per plot ± standard errors; $n$ = 24). * $P<0.05$, ** $P<0.01$, *** $P<0.001$, ns not significant.

<table>
<thead>
<tr>
<th>Site</th>
<th>Species</th>
<th>Unloosened</th>
<th>Shallow</th>
<th>Deep</th>
<th>$F_{2,51}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aberbran</td>
<td><em>Achillea millefolium</em></td>
<td>0.5 ± 0.13</td>
<td>0.5 ± 0.12</td>
<td>0.8 ± 0.26</td>
<td>0.2 ns</td>
</tr>
<tr>
<td></td>
<td><em>Centaurea nigra</em></td>
<td>1.2 ± 0.22</td>
<td>1.6 ± 0.38</td>
<td>1.2 ± 0.24</td>
<td>0.5 ns</td>
</tr>
<tr>
<td></td>
<td><em>Cichorium intybus</em></td>
<td>1.1 ± 0.30</td>
<td>0.5 ± 0.25</td>
<td>0.5 ± 0.13</td>
<td>6.4**</td>
</tr>
<tr>
<td></td>
<td><em>Hypochaeris radicata</em></td>
<td>1.0 ± 0.27</td>
<td>0.7 ± 0.18</td>
<td>0.8 ± 0.21</td>
<td>0.8 ns</td>
</tr>
<tr>
<td></td>
<td><em>Lotus corniculatus</em></td>
<td>0.3 ± 0.12</td>
<td>0.3 ± 0.11</td>
<td>0.2 ± 0.08</td>
<td>1.3 ns</td>
</tr>
<tr>
<td></td>
<td><em>Plantago lanceolata</em></td>
<td>1.4 ± 0.29</td>
<td>1.1 ± 0.29</td>
<td>1.5 ± 0.28</td>
<td>1.6 ns</td>
</tr>
<tr>
<td></td>
<td><em>Sanguisorba minor ssp. muricata</em></td>
<td>0.4 ± 0.12</td>
<td>0.5 ± 0.13</td>
<td>0.5 ± 0.12</td>
<td>0.1 ns</td>
</tr>
<tr>
<td></td>
<td><em>Trifolium pratense</em></td>
<td>0.8 ± 0.20</td>
<td>0.8 ± 0.22</td>
<td>0.4 ± 0.15</td>
<td>2.6 ns</td>
</tr>
<tr>
<td>Bicton</td>
<td><em>Achillea millefolium</em></td>
<td>3.3 ± 0.44</td>
<td>1.9 ± 0.44</td>
<td>1.8 ± 0.30</td>
<td>9.6**</td>
</tr>
<tr>
<td></td>
<td><em>Centaurea nigra</em></td>
<td>1.7 ± 0.20</td>
<td>1.5 ± 0.19</td>
<td>2.2 ± 0.29</td>
<td>0.3 ns</td>
</tr>
<tr>
<td></td>
<td><em>Cichorium intybus</em></td>
<td>6.5 ± 0.65</td>
<td>3.0 ± 0.43</td>
<td>3.8 ± 0.31</td>
<td>8.8**</td>
</tr>
<tr>
<td></td>
<td><em>Hypochaeris radicata</em></td>
<td>1.4 ± 0.13</td>
<td>0.5 ± 0.12</td>
<td>0.7 ± 0.16</td>
<td>12.4***</td>
</tr>
<tr>
<td></td>
<td><em>Lotus corniculatus</em></td>
<td>2.4 ± 0.25</td>
<td>1.5 ± 0.29</td>
<td>1.3 ± 0.27</td>
<td>3.2 ns</td>
</tr>
<tr>
<td></td>
<td><em>Plantago lanceolata</em></td>
<td>4.7 ± 0.88</td>
<td>2.5 ± 0.26</td>
<td>2.4 ± 0.31</td>
<td>4.1*</td>
</tr>
<tr>
<td></td>
<td><em>Sanguisorba minor ssp. muricata</em></td>
<td>1.0 ± 0.21</td>
<td>0.6 ± 0.10</td>
<td>0.6 ± 0.10</td>
<td>0.5 ns</td>
</tr>
<tr>
<td></td>
<td><em>Trifolium pratense</em></td>
<td>2.8 ± 0.89</td>
<td>1.5 ± 0.23</td>
<td>2.0 ± 0.30</td>
<td>0.7 ns</td>
</tr>
<tr>
<td>Nafferton</td>
<td><em>Achillea millefolium</em></td>
<td>0.7 ± 0.16</td>
<td>0.3 ± 0.12</td>
<td>0.4 ± 0.16</td>
<td>2.5 ns</td>
</tr>
<tr>
<td></td>
<td><em>Centaurea nigra</em></td>
<td>0.6 ± 0.18</td>
<td>0.1 ± 0.09</td>
<td>0.5 ± 0.13</td>
<td>6.0*</td>
</tr>
<tr>
<td></td>
<td><em>Cichorium intybus</em></td>
<td>0.5 ± 0.15</td>
<td>0.6 ± 0.20</td>
<td>0.5 ± 0.13</td>
<td>0.3 ns</td>
</tr>
<tr>
<td></td>
<td><em>Hypochaeris radicata</em></td>
<td>0.5 ± 0.15</td>
<td>0.6 ± 0.17</td>
<td>0.3 ± 0.09</td>
<td>1.2 ns</td>
</tr>
<tr>
<td></td>
<td><em>Lotus corniculatus</em></td>
<td>0.2 ± 0.10</td>
<td>0.3 ± 0.13</td>
<td>0.4 ± 0.18</td>
<td>0.4 ns</td>
</tr>
<tr>
<td></td>
<td><em>Plantago lanceolata</em></td>
<td>0.8 ± 0.21</td>
<td>0.8 ± 0.21</td>
<td>1.0 ± 0.19</td>
<td>1.0 ns</td>
</tr>
<tr>
<td></td>
<td><em>Sanguisorba minor ssp. muricata</em></td>
<td>0.3 ± 0.16</td>
<td>0.2 ± 0.10</td>
<td>0.3 ± 0.13</td>
<td>0.4 ns</td>
</tr>
<tr>
<td></td>
<td><em>Trifolium pratense</em></td>
<td>0.3 ± 0.13</td>
<td>0.1 ± 0.07</td>
<td>0.6 ± 0.22</td>
<td>2.5 ns</td>
</tr>
<tr>
<td>Odstone</td>
<td><em>Achillea millefolium</em></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td><em>Centaurea nigra</em></td>
<td>0.6 ± 0.13</td>
<td>0.2 ± 0.08</td>
<td>0.2 ± 0.10</td>
<td>3.4 ns</td>
</tr>
<tr>
<td></td>
<td><em>Cichorium intybus</em></td>
<td>6.0 ± 0.83</td>
<td>3.6 ± 0.47</td>
<td>3.5 ± 0.50</td>
<td>3.9*</td>
</tr>
<tr>
<td></td>
<td><em>Hypochaeris radicata</em></td>
<td>0.1 ± 0.07</td>
<td>0.3 ± 0.22</td>
<td>0.1 ± 0.10</td>
<td>0.6 ns</td>
</tr>
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<td><em>Lotus corniculatus</em></td>
<td>0.1 ± 0.06</td>
<td>0.0 ± 0.04</td>
<td>0.2 ± 0.13</td>
<td>0.9 ns</td>
</tr>
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<td></td>
<td><em>Plantago lanceolata</em></td>
<td>0.8 ± 0.25</td>
<td>0.6 ± 0.17</td>
<td>0.6 ± 0.13</td>
<td>0.1 ns</td>
</tr>
<tr>
<td></td>
<td><em>Sanguisorba minor ssp. muricata</em></td>
<td>0.1 ± 0.06</td>
<td>0.3 ± 0.13</td>
<td>0.0 ± 0.04</td>
<td>2.9 ns</td>
</tr>
<tr>
<td></td>
<td><em>Trifolium pratense</em></td>
<td>7.4 ± 2.18</td>
<td>5.5 ± 1.37</td>
<td>4.3 ± 1.17</td>
<td>1.9 ns</td>
</tr>
</tbody>
</table>
Table 14. Site x year interactions from the multivariate repeated-measures ANOVAs of mean counts and plant sizes per plot of sown forbs, across all three loosening treatments in 2011, 2012 and 2013 (- = insufficient data). ** P<0.01, *** P<0.001.

<table>
<thead>
<tr>
<th></th>
<th>Counts</th>
<th></th>
<th>Sizes</th>
<th></th>
</tr>
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<td></td>
<td>F</td>
<td>d.f.</td>
<td>F</td>
<td>d.f.</td>
</tr>
<tr>
<td><strong>Achillea millofolium</strong></td>
<td>17.0</td>
<td>6,76</td>
<td>***</td>
<td>33.5</td>
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<tr>
<td><strong>Centaurea nigra</strong></td>
<td>24.3</td>
<td>6,76</td>
<td>***</td>
<td>7.1</td>
</tr>
<tr>
<td><strong>Cichorium intybus</strong></td>
<td>23.3</td>
<td>6,76</td>
<td>***</td>
<td>10.0</td>
</tr>
<tr>
<td><strong>Hypochaeris radicata</strong></td>
<td>9.7</td>
<td>6,76</td>
<td>***</td>
<td>5.4</td>
</tr>
<tr>
<td><strong>Lotus corniculatus</strong></td>
<td>3.2</td>
<td>6,76</td>
<td>**</td>
<td>6.6</td>
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<tr>
<td><strong>Plantago lanceolata</strong></td>
<td>24.0</td>
<td>6,76</td>
<td>***</td>
<td>23.0</td>
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<tr>
<td><strong>Sanguisorba minor muricata</strong></td>
<td>5.9</td>
<td>6,76</td>
<td>***</td>
<td>-</td>
</tr>
<tr>
<td><strong>Trifolium pratense</strong></td>
<td>11.5</td>
<td>6,76</td>
<td>***</td>
<td>10.8</td>
</tr>
</tbody>
</table>

6.5.2 Grassland plant communities

The plant community at Aberbran differed from the other three sites, as shown by its separation from the others in the output of the Principal Components Analysis (PCA) of species cover in 2011 (Figure 20). The grassland at Aberbran was slightly less agriculturally improved, and characterised by species such as Agrostis capillaris, Ranunculus repens and Alopecurus geniculatus. Nafferton and Odstone were also separated from one another along the same gradient, Odstone being the most agriculturally improved of the four sites. The PCA also showed a clear separation of plots at each site according to the seeding treatment, with seeded plots having a distinctive community due to the addition of species. This was confirmed by the Partial Redundancy Analyses (pRDAs), which showed a significant effect of seed addition, accounting for 20% of the total variance in the plant community (Table 15). This was, as expected, almost entirely attributable to the presence of the sown species in the sward (Figure 21 and
Table 15). Cultivation alone also had a significant, albeit smaller, effect on the plant community and resulted in an increase in a range of annuals and other species associated with disturbance. Species most strongly associated with the uncultivated plots were *L. perenne* and *T. repens*; the latter was already present in the swards before the experimental treatments were applied although it was also included in the seed mixture. These three treatments also had a significant effect on the plant community when the sown species were excluded from the analysis (}
Table 15). However, the greatest variation was between the uncultivated plots and the other treatments, i.e. cultivation had the strongest effect on the plant community when sown species were discounted. In contrast, no effects of loosening treatments on the plant community were detected (
By 2013, the seeding treatments still had a highly significant effect on the plant community, although the effect was relatively small at Aberbran. Seed addition still accounted for most variation (17%) but the plant community also differed significantly in the cultivated and uncultivated treatments (Table 15). In the pRDA excluding the sown species, all three seeding treatments also had a small but significant effect on the remaining community (2-4%). As previously, no effects were detected of loosening treatment on the plant community.
Table 15. Results of pRDAs showing treatment effects on the plant community (log-transformed species cover). a) all species, b) sown species excluded. Lambda represents the additional variance explained by each variable when added to the model. () signifies the final nominal variable in each model, which explains the same variance as the next lowest variable in the model hierarchy. *** P<0.001, ns not significant.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lambda</th>
<th>F</th>
<th>Lambda</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Seeding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncultivated</td>
<td>0.03</td>
<td>11.3***</td>
<td>0.01</td>
<td>4.8***</td>
</tr>
<tr>
<td>Cultivated</td>
<td>()</td>
<td>()</td>
<td>()</td>
<td>()</td>
</tr>
<tr>
<td>Cultivated + Seeded</td>
<td>0.20</td>
<td>61.2***</td>
<td>0.17</td>
<td>50.1***</td>
</tr>
<tr>
<td>Loosening</td>
<td></td>
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</tr>
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<td>Unloosened</td>
<td>0.01</td>
<td>0.7 ns</td>
<td>0.01</td>
<td>1.0 ns</td>
</tr>
<tr>
<td>Shallow</td>
<td>0.00</td>
<td>1.1 ns</td>
<td>0.00</td>
<td>0.4 ns</td>
</tr>
<tr>
<td>Deep</td>
<td>()</td>
<td>()</td>
<td>()</td>
<td>()</td>
</tr>
<tr>
<td>b) Seeding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncultivated</td>
<td>0.07</td>
<td>19.3***</td>
<td>0.04</td>
<td>9.3***</td>
</tr>
<tr>
<td>Cultivated</td>
<td>0.02</td>
<td>4.1***</td>
<td>0.03</td>
<td>5.8***</td>
</tr>
<tr>
<td>Cultivated + Seeded</td>
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<td>()</td>
<td>()</td>
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<tr>
<td>Loosening</td>
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<tr>
<td>Unloosened</td>
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<td>0.8 ns</td>
<td>0.00</td>
<td>1.0 ns</td>
</tr>
<tr>
<td>Shallow</td>
<td>0.00</td>
<td>1.2 ns</td>
<td>0.00</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>Deep</td>
<td>()</td>
<td>()</td>
<td>()</td>
<td>()</td>
</tr>
</tbody>
</table>

Figure 20. Distribution of individual plots along the first two axes of variation from a Principal Components Analysis of plant species cover data from 2011, with plots coded by site and seeding treatment. Circles = Aberbran, squares = Bicton, diamonds = Nafferton, triangles = Odstone; black = cultivated & seeded, grey = cultivated, white = untreated.
Figure 21. Biplot of first two axes of variation from pRDA of species cover and seeding treatment. Only species with fit ≥ 1 shown for clarity. Sown species are highlighted in blue.

Table 16. Cover (%) of key species and bare ground in 2013 with $F$ values from the split-plot ANOVAs including all sites and all nine treatments. Untransformed data (mean per plot ± standard errors) shown for clarity. None of the loosening treatments were significant (apart from bare ground, see text) so data are not shown. * $P<0.05$, ** $P<0.01$, *** $P<0.001$, ns not significant.

<table>
<thead>
<tr>
<th></th>
<th>Aberbran</th>
<th>Bicton</th>
<th>Nafferton</th>
<th>Odstone</th>
<th>Site $F_{3,12}$</th>
<th>Uncultivated</th>
<th>Cultivated</th>
<th>Cultivated + Seeded</th>
<th>$F_{2,72}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>48</td>
<td>48</td>
<td>48</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td><strong>Bare ground</strong></td>
<td>12.3 ± 1.02</td>
<td>6.7 ± 0.64</td>
<td>1.5 ± 0.23</td>
<td>2.7 ± 0.45</td>
<td>26.3***</td>
<td>6.3 ± 0.97</td>
<td>6.7 ± 0.76</td>
<td>4.4 ± 0.72</td>
<td>10.2***</td>
</tr>
<tr>
<td><em>Cirsium arvense</em></td>
<td>0.0 ± 0.00</td>
<td>0.5 ± 0.22</td>
<td>0.0 ± 0.01</td>
<td>0.0 ± 0.00</td>
<td>1.9 ns</td>
<td>0.1 ± 0.08</td>
<td>0.1 ± 0.06</td>
<td>0.2 ± 0.14</td>
<td>0.3 ns</td>
</tr>
<tr>
<td><em>Poa annua</em></td>
<td>0.0 ± 0.02</td>
<td>0.4 ± 0.10</td>
<td>0.5 ± 0.16</td>
<td>1.4 ± 0.18</td>
<td>6.2**</td>
<td>0.4 ± 0.10</td>
<td>0.6 ± 0.14</td>
<td>0.7 ± 0.16</td>
<td>1.4 ns</td>
</tr>
<tr>
<td><em>Poa trivialis</em></td>
<td>13.4 ± 1.06</td>
<td>30.3 ± 2.78</td>
<td>19.8 ± 1.20</td>
<td>13.2 ± 1.84</td>
<td>8.7**</td>
<td>23.2 ± 2.40</td>
<td>19.1 ± 1.76</td>
<td>15.1 ± 1.06</td>
<td>4.7*</td>
</tr>
<tr>
<td><em>Rumex obtusifolius</em></td>
<td>0.4 ± 0.16</td>
<td>8.1 ± 2.01</td>
<td>3.6 ± 0.93</td>
<td>1.7 ± 0.38</td>
<td>12.5***</td>
<td>0.8 ± 0.25</td>
<td>5.6 ± 1.56</td>
<td>3.9 ± 0.80</td>
<td>30.9***</td>
</tr>
<tr>
<td><em>Trifolium repens</em></td>
<td>0.4 ± 0.10</td>
<td>6.8 ± 1.11</td>
<td>43.9 ± 2.06</td>
<td>9.2 ± 1.41</td>
<td>88.1***</td>
<td>14.5 ± 2.67</td>
<td>18.3 ± 3.19</td>
<td>12.5 ± 2.20</td>
<td>8.2***</td>
</tr>
</tbody>
</table>
By 2013, there were significant differences between sites in the cover of the four invasive species analysed (Table 16). *Poa trivialis*, *Rumex obtusifolius* and *Cirsium arvense* had greatest levels of cover at Biton, whereas *P. annua* had highest cover at Odstone. However, *P. annua* and *C. arvense* were only present at very low levels of cover and the latter was not recorded in quadrats at Aberbran or Odstone. *R. obtusifolius* had significantly greater cover in cultivated than uncultivated plots (apart from at Aberbran where it was virtually absent; site x seeding interaction $F_{6,72}=13.4$, $P<0.001$), and its cover was reduced slightly if sown species were also added. In contrast, there was a small but significant reduction in cover of *P. trivialis* in cultivated compared to uncultivated plots, although not at Odstone (site x seeding interaction $F_{6,72}=3.1$, $P<0.01$). No effect of cultivation or seed addition was detected on *C. arvense* or *P. annua*. *Trifolium repens* is an important agricultural species that was a component of the sward at the start of the experiment but was also included in the seed mixture. There was significantly greater cover of *T. repens* at Nafferton than the other sites reflecting its organic status. Surprisingly, there was significantly greater cover there in the cultivated (power-harrowed) plots without seed addition than in uncultivated plots or those with seed added (site x seeding interaction $F_{6,72}=5.7$, $P<0.001$). This suggests that *T. repens* benefited from the soil disturbance although competition from the sown species also displaced it to some extent. A possible explanation is the ability of *T. repens* to regenerate readily from stolon fragments.

Vegetation height and density were consistently highest at Odstone for the duration of the experiment, with Nafferton also having relatively high values in 2013 (Table 17). However, spatial variability (coefficients of variation) in both height ($F_{3,12}=13.4$, $P<0.001$) and density ($F_{3,12}=75.1$, $P<0.001$) were greater at Aberbran and Biton in 2013. Vegetation heights and densities were notably lower in 2013 compared to previous years, attributable to a late growing season caused by a cold, dry early spring. The effects of loosening and seeding treatments on vegetation structure varied between sites each year but overall there were no consistent trends, indicating that differences were attributable primarily to annual and between-site variation in the growth of vegetation. By 2013 there was significantly more bare ground in shallower (6.4% ± 0.92 s.e.) and deeper (6.3% ± 0.87 s.e.) loosening treatments than unloosened plots (4.7% ± 0.67 s.e.) ($F_{2,24}=3.6$, $P<0.05$). There was also more bare ground in cultivated, unseeded plots than those cultivated with seed added (Table 16), but only at Biton and Odstone (site x seeding interaction $F_{6,72}=9.9$, $P<0.001$). These differences in percentage cover of bare ground show that the disturbance effects of both cultivation and soil loosening were still evident, at least at some sites, after three years.

**Table 17.** Vegetation height and density (cm) in 2011, 2012 and 2013 in each site, with $F$ values from the split-plot ANOVAs including all nine treatments (mean per plot ± standard errors). * $P<0.05$, ** $P<0.01$, *** $P<0.001$.

<table>
<thead>
<tr>
<th>Year</th>
<th>n</th>
<th>Aberbran</th>
<th>Bicton</th>
<th>Nafferton</th>
<th>Odstone</th>
<th>$F_{3,12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td></td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td></td>
<td>26.8 ± 0.81</td>
<td>24.5 ± 0.83</td>
<td>21.5 ± 0.49</td>
<td>37.3 ± 0.53</td>
<td>31.2***</td>
</tr>
<tr>
<td>Density</td>
<td></td>
<td>24.6 ± 1.16</td>
<td>20.1 ± 0.75</td>
<td>23.2 ± 0.63</td>
<td>32.9 ± 0.67</td>
<td>9.9**</td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td>19.6 ± 0.42</td>
<td>21.8 ± 0.86</td>
<td>21.5 ± 0.49</td>
<td>25.6 ± 0.78</td>
<td>5.1*</td>
</tr>
<tr>
<td>Height</td>
<td></td>
<td>17.9 ± 0.48</td>
<td>15.5 ± 0.68</td>
<td>19.8 ± 0.55</td>
<td>22.1 ± 0.96</td>
<td>5.8*</td>
</tr>
<tr>
<td>Density</td>
<td></td>
<td>6.0 ± 0.27</td>
<td>8.9 ± 0.34</td>
<td>14.2 ± 0.35</td>
<td>15.0 ± 0.69</td>
<td>74.6***</td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td>2.8 ± 0.40</td>
<td>2.3 ± 0.32</td>
<td>14.4 ± 0.43</td>
<td>16.5 ± 0.91</td>
<td>268.9***</td>
</tr>
</tbody>
</table>
6.5.3 Treatment effects on root characteristics

The total mass of plant roots in 2013 was greater near the surface than at the deeper sampling depths at both Nafferton and Odstone (Table 18). Contrasting values for specific root length (SRL) indicated that roots were finer and of lower mass density at Nafferton than at Odstone and this was confirmed, respectively, by the mean root diameters and the ratios of root surface area to dry weight. This would be attributable to the differences in plant species composition between the two sites as well as differences in soil properties.

**Table 18.** Plant root characteristics at different sampling depths at Nafferton and Odstone in 2013, in Treatments 1, 3, 7 and 9 (overall means ± standard errors; n = 16 plots).

<table>
<thead>
<tr>
<th></th>
<th>Nafferton</th>
<th>Odstone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 – 20 cm</td>
<td>20 – 30 cm</td>
</tr>
<tr>
<td>Root length density (cm per cm³ of soil)</td>
<td>1.98 ± 0.126</td>
<td>1.93 ± 0.086</td>
</tr>
<tr>
<td>Surface area (cm² per cm³ of soil)</td>
<td>0.56 ± 0.046</td>
<td>0.22 ± 0.017</td>
</tr>
<tr>
<td>Mean diameter (mm)</td>
<td>1.00 ± 0.091</td>
<td>0.36 ± 0.017</td>
</tr>
<tr>
<td>Dry weight (mg per cm³)</td>
<td>1.14 ± 0.128</td>
<td>0.17 ± 0.018</td>
</tr>
<tr>
<td>Specific root length (m g⁻¹)</td>
<td>20.0 ± 2.07</td>
<td>158.0 ± 41.90</td>
</tr>
</tbody>
</table>

At both sites at the deeper sampling depth, the root length density (RLD) was significantly greater in the deeper loosened than unloosened treatment (Nafferton $F_{1,3}=180.9$, $P<0.001$;
Odstone $F_{1.3}=13.6$, $P<0.05$;
This indicates that the deeper loosening treatment resulted in increased development of plant roots. At Nafferton, this was supported by a similar trend for the total root surface area per volume of soil, although this was just outside the limits of statistical significance ($F_{1,3}=8.5, P=0.06$). At Odstone, the mean root diameter was smaller in the deeper loosened plots ($F_{1,3}=15.4, P<0.05$) and SRL values were higher ($F_{1,3}=13.2, P<0.05$), suggesting that finer roots (or roots with lower tissue density) had developed in the deeper loosened plots (Figure 22).

At Odstone, in the shallower samples above the compacted layer, the mean diameter of roots was significantly greater in the unloosened, unseeded plots than in the other treatment combinations ($F_{1,6}=9.6, P<0.05$; Figure 22). Also at Odstone, there was an indication that in the unloosened treatment, SRL values tended to be lower (indicating the presence of larger, or more dense roots) if they were not seeded, although the difference was just outside the limits of statistical significance ($F_{1,6}=4.6, P=0.08$). Similarly, at both sites there was an indication that total dry weight in the shallower samples might be greatest in the unloosened, unseeded plots (Odstone loosening x seeding interaction $F_{1,6}=4.3, P=0.08$; Nafferton $F_{1,6}=3.9, P=0.10$). Although not statistically significant, these consistent trends suggest that, at the shallower depths, disturbance from either loosening or cultivation might have reduced the mass and, at Odstone, the size of roots.
Figure 22. Effects of experimental treatments on plant root characteristics at Nafferton and Odstone in 2013 in Treatments 1, 3, 7 and 9 (means and 95% confidence intervals). U = unloosened, D = deeper loosened.

6.6 Treatment effects on microbial biomass – 2013 only

Analysis of the data for all sites combined indicated no differences in microbial biomass C or microbial biomass N between treatments (P>0.05). There were, however, differences between sites and differences between treatments at individual sites. Biomass N was lowest at Bicton
(P=0.01), perhaps reflecting the lower clay content (lighter soil) at this site. Biomass C was highest at Aberbran (P<0.05).

There were no differences in microbial biomass between treatments at Odstone and Aberbran. However, at Nafferton microbial biomass nitrogen (N) was higher on the shallower loosened plots (mean = 116 mg/kg) compared with the unloosened plots (mean = 107 mg/kg; P<0.05); and at Bicton microbial biomass N was higher on the seed mix plots (mean = 98 mg/kg; P<0.001) compared with the plots cultivated without seed addition (mean = 84 mg/kg) and the uncultivated control (mean = 88 mg/kg). This indicates that there was some change in microbial biomass due to shallower loosening at Nafferton and due to the introduction of seed mix species at Bicton, with both mechanical and biological methods giving rise to increases in microbial biomass N. At Nafferton, shallower loosening may have increased mineralisation of soil organic matter and made more inorganic nitrogen available for use by soil microbes. However, the fact that differences were measured three years after loosening was surprising. It is possible that the increase in microbial biomass N at Bicton was attributable to the greater cover and counts of sown forbs at this site (section 6.5.1; Table 12).

To test the hypothesis that earthworms, clover content or other variables may have affected soil organic N content and therefore microbial biomass N, generalized linear mixed-effects models (GLMMs) were used to assess effects of predictor variables on microbial biomass N at Nafferton, with microbial biomass N as the response variable and dry matter yield, clover percentage cover, MPR to 15 cm depth, pH, soil organic C and earthworm number/abundance as predictors (all log transformed).

\[
\text{Microbial biomass N} = \text{DM yield} + \% \text{ clover} + \text{MPR 15 cm} + \text{pH} + \text{SOC} + \text{worm number/abundance} + \text{year}
\]

Separate models were run for worm abundance and biomass in 2012 and 2014 with four models run in total; microbial biomass N was measured in autumn 2013 and earthworm biomass/number in autumn 2012 and spring 2014. Soil pH was the only significant predictor of microbial biomass N in all four models (P<0.001). Table 19 presents the model using earthworm abundance in 2012.

**Table 19.** Results of generalized linear mixed-effects models (GLMMs) of microbial biomass N, as a function of dry matter yield, clover percentage cover, MPR to 15 cm depth, pH, soil organic C and earthworm abundance in 2012. The GLMM was fitted using the Laplace method.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Estimate</th>
<th>Standard error (se)</th>
<th>t value</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1.21</td>
<td>0.616</td>
<td>1.96</td>
<td>0.06</td>
</tr>
<tr>
<td>DM yield</td>
<td>0.22</td>
<td>0.126</td>
<td>1.74</td>
<td>0.09</td>
</tr>
<tr>
<td>% clover</td>
<td>0.14</td>
<td>0.172</td>
<td>0.79</td>
<td>0.44</td>
</tr>
<tr>
<td>MPR 15 cm</td>
<td>-0.17</td>
<td>0.281</td>
<td>-0.60</td>
<td>0.56</td>
</tr>
<tr>
<td>pH</td>
<td>0.16</td>
<td>0.038</td>
<td>4.08</td>
<td>0.0003</td>
</tr>
<tr>
<td>SOC</td>
<td>0.23</td>
<td>0.188</td>
<td>1.24</td>
<td>0.22</td>
</tr>
<tr>
<td>Worm abundance</td>
<td>-0.01</td>
<td>0.051</td>
<td>--0.14</td>
<td>0.89</td>
</tr>
</tbody>
</table>

This analysis indicates that, at Nafferton, microbial biomass N was related to both shallower loosening and soil pH, but that there was no relationship between shallower loosening and soil pH. Clover content, dry matter yield, soil organic carbon and earthworm abundance/biomass did not have a strong influence on microbial biomass N.
6.7 Treatment effects on water infiltration rate

Of all the treatments, deeper mechanical loosening had the greatest effect on both initial and saturated infiltration rates. Effects were greatest on the ‘medium’ soil sites (Nafferton, Odstone and Aberbran) and were suppressed to some extent at Nafferton and Odstone by power-harrowing. At Bicton, the only ‘sandy’ soil site (topsoil clay content < 18%), deeper loosening increased what were already relatively high saturated infiltration rates (mean = 269 mm/h) in 2011 (one year after mechanical loosening), but there was no effect in subsequent years (Figure 23). Infiltration rates were measured at Bicton in 2011, 2012 and 2013, but with no significant differences after 2011, additional water infiltration measurements were not carried out in spring 2014.

![Figure 23. Effect of mechanical loosening at Bicton. [Error bars give the standard error of the mean]](image)

At the three ‘medium’ soil sites, mechanical loosening reduced infiltration rates into a fourth year post loosening, although dramatic increases were only detected in 2011 and 2012 (Figures 24 and 25). Mean initial water infiltration rates in 2011, 2012, 2013 and 2014 are presented for all three ‘medium soil’ sites in Figure 24 and saturated infiltration rates are presented in Figure 25. Both shallower and deeper loosening resulted in higher ($P<0.001$) saturated infiltration rates (compared with the un-loosened control) in 2011 (c.6 months post loosening) and 2012 (c.18 months post loosening). By spring 2013 (c.30 months post loosening), while infiltration rates were notably reduced overall compared with rates in 2011 and 2012, infiltration rates were still higher ($P<0.001$) on the deeper loosened treatment compared with the un-loosened control and this effect persisted into spring 2014. Notably, both initial and saturated infiltration rates in spring 2013 and 2014 on all three treatments were lower than in previous years, which may be a reflection of very wet weather during 2012. The effect of deeper mechanical loosening had reduced from a three- to seven-fold increase in water infiltration rates (compared to the unloosened control) to an increase of 1.5- to 2-fold. Nevertheless, the effect of autumn mechanical loosening on water infiltration rates persisted into the fourth spring (42 months) post loosening.
Figure 24. Effect of mechanical loosening on initial water infiltration rates (mm/hour) on medium grassland soils with ‘high’ bulk density. [Error bars give the standard error of the mean; n = 27]

Figure 25. Effect of mechanical loosening on saturated water infiltration rates (mm/h) on medium grassland soils with ‘high’ bulk density. [Error bars give the standard error of the mean; n = 27]
The deep rooting herbs and legumes had no effect on water infiltration, but at Nafferton and Odstone in 2011, the power-harrowing treatment (used to help establish the seed mix) suppressed water infiltration rates \((P<0.001)\). At Odstone, the effect on both initial and saturated infiltration rates lasted until 2012; two years after the power-harrowing treatment \((P<0.05\); Figure 26).

![Figure 26. Effect of power-harrowing on water infiltration rates (mm/h) at Odstone in 2011 and 2012. [Error bars give the standard error of the mean]](image)

6.7.1 Water infiltration rate models using GLMMs

Models with treatment as a nine level factor provided a much better fit for initial infiltration rate than the three level factor \((\chi^2 = 22389, \text{D.F.} = 8, P<0.001)\). The best fitting model for both initial and saturated infiltration rate (below) included the interaction between treatment and site (i.e. allowing treatment effects to vary across sites). This model provided a much better fit to the data \((\chi^2=38915, \text{D.F.} = 88, P<0.001)\) than models that did not allow treatment to vary between sites (Table 20).

Water infiltration rate was used as the response variable with a Poisson error structure and log link function.

Water infiltration rate = treatment + year + 1|plot + (treatment x site/block)

Note that the parameter estimate for the unloosened, uncultivated control (1) is reported as 5.60 mm/h, while all other parameter estimates for treatments in column 2 are reported relative to the unloosened and uncultivated control (Intercept); so saturated infiltration rates on treatments 2 (shallower loosened without cultivation) and 3 (deeper loosened without cultivation) were significantly higher than on the unloosened control \((P<0.01)\). There were also indications that cultivation suppressed water infiltration rates (treatment 7). Deeper loosening was the most effective treatment in increasing water infiltration rates. Estimates for Year 2013 are also relative to Year 2012.
Table 20. Results of generalized linear mixed-effects models (GLMMs) of saturated water infiltration rate, as a function of treatment, year, plot, site and replicate block. The GLMM was fitted using the Laplace method. Parameter estimates for treatments 2-9 are presented relative to treatment 1. The year 2 estimate is presented relative to year 1.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Estimate (mm/h)</th>
<th>Standard error (se)</th>
<th>z</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Treatments</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Unloosened, uncultivated control (Intercept)</td>
<td>5.60</td>
<td>0.451</td>
<td>12.43</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Relative to 1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) Shallower loosened (SL)</td>
<td>0.78</td>
<td>0.281</td>
<td>2.79</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>3) Deeper loosened (DL)</td>
<td>1.03</td>
<td>0.314</td>
<td>3.27</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>4) Unloosened (UL) &amp; power-harrowed (cult) without seed mix (SM)</td>
<td>-0.16</td>
<td>0.167</td>
<td>-0.94</td>
<td>0.35</td>
</tr>
<tr>
<td>5) SL &amp; cult without SM</td>
<td>0.14</td>
<td>0.142</td>
<td>1.02</td>
<td>0.31</td>
</tr>
<tr>
<td>6) DL &amp; cult without SM</td>
<td>0.67</td>
<td>0.279</td>
<td>2.39</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>7) UL &amp; cult with SM</td>
<td>-0.44</td>
<td>0.231</td>
<td>-1.91</td>
<td>0.06</td>
</tr>
<tr>
<td>8) SL &amp; cult with SM</td>
<td>0.62</td>
<td>0.265</td>
<td>2.38</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>9) DL &amp; cult with SM</td>
<td>0.86</td>
<td>0.213</td>
<td>4.04</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td><strong>Years</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Year 2012</td>
<td>0.12</td>
<td>0.004</td>
<td>25.93</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>2) Year 2013</td>
<td>-1.04</td>
<td>0.007</td>
<td>-155.55</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

To determine whether the seed mix had any effect on water infiltration rates and to investigate the relationship between soil physical properties and water infiltration rates, separate models were run with mechanical loosening and seed mix as factors; maximum penetration resistance (MPR: 15-30 cm), shear strength (SS; 0-5 cm) and BD (0-10 cm) as predictor variables; and initial and saturated water infiltration rates as response variables for 2011-13.

For initial water infiltration rates, a model with mechanical loosening as the principal factor indicated that rates on both unloosened and shallower loosened plots were lower than on deeper loosened plots ($P<0.01$; Table 21).

Initial water infiltration rate = mechanical loosening + MPR + SS + BD + year + site

There was also a possible negative relationship with shear strength, with water infiltration rate increasing as shear strength reduced ($P<0.05$); a positive relationship with BD, with water infiltration rate increasing with BD ($P<0.05$); a strong negative relationship with year (i.e. water infiltration rates generally decreased with time; $P<0.0001$); and a significant difference between sites ($P<0.001$). However, the positive relationship between initial water infiltration rate and BD may be due to the correlation between clay content, BD and water infiltration rate, i.e. the lighter textured sites have the highest initial water infiltration rates and highest 0-10 cm BD.
Table 21. Results of a generalized linear mixed-effects model (GLMM) of initial water infiltration rate, as a function of mechanical loosening, penetration resistance, shear strength, bulk density, year and site. The GLMM was fitted using the Laplace method. Parameter estimates for treatments/sites 2 and 3 are presented relative to treatment/site 1.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Estimate (mm/h)</th>
<th>Standard error (se)</th>
<th>z</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatments</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Deeper loosened (Intercept)</td>
<td>378.66</td>
<td>75.092</td>
<td>5.04</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>2) Shallower loosened (SL)</td>
<td>-0.14</td>
<td>0.051</td>
<td>-2.73</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>3) Unloosened (UL)</td>
<td>-0.43</td>
<td>0.052</td>
<td>-8.34</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Relative to 1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sites</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Bicton</td>
<td>0.08</td>
<td>0.077</td>
<td>1.10</td>
<td>0.271</td>
</tr>
<tr>
<td>2) Nafferton</td>
<td>-0.30</td>
<td>0.100</td>
<td>-3.02</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>3) Odstone</td>
<td>-0.79</td>
<td>0.086</td>
<td>-9.16</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD (0-10 cm)</td>
<td>2.80</td>
<td>1.413</td>
<td>1.91</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>MPR (15-30 cm)</td>
<td>-0.18</td>
<td>0.143</td>
<td>-1.26</td>
<td>0.210</td>
</tr>
<tr>
<td>Shear strength (0-5 cm)</td>
<td>-0.47</td>
<td>0.196</td>
<td>-2.37</td>
<td>0.018</td>
</tr>
<tr>
<td>Year</td>
<td>-0.19</td>
<td>0.037</td>
<td>-4.99</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

The model with the cultivation/seed mix treatment as the principal factor indicated that initial water infiltration rates were significantly higher on uncultivated plots (P<0.01; Table 22). There was no difference between cultivated plots with and without the seed mix (P>0.05). However, there were indications that infiltration rates increased with decreasing penetration resistance (P<0.05), shear strength (P<0.05) and bulk density (P<0.05).

Initial water infiltration rate = cultivation/seed mix + MPR + SS + BD + year + site

For saturated water infiltration rates, a model with mechanical loosening as the principal factor also indicated that rates on both unloosened and shallower loosened plots were lower than on deeper loosened plots (P<0.0001; Table 23).

Saturated water infiltration rate = mechanical loosening + MPR + SS + BD + year + site

There was also a possible negative relationship with soil physical properties, with water infiltration rates increasing with decreasing shear strength (P<0.01) and penetration resistance (P<0.05). There was also a strong effect of year and site with rates generally lower at Aberbran than at Bicton (P<0.0001) and Nafferton (P<0.05).

The model with the cultivation/seed mix treatment as the principal factor indicated that saturated water infiltration rates were significantly higher on uncultivated plots (P<0.01; Table 24). There was no difference between cultivated plots with and without the seed mix (P>0.05). However, there were indications that infiltration rates increased with decreasing penetration resistance (P<0.001) and decreasing shear strength (P<0.001).

Saturated water infiltration rate = cultivation/seed mix + MPR + SS + BD + year + site
Table 22. Results of a generalized linear mixed-effects model (GLMM) of initial water infiltration rate, as a function of cultivation/seed mix introduction, penetration resistance, shear strength, bulk density, year and site. The GLMM was fitted using the Laplace method. Parameter estimates for treatments/sites 2 and 3 are presented relative to treatment/site 1.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Estimate (mm/h)</th>
<th>Standard error (se)</th>
<th>z</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Treatments</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Cultivated without seed mix (Intercept)</td>
<td>374.98</td>
<td>80.56</td>
<td>4.67</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Relative to 1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) Seed mix</td>
<td>0.08</td>
<td>0.055</td>
<td>1.51</td>
<td>0.133</td>
</tr>
<tr>
<td>3) Uncultivated</td>
<td>0.16</td>
<td>0.055</td>
<td>2.87</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td><strong>Sites</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Bicton</td>
<td>0.08</td>
<td>0.082</td>
<td>0.95</td>
<td>0.345</td>
</tr>
<tr>
<td>2) Nafferton</td>
<td>-0.34</td>
<td>0.107</td>
<td>-3.17</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>3) Odstone</td>
<td>-0.81</td>
<td>0.092</td>
<td>-8.84</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD (0-10 cm)</td>
<td>3.13</td>
<td>1.514</td>
<td>2.07</td>
<td>0.039</td>
</tr>
<tr>
<td>MPR (15-30 cm)</td>
<td>-0.30</td>
<td>0.152</td>
<td>-1.97</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Shear strength (0-5 cm)</td>
<td>-0.48</td>
<td>0.211</td>
<td>-2.25</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Year</td>
<td>-0.18</td>
<td>0.040</td>
<td>-4.60</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

Table 23. Results of a generalized linear mixed-effects model (GLMM) of saturated water infiltration rate, as a function of mechanical loosening, penetration resistance, shear strength, bulk density, year and site. The GLMM was fitted using the Laplace method. Parameter estimates for treatments/sites 2 and 3 are presented relative to treatment/site 1.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Estimate (mm/h)</th>
<th>Standard error (se)</th>
<th>z</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Treatments</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Deeper loosened (Intercept)</td>
<td>371.72</td>
<td>78.336</td>
<td>4.75</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Relative to 1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) Shallower loosened (SL)</td>
<td>-0.23</td>
<td>0.054</td>
<td>-4.21</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>3) Unloosened (UL)</td>
<td>-0.66</td>
<td>0.054</td>
<td>-12.27</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td><strong>Sites</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Bicton</td>
<td>0.47</td>
<td>0.080</td>
<td>5.85</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>2) Nafferton</td>
<td>0.21</td>
<td>0.104</td>
<td>2.00</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>3) Odstone</td>
<td>-0.06</td>
<td>0.09</td>
<td>-0.64</td>
<td>0.525</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD (0-10 cm)</td>
<td>1.16</td>
<td>1.474</td>
<td>0.79</td>
<td>0.432</td>
</tr>
<tr>
<td>MPR (15-30 cm)</td>
<td>-0.31</td>
<td>0.149</td>
<td>-2.09</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Shear strength (0-5 cm)</td>
<td>-0.63</td>
<td>-0.205</td>
<td>-3.05</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Year</td>
<td>-0.18</td>
<td>0.039</td>
<td>-4.69</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
Table 24. Results of a generalized linear mixed-effects model (GLMM) of saturated water infiltration rate, as a function of cultivation/seed mix introduction, penetration resistance, shear strength, bulk density, year and site. The GLMM was fitted using the Laplace method. Parameter estimates for treatments/sites 2 and 3 are presented relative to treatment/site 1.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Estimate (mm/h)</th>
<th>Standard error (se)</th>
<th>z</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Treatments</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Cultivated</td>
<td>362.06</td>
<td>90.990</td>
<td>3.98</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>without seed mix</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Intercept)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) Seed mix</td>
<td>0.08</td>
<td>0.621</td>
<td>1.23</td>
<td>0.220</td>
</tr>
<tr>
<td>3) Uncultivated</td>
<td>0.16</td>
<td>0.062</td>
<td>2.60</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td><strong>Relative to 1)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sites</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Bicton</td>
<td>0.46</td>
<td>0.093</td>
<td>4.94</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>2) Nafferton</td>
<td>0.16</td>
<td>0.121</td>
<td>1.29</td>
<td>0.198</td>
</tr>
<tr>
<td>3) Odstone</td>
<td>-0.09</td>
<td>0.104</td>
<td>-0.91</td>
<td>0.363</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD (0-10 cm)</td>
<td>1.64</td>
<td>1.710</td>
<td>0.96</td>
<td>0.338</td>
</tr>
<tr>
<td>MPR (15-30 cm)</td>
<td>-0.50</td>
<td>0.172</td>
<td>-2.89</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Shear strength (0-5 cm)</td>
<td>-0.65</td>
<td>0.238</td>
<td>-2.73</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Year</td>
<td>-0.18</td>
<td>0.045</td>
<td>-3.93</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

6.8 **Treatment effects on earthworm numbers and biomass – Nafferton**

6.8.1 All Earthworm species

*Unloosened vs shallower loosened vs deeper loosened*

There was a significant effect of loosening treatment on earthworm abundance and biomass overall; data from years 2011, 2012 and 2014 combined (abundance: \( F=10.12, P<0.001 \); biomass \( F=15.53 \)). Unloosened treatments had significantly higher earthworm abundance and biomass than either shallower or deeper loosened plots (\( P<0.01 \)), while shallower and deeper loosening treatments did not differ from one another significantly (\( P=0.568 \)) (Tukey post-hoc tests). Patterns differed significantly between years, however (Table 25).

In 2011, there was a significant effect of loosening overall (\( F=6.212, p<0.005 \)). The unloosened treatment had significantly higher earthworm abundance than either the shallower or deeper loosened treatments (\( 46.2 \pm 4.2 \) (1SE) worms per m\(^2\) vs. \( 31.4 \pm 3.6 \) and \( 33.0 \pm 1.9 \) respectively; \( P<0.001 \) in Tukey post-hoc tests; Figure 27). Shallow and deeper loosening treatments did not differ significantly from one another (\( P=0.94 \)). Loosening also had a significant effect on earthworm biomass (\( F=14.46, P<0.001 \)). Biomass was significantly lower (\( P<0.001 \)) on the shallower and deeper loosened treatments than on the un-loosened control in 2011 (\( 102.4 \pm 7.8 \) vs. \( 61.3 \pm 7.2 \) and \( 59.9 \pm 4.1 \) respectively; Figure 28), but not different between the shallower and deeper loosened treatments (\( P=0.987 \)).

In 2012, there remained a difference between the treatments in terms of both earthworm abundance and biomass (\( F=10.32, P<0.001, F=12.63 P<0.001 \) respectively). However the pattern changed, with earthworm abundance and biomass in the deeper loosened treatment recovering to levels similar to those on the unloosened control i.e. the difference was no longer significant (abundance, \( P=0.505 \); biomass, \( P=0.388 \), while significant differences remained between the unloosened and shallower loosened treatments (\( P<0.001 \), and now also between
the deeper and shallower loosened treatments ($P<0.005$; unloosened plots: 50.3 ± 4.6 (1SE) worms per m$^2$, shallower: 27.5 ± 2.7 and deeper:44.5 ± 3.5) (Figures 27 and 28)

The sampling carried out in Spring 2014 identified far lower abundance and biomass of worms in each of the three treatments (abundance: unloosened 17.6 ± 1.80(1SE), shallower 17.2 ± 3.50, deeper 21.3 ± 3.6 worms per m$^2$; biomass: unloosened 19.9 ± 4.4, shallower 24.0 ± 10.0, deeper 27.3 ± 4.5 g m$^2$. However, there were no significant differences between the treatments (abundance: $T=0.53$, $P=0.594$; biomass: $T=0.301$, $P = 0.742$, Figures 27 and 28). For details of individual worm species abundance and biomass across the treatments see Appendix 4a.

**Untreated control vs. Uncultivated loosening treatments vs. power-harrow without species mix vs. power-harrow with species mix**

While there was no significant effect of cultivation treatment on earthworm abundance overall, there was an effect on biomass (data from years 2011, 2012 and 2014 combined) (abundance $F= 1.144$, $P=0.333$, biomass $F=4.76$, $P < 0.005$). All treatments with power harrowing and loosening had significantly lower worm biomass than the control treatment which had not received either treatment (unloosened-control, $P <0.05$, with species-control $P <0.005$, without species-control $P < 0.05$). None of the other treatments differed from one another.

Patterns differed significantly between years ($P <0.001$). 2011 followed the overall pattern; there was a significant effect of cultivation overall on biomass but not on abundance (abundance $F=2.041$, $P =0.113$, biomass $F=4.389$, $P < 0.001$) and every treatment held less worm biomass than the control treatment ($P <0.05$). In 2012, there was no significant difference in earthworm abundance or biomass between any of the treatments (abundance: $F=0.484$, $P =0.695$, biomass: $F=1.973$, $P = 0.132$). This was the same pattern (abundance $F=1.343$, $P =0.278$; biomass $F=0.243$, $P =0.866$) (Figures 29 and 30).

![Figure 27. Mean number of earthworms per m$^2$ (±1SE) in the untreated control and the two individual loosening treatments (shallower and deeper loosened).](image-url)
Table 25. Results of generalized linear mixed-effects models (GLMMs) of the total biomass of earthworms, as a function of ground treatment (unloosened vs. shallow loosening vs. deep loosening), accounting for variations in temperature and time of day. The GLMM was fitted using the Laplace method.

<table>
<thead>
<tr>
<th>Fixed Effects</th>
<th>Estimate</th>
<th>Se</th>
<th>t</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>6.21</td>
<td>0.65</td>
<td>9.56</td>
<td>0.00</td>
</tr>
<tr>
<td>Shallow loosening</td>
<td>-2.01</td>
<td>0.33</td>
<td>-6.12</td>
<td>0.00</td>
</tr>
<tr>
<td>Deep loosening</td>
<td>-1.72</td>
<td>0.33</td>
<td>-5.26</td>
<td>0.00</td>
</tr>
<tr>
<td>Time of day</td>
<td>0.00</td>
<td>0.00</td>
<td>0.59</td>
<td>0.56</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.03</td>
<td>0.02</td>
<td>1.38</td>
<td>0.17</td>
</tr>
<tr>
<td>Year 2</td>
<td>-1.44</td>
<td>0.27</td>
<td>-5.34</td>
<td>0.00</td>
</tr>
<tr>
<td>Year 2 * shallower loosening</td>
<td>0.33</td>
<td>0.38</td>
<td>0.87</td>
<td>0.39</td>
</tr>
<tr>
<td>Year 2 * deeper loosening</td>
<td>1.38</td>
<td>0.37</td>
<td>3.68</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Figure 28. Mean biomass of earthworms (g per m²; ±1SE) in the unloosened control and the two individual loosened treatments (shallow and deep loosened).
Figure 29. The effect of mechanical loosening and cultivation on mean abundance of earthworms (number/m²; ±1SE).

Figure 30. The effect of mechanical loosening and cultivation on mean biomass of earthworms (g/m²; ±1SE).
6.8.2 Endogeic species

*Unloosened vs shallower loosened vs deeper loosened*

All years combined, loosening treatments had a significant effect on endogeic worm biomass ($F=3.198$, $P < 0.05$), but not abundance ($F=2.916$, $P = 0.057$). There was significantly lower earthworm biomass in the shallower loosened treatments than either unloosened or deeper loosened treatments ($P < 0.05$). However, there was also a significant difference in this pattern between years ($P <0.001$).

In 2011, neither abundance nor biomass were significantly different between treatments (abundance $F=0.715$, $P = 0.491$; biomass $F=1.842$, $P =0.164$). In 2012, there was a significant difference between treatments in terms of both abundance and biomass (abundance: $F=7.785$, $P < 0.005$, biomass $F=7.96$, $P= 0.005$). Worms were significantly less abundant and had lower biomass in the shallower loosened treatment than in either the unloosened or deeper loosened treatment ($P <0.01$) (Figure 31 and 32). There were no significant difference in 2014 (abundance $F=1.109$, $P =0.342$; biomass $F=0.048$, $P = 0.953$).

*Figure 31. Mean number of endogeic earthworms per m² (±1SE) in the untreated control and the two individual loosening treatments (shallow and deep loosened).*
Figure 32. Mean biomass of endogeic earthworms (g per m²; ±1SE) in the untreated control and the individual loosening treatments (shallow and deep loosened).

Untreated control vs. Uncultivated loosening treatments vs. power-harrow without species mix vs. power-harrow with species mix

All years combined, loosening treatments, when subdivided by cultivation and species mix treatments, did not have a significant effect on endogeic worm abundance or biomass (abundance F=1.219, P = 0.305; biomass F= 2.008, P = 0.115).

This pattern held in all years (2011 abundance: F=1.876, P = 0.139, biomass: F=1.213, P = 0.309; 2012 abundance: F=0.637, P = 0.595, biomass: F=0.973, P = 0.414; 2014 abundance: F= 1.66, P = 0.12, biomass: F=1.93, P = 0.145 (Figures 33 and 34).
Figure 33. The effect of mechanical loosening and cultivation on mean abundance of endogeic earthworms (no./m²; ±1SE).

Figure 34. The effect of mechanical loosening and cultivation on mean biomass of endogeic earthworms (g/m²; ±1SE).
6.8.3 Anecic species

*Unloosened vs shallow loosened vs deep loosened*

All years combined, loosening treatments had a significant effect on anecic worm abundance and biomass (abundance $F=11.87$, $P<0.001$, biomass $F=12.53$, $P<0.001$). There was significantly lower biomass and fewer anecic worms in the shallower or deeper loosened treatments than in the unloosened treatment ($P<0.001$), while there was no difference overall between shallower and deeper loosened treatments ($P>0.05$). However there were differences between years.

In 2011, abundance and biomass were both significantly greater in the unloosened treatment compared with either of the loosened treatments ($P<0.001$). However in 2012 this pattern changed, with the shallower loosened treatment having lower abundances and biomass than either unloosened or deeper loosened treatments ($P<0.001$). There was no difference between shallower and deeper loosened treatments ($P>0.05$).

There were no significant differences between the treatments in 2014 (abundance $F=2.132$, $P=0.135$; biomass $F=1.087$, $P=0.349$). Figure 35 and 36.

![Bar chart showing mean number of anecic earthworms per m² (±1SE) in the untreated control and individual loosening treatments (shallow and deep loosening).](image)

*Figure 35. Mean number of anecic earthworms per m² (±1SE) in the untreated control and individual loosening treatments (shallow and deep loosening).*
Figure 36. Mean biomass of anecic earthworms (g per m²; ±1SE) in the untreated control and the individual loosening treatments (shallower and deeper loosening).

Untreated control vs. Uncultivated loosening treatments vs. power-harrow without species mix vs. power-harrow with species mix

All years combined, cultivation treatments had a significant effect on anecic worm abundance and biomass (abundance F= 3.382, $P < 0.05$, biomass F= 4.466, $P < 0.005$. Anecic earthworm abundance and biomass was significantly lower in all treatments relative to the control ($P < 0.05$). However, there were significant differences between years.

Only in 2011 were there significant differences between the treatments (abundance F=4.429, $P < 0.01$; biomass F= 4.634 $P < 0.005$), with all treatments containing lower anecic worm abundances and biomass than the control ($P < 0.05$). There were no significant differences between the treatments in 2012 or 2014 (2012 abundance: F=0.686, $P = 0.566$, biomass: F=1.808, $P = 0.16$; 2014 abundance: F=0.45, $P = 0.719$, biomass: F=1.811, $P = 0.165$) (Figures 37 and 38).
Figure 37. Effect of mechanical loosening and cultivation on mean number of anecic earthworms per m² (±1SE).

Figure 38. Mean biomass of anecic earthworms (g per m²; ±1SE) in the untreated control and the three types of loosening treatment (uncultivated loosening, power-harrow with and without species mix).
6.8.4 Changes in mass of worms and proportion of juveniles over time

The mean weight of individual anecic worms declined significantly between 2011 and 2012 ($P < 0.001$), but remained similar between years 2012 and 2014 ($P = 0.766$). Mean weight between the first and final year was not significantly different ($P = 0.250$). The mean weight of individual endogeic worms did not differ significantly throughout the trial period ($F = 0.086, P = 0.918$) (Figure 39).

The proportion of juvenile worms in the samples (all species combined) increased significantly between 2011 and 2012 in terms of both proportion by abundance and by biomass ($P < 0.001$). The proportion of juveniles by biomass, but not abundance, differed significantly between 2012 and 2014 ($P < 0.05$ vs. $P = 0.678$). Proportion of juveniles in 2014 was significantly higher than in 2011 for both abundance and biomass ($P < 0.001$) (Figure 40).

![Figure 39. Changes in mean biomass (wet weight in g; ±1SE) of individual endogeic and anecic worms over the trial period.](image1)

![Figure 40. Changes in the mean proportion of juveniles (±1SE) in samples (all species) in terms of both abundance and biomass over the trial period.](image2)
6.8.5 Earthworms, soil physico-chemical properties and vegetation density
When data for 2011 and 2012 were pooled, none of the soil (physico-chemical) property or botanical variables were significant predictors of earthworm abundance or biomass (all species, anecic or endogeic). However, when the two years were studied separately, there was a marked effect of vegetation density; a highly significant positive relationship in 2011 and a negative relationship in 2012 (2011 total abundance: t value= 3.577, P < 0.005, total biomass: 2.128, P <0.05; 2012 total abundance: t value= -2.767, P <0.005, total biomass: t value= -2.290, P <0.05). See Appendix 4b for full details; and for results for anecic and endogeic worm groups. Vegetation density was assessed during the spring botanical surveys by recording the lowest 10 cm mark on the sward stick that was visible above or through the vegetation.

6.9 Treatment effects on bird foraging behaviour
A complete list of key parameter means (penetration resistance, grass length, temperature, root rate, total number and percentage of successful roots) is shown in Table 26. Overall, there was only one significant difference, either within years or with years combined. Grass in the shallower loosened treatment was significantly longer than in other treatments (F= 5.04, P <0.05). There were no other significant differences in grass length between the individual treatments (F= 1.74, P = 0.09) or the cultivation treatments (F=1.64, P =0.18). There were also no significant differences in penetration resistance, either between individual treatments (F= 0.41, P =0.92), loosening treatments (F=0.01, P =0.99) or cultivation treatments (F=0.49, P =0.69) (see Figures 41-46).

6.9.1 GLMMs: Unloosened control treatment vs. shallower loosened treatments vs. deeper loosened treatments
After controlling for a wide range of external factors (penetration resistance, Julian date, grass length, time of day, temperature, year) (Table 26), no significant differences were detected between treatments for any of the three bird feeding parameters observed (roots per minute, number of successful roots, percentage of successful roots) (Table 27).

In each of the three models, Julian date and penetration resistance were significantly correlated, but were not interchangeable within the full model. Neither were Julian date and grass length, Julian date and time of day, Julian date and temperature or temperature and grass length. The interaction term 'year * treatment' was not significant.

6.9.2 GLMMs: Untreated control vs. Uncultivated loosening treatments vs. power-harrow without species mix vs. power-harrow with species mix
As with loosening treatments, after controlling for a wide range of external factors (penetration resistance, Julian date, grass length, time of day, temperature, year), no significant differences were detected between any the bird foraging parameters and any of the seeding treatments, including the untreated control (Table 28). Correlations between variables and interaction terms followed the same pattern as outlined for loosening treatments in 6.9.1.
Table 26. Mean penetration resistance (Mean PR), grass length, temperature, root rate, success rate and the percentage of successful roots per 10 minute trial in relation to treatment type. Results are quoted in the form of mean (± se).

<table>
<thead>
<tr>
<th></th>
<th>Unloosened</th>
<th>Shallower Loosened</th>
<th>Deeper Loosened</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1* (n = 29)</td>
<td>2 (n = 28)</td>
<td>3 (n = 29)</td>
</tr>
<tr>
<td>Mean PR</td>
<td>2.44 ± 0.21</td>
<td>2.58 ± 0.19</td>
<td>3.11 ± 0.65</td>
</tr>
<tr>
<td>Mean grass length (cm)</td>
<td>3.46 ± 0.33</td>
<td>3.73 ± 0.17</td>
<td>3.26 ± 0.19</td>
</tr>
<tr>
<td>Mean temperature(°C)</td>
<td>9.14 ± 0.93</td>
<td>8.10 ± 0.17</td>
<td>9.39 ± 0.83</td>
</tr>
<tr>
<td>Root rate</td>
<td>1.79 ± 0.34</td>
<td>1.06 ± 0.22</td>
<td>1.59 ± 0.74</td>
</tr>
<tr>
<td>Success rate</td>
<td>0.06 ± 0.05</td>
<td>0.02 ± 0.01</td>
<td>0.06 ± 0.04</td>
</tr>
<tr>
<td>Percentage of success</td>
<td>1.13 ± 0.05</td>
<td>1.05 ± 0.01</td>
<td>1.71 ± 0.04</td>
</tr>
</tbody>
</table>

2011 (n = 122)

| Mean PR              | 4.54 ± 0.07 | 4.59 ± 0.06 | 4.33 ± 0.08 | 3.93 ± 0.08 | 4.44 ± 0.10 |
| Mean grass length (cm) | 3.91 ± 0.23 | 4.54 ± 0.32 | 4.37 ± 0.34 | 3.74 ± 0.34 | 3.73 ± 0.16 |
| Mean temperature(°C) | 5.08 ± 0.95 | 6.07 ± 0.32 | 7.40 ± 0.23 | 6.71 ± 0.23 | 6.60 ± 0.09 |
| Root rate            | 1.73 ± 0.31 | 1.60 ± 0.42 | 1.15 ± 0.33 | 1.40 ± 0.56 | 1.28 ± 0.28 |
| Success rate         | 0.08 ± 0.01 | 0.06 ± 0.04 | 0.07 ± 0.05 | 0.12 ± 0.05 | 0.06 ± 0.04 |
| Percentage of success| 2.99 ± 0.83 | 1.56 ± 0.77 | 7.89 ± 0.40 | 2.69 ± 0.06 | 0.06 ± 0.01 |

2012 (n = 130)

| Mean PR              | 3.52 ± 0.21 | 3.58 ± 0.22 | 3.74 ± 0.42 | 3.27 ± 0.22 | 3.57 ± 0.21 |
| Mean grass length (cm) | 3.69 ± 0.14 | 4.14 ± 0.19 | 3.84 ± 0.20 | 3.64 ± 0.20 | 3.65 ± 0.14 |
| Mean temperature(°C) | 7.01 ± 0.68 | 7.09 ± 0.64 | 8.36 ± 0.64 | 7.48 ± 0.67 | 7.79 ± 0.71 |
| Root rate            | 1.76 ± 0.24 | 1.33 ± 0.24 | 1.37 ± 0.23 | 1.58 ± 0.37 | 1.40 ± 0.19 |
| Success rate         | 0.03 ± 0.01 | 0.01 ± 0.01 | 0.03 ± 0.01 | 0.02 ± 0.01 | 0.02 ± 0.01 |
| Percentage of success| 1.95 ± 1.62 | 1.31 ± 0.50 | 4.28 ± 1.28 | 1.29 ± 1.80 | 1.80 ± 0.60 |

Overall (n = 252)

| Mean PR              | 3.58 ± 0.22 | 3.57 ± 0.22 | 3.74 ± 0.42 | 3.27 ± 0.22 | 3.57 ± 0.21 |
| Mean grass length (cm) | 3.69 ± 0.14 | 4.14 ± 0.19 | 3.84 ± 0.20 | 3.64 ± 0.20 | 3.65 ± 0.14 |
| Mean temperature(°C) | 7.01 ± 0.68 | 7.09 ± 0.64 | 8.36 ± 0.64 | 7.48 ± 0.67 | 7.79 ± 0.71 |
| Root rate            | 1.76 ± 0.24 | 1.33 ± 0.24 | 1.37 ± 0.23 | 1.58 ± 0.37 | 1.40 ± 0.19 |
| Success rate         | 0.03 ± 0.01 | 0.01 ± 0.01 | 0.03 ± 0.01 | 0.02 ± 0.01 | 0.02 ± 0.01 |
| Percentage of success| 1.95 ± 1.62 | 1.31 ± 0.50 | 4.28 ± 1.28 | 1.29 ± 1.80 | 1.80 ± 0.60 |

Treatment categories: (1) unloosened control – uncultivated (2) shallower loosening – uncultivated (3) deeper loosening – uncultivated (4) no loosening – power-harrow, without species introduction (5) shallower loosening – power harrow/ rotavation, without species introduction (6) deeper loosening – power-harrow, without species introduction (7) no loosening – power-harrow and species mix (8) shallower loosening – power-harrow and species mix (9) deeper loosening – power-harrow and species mix. * Untreated control
Table 27. Loosening treatment: Results of generalized linear mixed-effects models (GLMM) of the number of roots per minute, the number of successful roots per minute and the percentage of roots that were successful per minute by wild-caught captive Starlings rooting the ground for invertebrate prey during a ten minute observation period as a function of the mean penetration resistance and ground treatment (unloosened treatments vs. shallower loosening treatments vs. deeper loosening treatments), accounting for variations in Julian date, grass length, temperature and time of day. The GLMM was fitted using the Laplace method.

<table>
<thead>
<tr>
<th></th>
<th>Root rate (per min)</th>
<th>No. successful roots (per min)</th>
<th>% successful roots (per min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate</td>
<td>se</td>
<td>df</td>
</tr>
<tr>
<td>Intercept</td>
<td>0.81</td>
<td>3.41</td>
<td>1</td>
</tr>
<tr>
<td>Penetration</td>
<td>-0.10</td>
<td>0.08</td>
<td>1</td>
</tr>
<tr>
<td>Shallow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loosening</td>
<td>0.05</td>
<td>0.29</td>
<td>1</td>
</tr>
<tr>
<td>Deep Loosening</td>
<td>-0.07</td>
<td>0.29</td>
<td>1</td>
</tr>
<tr>
<td>Julian date</td>
<td>0.00</td>
<td>0.00</td>
<td>1</td>
</tr>
<tr>
<td>Grass length</td>
<td>-0.03</td>
<td>0.07</td>
<td>1</td>
</tr>
<tr>
<td>Time of day</td>
<td>0.00</td>
<td>0.00</td>
<td>1</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.00</td>
<td>0.02</td>
<td>1</td>
</tr>
<tr>
<td>Year</td>
<td>-5.43</td>
<td>6.93</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 41. Mean number of roots per minute (± se) in relation to soil compaction treatments at Nafferton Farm, Northumberland, UK.

Figure 42. Mean number of successful roots per minute (± se) in relation to soil compaction treatments at Nafferton Farm, Northumberland, UK.
Figure 43. Percentage of successful roots per minute (± se) in relation to soil compaction treatments at Nafferton Farm, Northumberland, UK.
Table 28. Cultivation treatment: Results of generalized linear mixed-effects models (GLMM) of the number of roots per minute, the number of successful roots per minute and the percentage of roots that were successful per minute by wild-caught captive Starlings rooting the ground for invertebrate prey during a ten minute observation period as a function of the mean penetration resistance and ground treatment (Level 1, untreated control; Level 2, uncultivated loosening treatments; Level 3, power-harrow without species mix; and Level 4, power-harrow with species mix), accounting for variations in Julian date, grass length, temperature and time of day and year. The GLMM was fitted using the Laplace method.

<table>
<thead>
<tr>
<th></th>
<th>Root rate (per min)</th>
<th>No. successful roots (per min)</th>
<th>% successful roots (per min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate se df z P</td>
<td>Estimate se df z P</td>
<td>Estimate se df z P</td>
</tr>
<tr>
<td>Intercept</td>
<td>-50.94 80.66 1 -0.63 0.53 -144.60 37.10 1 -0.39 0.70 -43.82 479.08 1 -0.09 0.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Penetration resistance</td>
<td>-0.07 0.09 1 -0.79 0.43 -0.30 0.52 1 -0.57 0.57 -0.24 0.59 1 -0.41 0.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 2</td>
<td>-0.22 0.43 1 -0.51 0.61 -0.09 0.91 1 -0.10 0.92 0.09 1.11 1 0.08 0.94</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 3</td>
<td>-0.19 0.40 1 -0.48 0.63 -0.34 0.84 1 -0.40 0.69 -0.14 1.03 1 -0.14 0.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 4</td>
<td>-0.06 0.40 1 -0.14 0.89 0.11 0.80 1 0.14 0.89 0.22 0.98 1 0.23 0.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Julian date</td>
<td>0.00 0.01 1 0.63 0.53 0.01 0.03 1 0.38 0.71 0.00 0.04 1 0.08 0.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grass length</td>
<td>-0.03 0.07 1 -0.47 0.64 -0.15 0.30 1 -0.49 0.62 -0.15 0.36 1 -0.41 0.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time of day</td>
<td>0.00 0.00 1 1.47 0.14 0.00 0.00 1 1.07 0.28 0.00 0.00 1 0.57 0.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>0.01 0.02 1 0.44 0.66 -0.04 0.09 1 -0.48 0.63 -0.07 0.12 1 -0.60 0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year</td>
<td>-4.47 6.94 1 -0.64 0.52 -11.40 32.38 1 -0.35 0.73 -2.58 41.34 1 -0.06 0.95</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 44. Mean number of roots per minute (± se) in relation to soil compaction treatments at Nafferton Farm, Northumberland, UK.

Figure 45. Mean number of successful roots per minute (± se) in relation to soil compaction treatments at Nafferton Farm, Northumberland, UK.
Figure 46. Percentage of successful roots per minute (± se) in relation to soil compaction treatments at Nafferton Farm, Northumberland, UK.
6.10 Treatment effects on dry matter (DM) yield and quality

Dry matter yield and quality were not affected by mechanical loosening, relative to the unloosened control, at any site or in any year (\(P<0.05\)). The main factors influencing DM yield were the use of manufactured fertiliser N, power-harrowing and the introduction of the deep-rooting herb and legume seed mix.

Data analysis across all sites indicated that in 2012 the seed mix increased yields relative to the uncultivated control and the cultivated treatment without the seed mix (Figure 47; \(P<0.001\)). No N fertiliser was applied in these comparisons.

![Figure 47. Effect of power-harrowing and the introduction of the seed mix on DM yield at all sites in 2011 and 2012. [Error bars give the standard error of the mean]](image)

Power-harrowing reduced yield relative to the uncultivated control at Bicton in 2011 (\(P<0.05\)) and at Nafferton in 2012 (\(P<0.01\)); and the seed mix increased yields relative to the uncultivated control and/or the power-harrow treatment without seeding at Odstone (\(P<0.05\)) and Bicton (\(P<0.001\)) in 2012 and at Odstone in 2013 (\(P<0.05\); Figure 48).

Mechanical loosening had no effect on DM yields other than at Odstone in 2011 (eight months after loosening) when yields were lower on the deeper loosened plots than on the shallower loosened plots (\(P<0.05\); Figure 49). However, there was no difference between deeper or shallower loosening and the unloosened control. The difference was due to lower DM% in grass from the deeper loosened plots (\(P<0.05\)), although the opposite was true at Nafferton in the same year where both power-harrowing and mechanical loosening (shallower and deeper) increased grass DM%, but without an associated increase in DM yield.

At Odstone, Aberbran and Bicton it was possible to compare the effect of manufactured N fertiliser with the effect of the forb and legume seed mix on DM yields in 2012; and at Odstone the fertiliser N treatments were repeated in 2013. At Aberbran there were no differences in DM yield between treatments, but at Bicton in 2012, the seed mix increased forage yield by 2.9 t DM/ha (56%; \(P<0.001\)) relative to the unfertilised control (i.e. zero fertiliser N), and by 1.8 t DM/ha (30%; \(P<0.001\)) relative to the fertiliser N plots (80 kg N/ha). This was most probably due to the N fixing effect of the legumes within the seed mix. N offtakes were also higher on the
seed mix plots (mean = 137 kg N/ha) relative to the fertiliser N (mean = 101 kg N/ha) and unfertilised control plots (73 kg N/ha; \( P < 0.001 \)).

![Figure 48. Effect of power-harrowing and the introduction of the seed mix on DM yield at Odstone in 2012 and 2013. [Error bars give the standard error of the mean]](image)

At Odstone in 2012, the seed mix increased forage yield by 0.7 t DM/ha (16%; \( P < 0.001 \)) relative to the unfertilised control, but 100 kg fertiliser N/ha increased yield by 1.3 t DM/ha (31%; \( P < 0.001 \); Figure 51). There was no interaction between the effect of manufactured N fertiliser and the effect of mechanical loosening. D-values were slightly lower on N fertiliser plots \( (P < 0.05) \), but not sufficient to counteract the effect of increased yield. N offtakes (kg N/ha) were also higher on the N fertiliser grass (mean = 159 kg N/ha) and the seed mix plots (mean = 145 kg N/ha) than on the unfertilised control (mean = 90 kg N/ha; \( P < 0.001 \)).
Figure 50. Effect of (a) mechanical loosening and fertiliser N combined; (b) N fertiliser; and (c) mechanical loosening on DM yield at Odstone in 2013. [Error bars give the standard error of the mean]
At Odstone in 2013, fresh grass yields were highest on the deeper loosened plots \( (P<0.001) \), but DM% was lower \( (P<0.05) \) resulting in no difference in DM yield due to mechanical loosening. However, when the effect of mechanical loosening was investigated with and without N fertiliser (Figure 50 – Odstone was the only site where with and without N fertiliser treatments were applied in 2013), deeper loosening (compared with shallower loosening) increased DM yield by 1.3 t DM/ha (29%; \( P<0.05 \)) where no fertiliser N was applied. However, there was no difference in yield between deeper loosening (5.7 t DM/ha) and the unloosened control (4.8 t DM/ha; \( P>0.05 \)) where no N fertiliser was applied (Figure 50). There was also no difference in dry matter yield due to mechanical loosening where N fertiliser was applied, and an indication that deeper loosening may have reduced the relative yield benefit from applying manufactured N fertiliser, although the result may reflect better yields from deeper loosening (improved soil structure and root proliferation) where fertiliser is not applied.

In 2013 at Odstone, the seed mix increased forage yield by 0.8 t DM/ha (15%; \( P<0.001 \)), but fertiliser N (100 kg N/ha) increased grass yield by 2.0 t DM/ha (39%; \( P<0.001 \); Figure 50). Mechanical loosening had no effect on DM yield, with or without manufactured fertiliser N \( (P>0.05) \). In 2013, N offtakes were higher on the fertiliser N plots (mean = 145 kg N/ha) relative to the seed mix (mean = 97 kg N/ha) and unfertilised control plots (mean = 66 kg N/ha; \( P<0.01 \)).

![Figure 51. Effect of seed mix addition and manufactured fertiliser N on grass DM yield at Odstone in 2012 and 2013. [Error bars give the standard error of the mean]](image)

6.11 Treatment effects on nitrous oxide emissions

6.11.1 Effect of deeper loosening on nitrous oxide emissions from unfertilised soil

Nitrous oxide (\( \text{N}_2\text{O} \)) measurements at Aberbran in the two months post loosening indicated that deeper loosening increased \( \text{N}_2\text{O} \) emissions by a small but significant amount (a 170% increase to 0.3 kg \( \text{N}_2\text{O} \)-N/ha; \( P<0.05 \)) in the short term. However, in the twelve months post loosening,
deeper loosening at Odstone and Aberbran had no overall effect on N\textsubscript{2}O emissions (Figures 52 and 53).

![Figure 52](image)

*Figure 52. Cumulative N\textsubscript{2}O emissions over 359 days post-loosening at Aberbran (September 2010 to September 2011).*

![Figure 53](image)

*Figure 53. Cumulative N\textsubscript{2}O emissions over 368 days post-loosening at Odstone (September 2010 to September 2011).*

6.11.2 Effect of deeper loosening on nitrous oxide emissions from applied N fertiliser

N\textsubscript{2}O measurements at Odstone and Aberbran in the twelve months post application of manufactured N fertiliser indicated that mechanical loosening had no effect on N\textsubscript{2}O emissions; measurements were carried out for twelve months post fertiliser application to meet scientific publication and Intergovernmental Panel on Climate Change (IPCC) reporting requirements (Figures 54 and 55). Nitrous oxide emissions generally increased when water-filled pore space (blue circles and dotted line) was greater than 60%. However, there was no significant difference in water-filled pore space (WFPS) between un-loosened and deeper loosened treatments at Odstone and Aberbran (P>0.05).
Figure 54. Variations in nitrous oxide emissions and water-filled pore space in the twelve months post manufactured N fertiliser application at Odstone; for deeper loosened and unloosened treatments with and without manufactured N fertiliser.
Figure 55. Variations in nitrous oxide emissions and water-filled pore space in the twelve months post manufactured N fertiliser application at Aberbran; for deeper loosened and unloosened treatments with and without manufactured N fertiliser.
To investigate any potential differences in N$_2$O emissions in the few weeks after fertiliser N application, further analysis was carried out to compare data for deeper loosened and un-loosened treatments up to the time when emissions returned to background levels (Figures 56 and 57). At Odstone, the application of fertiliser N (40 kg N/ha) resulted in an increase in N$_2$O emissions in the month post fertiliser application. However, there were no differences ($P>0.05$) in N$_2$O emissions between the loosened and un-loosened treatments. At Aberbran there were no differences ($P>0.05$) in N$_2$O emissions between any of the four treatments after manufactured N fertiliser application (i.e. until ‘return to background’).

In summary, at Aberbran and Odstone, deeper loosening had no significant effect ($P>0.05$) on N$_2$O emissions over the twelve month period post N fertiliser application. At Odstone, the N fertiliser emission factors (0.67 and 0.95% of total N applied) were similar to the IPCC default of 1%, while at Aberbran, there were no measurable N$_2$O emissions from fertiliser N application.

![Figure 56. Effect of manufactured N fertiliser application on nitrous oxide emissions up until ‘return to background levels’ at Odstone.](image-url)
Figure 57. Effect of manufactured N fertiliser application on nitrous oxide emissions up until ‘return to background levels’ at Aberbryn.
7 Bird foraging field-scale experiment results

116 visits were made to the 15 sites from February-June 2012 – 8 at each site, except from the Cornwall and Staffordshire sites which received 6 visits each. Birds were recorded foraging in fields on 68% of visits (79/116).

In total, 619 birds were observed foraging across the 15 sites – 224 on the unloosened plots and 395 on the loosened plots. While the absolute numbers of birds on the loosened plots were larger than that on the unloosened plots, this was largely because of one site, where a large number of rooks were recorded foraging across the whole field on a number of visits – a “flocking” effect (Figure 58). When mean numbers per visit was used rather than total numbers, there was no significant difference between numbers of birds observed on unloosened and loosened treatments (T=-1.32, P=0.187) (Figure 59).

![Figure 58. Total number of birds recorded by site.](image)

Taking the proportion of visits on which birds were recorded on one or the other treatment, there was no significant difference in bird use of the loosened and unloosened areas of the 15 fields. This was the case when taking all species together, or taking individual “functional” or “species” groups (all species: Z value 0.290, P=0.772; only soil probing species: Z-value 0.442, P=0.659; thrushes: Z – value 0.926, P =0.354; corvids: Z-value 0.565, P=0.572) (Figure 60; Table 29).
Figure 59. Mean number of birds per visit on unloosened and loosened plots. The difference is not significant ($T=-1.32$, $P=0.187$).

Figure 60. Total number of visits (all sites together) where birds were recorded on either unloosened (white bars) or loosened plots (Grey bars). Numbers above bars indicate the actual numbers of birds observed.
Table 29. Parameter estimates for the GLMMs of bird abundance and treatment (loosened/unloosened).

<table>
<thead>
<tr>
<th></th>
<th>Parameter estimate</th>
<th>Standard error</th>
<th>Z- value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>All species</td>
<td>0.0806</td>
<td>0.2775</td>
<td>0.290</td>
<td>0.772</td>
</tr>
<tr>
<td>Only invertebrate feeders</td>
<td>0.1250</td>
<td>0.2830</td>
<td>0.442</td>
<td>0.659</td>
</tr>
<tr>
<td>Thrushes only</td>
<td>0.3379</td>
<td>0.3647</td>
<td>0.926</td>
<td>0.354</td>
</tr>
<tr>
<td>Corvids only</td>
<td>0.2075</td>
<td>0.3676</td>
<td>0.565</td>
<td>0.572</td>
</tr>
</tbody>
</table>
8 Discussion of Results

8.1 Treatment effects on soil physico-chemical properties

8.1.1 Treatment effects on soil physical properties

Whereas mechanical loosening had the general effect of reducing soil strength as measured by a penetrometer or shear vane, the power harrow treatment (with and without the seed mix) initially reduced soil surface shear strength in the 2-3 months post cultivation, due to disruption of soil aggregates and the grass root mass, but then by the spring (5-6 months post cultivation) increased surface soil shear strength and maximum penetration resistance (MPR) to 15 cm depth. This increase in soil strength was most probably due to rain drop impact on the cultivated, bare soil and related crusting/capping processes (Mellius et al., 1996; Poesen, 1992), and corresponds with the generally reduced water infiltration rates due to cultivation detected in this study. This has implications for runoff and erosion risk in grassland soils and confirms that erosion and runoff risk is generally reduced when grassland swards are retained (Newell Price et al., 2011). Surface soil shear strength was also greater on power-harrowed plots (with and without the seed mix) in autumn 2013 (three years post-cultivation). However, this may have been due to the persistent effect of surface capping post-cultivation. It is unlikely to have been attributable to the rooting effect of ruderal (where the seed mix was not added) or seed mix species, because the root measurements in autumn 2013 did not indicate any consistent effect of power-harrowing or the seed mix on rooting other than reduced root diameter due to cultivation and the possibly associated collapse of soil aggregates.

Overall, MPR was the parameter that was most affected by mechanical loosening and the deep-rooting herb/legume mix, although bulk density (BD) was only measured to 0-10 cm depth in 2010, 2011 and 2012. Soil BD was measured at mid topsoil depth in autumn 2013 only, by which time no differences in soil physical properties could be detected, except MPR measurements and these only at Nafferton. However, the fact that no differences in 0-10 cm BD were detected in 2011-12, while water infiltration rates increased 4- to 10-fold in this time period, indicates firstly that BD measured at 0-10 cm depth was unaffected by mechanical loosening and secondly that mechanical loosening results in a general fracturing and reduction in soil strength in the mid to lower topsoil rather than reducing porosity or fracturing aggregates in the upper topsoil layer, which is generally better structured due to the grass root mass. This was supported to some extent by the nitrous oxide measurements, which indicated no effect of mechanical loosening on nitrous oxide emissions post manufactured N fertiliser application, although it is also possible that the 40 kg N/ha applied did not provide a sufficiently large 'signal' for an effect to be detected.

8.1.2 Treatment effects on soil chemical properties

The only treatment that had an effect on pH was the addition of manufactured N fertiliser. It is well established that manufactured N fertiliser can have an acidifying effect on soil pH (Stevens and Laughlin, 1996), but the fact that a reduction in pH was measured after only two years of N fertiliser application was surprising. This confirms the importance of regular soil testing for pH and major nutrients (P, K and Mg) in productive grasslands to maintain or improve nutrient use efficiency and productivity.

The small increases in soil extractable P and K due to mechanical loosening at some sites was unexpected. For potassium, mechanical loosening near the surface may have exposed micaceous clay minerals to mineralisation processes, thereby releasing ‘fixed’ lattice potassium (Kf) onto the soil exchange complex (Kex; Johnston et al., 2001). For phosphorus, the mechanism for increasing extractable P due to mechanical loosening is less clear. The small increase in soil extractable Mg due to the addition of manufactured N fertiliser at Odstone was also unexpected with the mechanism of action unclear, but it could be related to soil pH. As a
base cation, Mg behaves in soil in the same way as K and Johnston (2007) has reported that in Woburn and Rothamsted soils, more K remained exchangeable in acid soils (pH 5-6) than in neutral or calcareous soils (pH 7-8), suggesting that soil acidity should be taken into account in the relationship between different pools of K and Mg.

8.2 Water infiltration rate discussion

The saturated water infiltration rates on the unloosened plots were comparable with ‘typical’ infiltration rates reported in MAFF Reference Book 441 (1982) of 150-500 mm/h for sandy soils (as at Bicton) and 30-50 mm/h for clay loam sites using an initial hydraulic head of c. 5 cm (Nafferton, Odstone and Aberbran). The above results therefore suggest that mechanical loosening (particularly deeper loosening) can increase water infiltration rates that are commonly found on ‘high’ bulk density managed grassland soils by 4- to 10-fold. This increase in water infiltration rates compares with a 51% reduction in surface runoff using a hybrid of perennial ryegrass and meadow fescue (‘Festulolium cv. Prior’) at the laboratory scale as reported by MacLeod et al. (2013) and a c.60-fold increase in median water infiltration rates in the fifth year post tree planting compared with grazed pasture at the plot scale (Carroll et al., 2004; Marshall et al., 2014). Marshall et al. (2014) also measured surface runoff and found that increases in water infiltration rate usually corresponded with reductions in surface runoff volume, although results varied greatly and no consistent or significant relationship was established between the two variables. The findings from this project could therefore have important implications for the management of grassland to reduce surface runoff volumes and flooding risk at the local scale, although it is important to note that the results reported here were based on measurements at the plot scale. Nevertheless, mechanical loosening could potentially have an effect in attenuating the peak of the hydrograph in some sub-catchments prone to flooding. However, to determine whether or not this is the case would require further research at the field scale, using hydrologically isolated plots, as well as hydrological modelling to scale up impacts from the plot/field scale to the catchment scale.

Higher water infiltration rates on mechanically loosened plots corresponded with lower penetration resistance, lower BD (initially) and higher (better) visual soil structure scores. These measurements and observations indicate that mechanical loosening lifted and fractured the soils, resulting in reduced penetration resistance, reduced soil strength and vertical fissuring through the soil that not only improved soil structural condition over time, but also increased water infiltration rates through improved soil drainage. However, the deeper loosening did not have a significant effect on bulk density (an indicator of porosity) in the upper topsoil layer close to the surface. This has implications for the ability of deeper mechanical loosening to affect water-filled pore space and therefore nitrous oxide emissions in grassland soils.

The current project measured the effects of a single mechanical loosening treatment. However, it is not clear what effect a second mechanical loosening carried out a few years after an initial loosening would have on soil bio-physical quality and function i.e. what is an appropriate period of time between mechanical loosening operations; and what factors should be taken into account when considering ‘re-loosening’? For example, do the key guidelines for mechanical loosening on a first occasion (ADAS, 1984) equally apply on the second or third occasions? For example, are soils that have been mechanically loosened on a second occasion even more prone to re-compaction than soils that have been loosened once?

More information is needed on the effect of mechanical loosening on water infiltration and productivity in ‘heavy’ grassland soils (>35% clay) or soils in poor (rather than moderate) structural condition. Heavy soils cover a significant proportion of the grassland area. For example, ‘heavy’ soils underlie c.20% of the grassland area in South West England. According to the BD5001 survey, around 10% of grassland soils in England and Wales were in poor condition. However, in areas with recognised erosion and flooding risks, the proportion of soils in poor condition may be significantly higher. For example, from work in twelve flood-affected
catchments in south/west England and Wales, Palmer (2004) found that, based on a visual assessment of surface runoff risk, 21% of sites had ‘high degradation’ although it is not clear how this assessment corresponds to the measures used in the current project.

Within the time frame of this study, the seed mix had no effect on water infiltration rates. In fact, the power-harrowing carried out to establish the seed mix tended to suppress water infiltration rates. However, some forbs and legumes can take a few years to establish so it is possible that rooting effects could be observed once plants have been well established for 4-5 years, although there was no evidence from the root scanning measurements to indicate that the seed mix resulted in longer or thicker roots. In fact, there were indications that cultivation and mechanical loosening resulted in narrower root diameters in the surface (0-10/20 cm) layer compared with the uncultivated or unloosened control.

The results of this study contrast somewhat with the findings of Fychan et al. (2013) who reported that initial infiltration rates on both white clover and red clover plots were higher than on ryegrass (Lolium perenne) plots, with chicory plots intermediate (P<0.01). However, it is important to note that these differences were observed on monoculture plots established for three years, whereas the seed mix in this study was established into existing ryegrass swards with maximum key seed mix species covers of c.50%. This maximum cover was mainly due to white clover at Nafferton, where white clover was also prevalent on the control plots. The results from the two studies indicate that it is possible to increase water infiltration rates using monocultures, but that the overall effect of introducing species with desirable rooting characteristics into existing ryegrass swards is less clear and increasing water infiltration rates by this method is clearly more challenging. Another notable finding from the Fychan et al. (2013) study was that earthworm abundance was higher in white clover compared with all other treatments (ryegrass, chicory and red clover).

### 8.3 Grassland plant communities discussion

Overall, some of the sown species established successfully, despite the high bulk density soils and relatively intense competition from the agriculturally improved grassland swards. C. intybus tended to establish well, despite not being a natural component of grassland (Hill et al., 1999). However, it was relatively short-lived as it declined in abundance over the three-year period. Other species that established and persisted reasonably well were P. lanceolata, A. millefolium and C. nigra, which concurs with other studies on grassland restoration (Pywell et al., 2003). T. pratense also performed well in the current study, despite being relatively slow to establish in other experiments (Pywell et al., 2003). Establishment of H. radicata was more variable among the four sites. Other field experiments have also shown variable establishment success of this species in a range of artificially created microsites (Turkington & Aarssen, 1983). The remaining two forbs, L. corniculatus and S. minor ssp. muricata did not establish well, nor did they compete well in the existing swards. L. corniculatus is a common constituent in seed mixtures for the restoration of species-rich grasslands, establishing better than most other forbs (Pywell et al. 2003). However, it is tolerant of low nutrient conditions (Hopkins et al., 1996) and is rarely found in improved and semi-improved grasslands (Rodwell, 1992). Its scarcity in the sown treatments would therefore be a consequence of its relatively low competitive ability in agriculturally improved swards. S. minor ssp. muricata is commonly used as a forage species (Douglas et al., 1990; Viano et al., 1999), but was clearly a poor competitor in the improved grassland swards in this study.

There was some evidence of continuing recruitment of new individuals after the first year at two of the sites. The persistence of treatment effects on the area of bare ground three years into the experiment does suggest that there might still have been adequate gaps for recruitment of new individuals.

The introduction of species into the sward following cultivation only had a small effect on the remainder of the plant community (i.e. if the sown species were ignored). Disturbance by
cultivation poses the risk of competitive ruderal species invading the sward, but the presence of the sown species appeared to reduce the risk by occupying the available space. However, if the sown species failed to germinate or establish in a disturbed sward, there is potential for perennial weeds such as *R. obtusifolius* to establish. Cultivation also reduced the overall root mass, potentially reducing competition from species already present. However, this risk might actually be reduced if *T. repens* were prevalent in the sward, as it appeared to benefit from the cultivation treatment.

Variation among sites in the establishment and persistence of sown species indicated that site-specific factors will affect the outcomes. Some sown species established well at Nafferton, Odstone and Biton, despite the highly improved, competitive swards dominated by *Lolium perenne*. Surprisingly however, few differences were detected in root measurements between seeded and unseeded plots. In contrast, at Aberbran, establishment was relatively poor and those species that did establish in the first year showed a marked decline over the duration of the experiment to a very low level. This was surprising, since the existing plant community was less improved agriculturally and competition within the sward was expected to be less severe. An alternative explanation might be that species already in the sward, such as *Holcus lanatus* (Yorkshire fog) and *Agrostis capillaris* were well suited to lower nutrient input and were able to gain a competitive advantage.

Sown forbs established less well in plots subjected to mechanical loosening. In the experiment, cultivation and seeding had to be done before loosening operations were carried out to prevent cultivation machinery re-compacting the loosened soil. Loosening causes a certain amount of soil surface disturbance and this would have destroyed some of the seedlings that had already emerged as well as burying some of the seed that had been broadcast on the surface. This would explain the lower levels of sown forbs recorded in the loosened plots, and the slightly stronger effect of shallower loosening, which causes more surface disturbance than deeper loosening. For example, germination of *A. millefolium* is inhibited by burial deeper than c. 0.5 cm (Warwick and Black, 1982; Thompson, 1989). However, there was no evidence that loosening benefited or hindered the development of individual forbs, as individual plant sizes did not differ between treatments. This is surprising because root measurements from the whole community at Odstone and Nafferton suggested that deeper loosening affected overall root development, with a reduction in overall mass in the shallower layers sampled and an increase in root length in the deeper layers sampled. Therefore, loosening had mixed effects on the existing vegetation but was detrimental for the establishment of sown forbs using the methods applied in this study. If the cultivation and seeding could be done immediately after soil loosening in one operation then establishment might be more successful, although the risks of re-compacting fragile soils is significant (ADAS, 1984; Frost, 1988a). An alternative to cultivation, which might avoid the reduction in infiltration rate, could be to band-spray the existing sward with herbicide, followed by slot-seeding into the bands (Coulson et al., 2001).

No effects of loosening treatments were detected on the remainder of the plant community, despite the effect of disturbance and the slightly greater area of bare ground present three years into the experiment. This suggests that if loosening were applied as a treatment to alleviate soil compaction, it is unlikely to have any detrimental effects on the botanical composition of the grassland sward. Indeed, the overall effects could be beneficial, since root development in the deeper layers sampled appeared to be enhanced by deeper loosening at Odstone and Nafferton. This could be a response to alleviated soil compaction, as the root length of grasses and red clover can be reduced by soil compaction (Głab, 2013). The increase in root SRL in deeper loosened treatments at Odstone might also indicate improved nutrient supply and root proliferation (Ryser, 2006), while improved root development could also reduce drought stress and increase organic matter at depth.


8.4 Earthworm abundance and diversity discussion

In this study, both earthworm abundance and biomass were impacted by mechanical loosening and power-harrowing (cultivation), although it is important to note that these findings were based on a single site. At the broadest level, overall earthworm abundance and biomass were lower in loosened than unloosened treatments (Figures 27 and 28). There were significant differences between years however, which indicates that worms, at least in the deeper loosened plots were able to recover relatively quickly after disturbance (within 2 years for deeper loosened plots and 3.5 years for shallower loosened). It is important to note that the 2014 samples were collected at a different time of year than the samples in other years (spring vs. autumn), therefore, absolute numbers of worms (total numbers and biomass across all treatments) cannot be accurately compared across the three time periods. Relative differences between treatments, however, remain a valid comparison.

The differences between the biomass and abundance of earthworms in the different treatments may relate, at least in part, to the natural history of the different earthworm ecotypes. Endogeic earthworms tend to be small-bodied and make shallow horizontal temporary burrows which they use for feeding and travelling through the soil. Common species include *Aporrectodea rosea* (rosy-tipped worm) and *Alolobophora chlorotica* (green worm). Anecic earthworms tend to be large-bodied and make large permanent vertical burrows. These include the UK’s two largest species, *L. terrestris* (common or lob worm) and *Apporectodea longa* (black-headed worm) ([http://www.earthwormsociety.org.uk/earthworm-information/earthworm-information-page-2](http://www.earthwormsociety.org.uk/earthworm-information/earthworm-information-page-2)). Both endogeic and anecic species were impacted by loosening and cultivation treatments, but in different ways.

For endogeic earthworms, both abundance and biomass were significantly lower in the shallower loosened compared with the unloosened and deeper loosened treatments in 2012 (Figures 31 and 32). These results are supported to some extent by Ernst and Emmerling (2009) who found that the density of endogeic species was reduced by near surface tillage practices (discing and harrowing) and that a decrease in tillage intensity can have a positive effect on earthworm biodiversity, although it is important to note that their study focused on arable rather than grassland soils. Endogeic earthworm populations have been shown to be lower on reduced tillage compared with inversion tilled or ploughed soils, probably due to the near surface mechanical damage to earthworms caused by reduced tillage implements (Chan 2001). There was no reduction in mean endogeic worm weight across the time period (Figure 39) (evidence of survival by reproduction), but there was a marked increase in the number of juveniles in samples overall which provides some evidence that shallower loosening had impacted on the abundance of adult worms with recovery in subsequent years. Interestingly, however, the power-harrow (shallow cultivation) treatment did not have a significant effect on abundance or biomass of endogeic worms in any year (Figures 33 and 34). This may be partly due to the fact that the power-harrow treatment only aimed to create 50-80% bare soil, thereby leaving a proportion of the original sward intact.

Mechanical loosening produced a significant reduction in abundance and biomass of anecic species in both 2011 and 2012 (Figures 35 and 36). However, the pattern differed between years; in 2011 the level of reduction was similar in both the shallower and deeper loosened treatments. However, in 2012, abundance and biomass was significantly reduced in the shallower loosened treatment, with both metrics in the deeper loosened treatment recovering close to the unloosened control in that year (Figures 35 and 36). Numbers and biomass were lower overall in 2012, but as this was also true of earthworms in the unloosened plots this is likely to have been due to year-to-year environmental variation. Previous studies have found that populations of these large–bodied, deep burrowing species (e.g. *L. terrestris*) were lower in conventionally tilled (ploughed) fields compared to reduced tillage plots. This most likely results from the destruction of the permanent burrows on which these species rely (Wyss et al. 1992, Edwards & Lofty 1982). Indeed, anecic species have been shown to cease both growth and
breeding following the destruction of their burrows. In this study, there was some evidence of a population effect with time, with evidence of a reduction in mean anecic worm size and an increase in proportions of juveniles (of all species) over the experimental period. This could be evidence of survival by reproduction in these species. As these species dig very deep burrows (up to six feet in length) it may be that shallower loosening treatments impact them more than deeper loosening, as shallower loosening can disrupt the surface layer and prevent access to the soil surface. Deeper loosening, while initially causing disruption (i.e. in 2011), will most likely retain the upper part of burrows intact, thereby providing access to the soil surface and allowing worm populations to recover more rapidly.

In the multivariate analysis of earthworm abundance and biomass with soil physico-chemical and botanical parameters, the only significant predictor of earthworm abundance/biomass was vegetation density; a measure of vegetation structure, a higher number indicating more dense vegetation. Earthworm abundance/biomass and vegetation density might be expected, a priori, to be positively related, since earthworms have been shown to increase above ground vegetation density in a range of studies (e.g. Wurst et al. 2011). While this was the case in 2011, the opposite relationship was detected in 2012. However, this may result from the confounding factor of treatment; in 2012, vegetation density was significantly greater on shallower loosened plots (compared with unloosened and deeper loosened plots; P=0.004), which also had significantly fewer earthworms in that year.

In conclusion, earthworms in the current study were negatively affected by mechanical loosening, but this depended on loosening depth and worm functional group. Endogeic species (shallow burrowing species) appeared more robust to loosening and appeared only to show a decline in the shallower loosening treatments in year two. Larger, anecic worm species displayed reductions in both the shallower and deeper loosened treatments in year one, but by the second year, levels in the deeper loosened treatments had recovered to the unloosened levels. The results from the single site studied suggest that earthworm populations can recover well and reasonably quickly (within 2 years) from deeper loosening treatments, but not from shallower loosening. Deeper loosening may, therefore, exert less adverse impacts on earthworms than shallower loosening treatments, although populations appear able to recover within four years. Monitoring of earthworm populations following mechanical loosening at other sites would be extremely valuable, to determine whether the results found in this single site study were typical of other sites.

8.5 Dry matter yield discussion

Overall, mechanical loosening did not have a significant effect on DM yield across the four sites and three years of the field experiment. This may be due to a number of reasons, including the limited effect that mechanical loosening could have on soil structural condition and rooting within the time scale of the project; the fact that crop available water was not limited at first cut silage in the three study years (2011-13); and that the high bulk density soils were not in poor soil structural condition i.e. they were representative of the majority of grassland soils in England and Wales in terms of soil structural condition, and above the 75th percentile in terms of 0-10 cm BD, but not in poor condition. The field experiments aimed to investigate the effects of treatments in grassland soils that were typical of England and Wales in terms of soil structural condition, rather than the worst soils.

While mechanical loosening had no effect on grass yields, the seed mix increased DM yields relative to the unfertilised (zero N) and uncultivated control (i.e. the original sward without manufactured N fertiliser) at Odstone and Bicton, where the seed mix established well. These sites contrasted with Aberbran, where the seed mix established less well; and Nafferton, where white clover already had a significant presence in the sward before the experimental treatments were applied. The c.1 t DM/ha increase in first cut yield from the introduction of deep-rooting
herbs and legumes at Odstone and Bicton was most likely due to the additional N fixed by the seed mix legumes. The seed mix could therefore provide production benefits in low input systems as long as forb and legume palatability is not an issue in terms of grazing preference within specific herds.

Manufactured fertiliser N increased dry matter yields at Odstone relative to both the seed mix and the unfertilised control in 2012 and 2013, but did not do so in 2012 at Aberbran or Bicton with the addition of 80-120 kg N/ha. This was unexpected, but may have been due to nitrate leaching losses resulting in lower DM yield response to N fertiliser (i.e. loss of fertiliser N through nitrate leaching) at Aberbran and Bicton in the wet summer of 2012.

At Nafferton in 2012, the higher DM yields on the seed mix and uncultivated control plots compared with the ‘power-harrowed without seed mix’ plots was in spite of greater cover of \textit{T. repens} (white clover) on the power-harrowed plots without seed addition in 2013, indicating that the difference in yield was mainly due to the suppression effect of cultivation possibly combined with the introduction of ruderal species such as \textit{Rumex obtusifolius} (broad-leaved dock) at this site.

8.5.1 Nitrous oxide emissions discussion

The small increase in N\textsubscript{2}O emissions due to deeper mechanical loosening at Aberbran was most probably due to an increase in the rate of mineralisation and nitrification as soil aggregates and soil organic matter were exposed to the air and to aerobic soil microbes (Catt \textit{et al}., 1992; Silgram and Shepherd, 1999). The increase was small and of little significance either agronomically or compared with overall N\textsubscript{2}O emissions from grassland soils, particularly those associated with urine patches or N fertiliser/slurry applications.

The lack of a significant difference in water-filled pore space (WFPS) between un-loosened and deeper loosened treatments at Odstone and Aberbran indicates that the changes in physical soil properties resulting from deeper loosening (section 6.2) were not sufficient to affect water-filled pore space and related nitrous oxide emissions. This contrasts to some extent with findings by Hargreaves \textit{et al}.
\textit{(2013) at SRUC Crichton, who found that mechanical compaction (using two passes with a 10 tonne tractor, covering the whole plot, one week apart) and trampling compaction (12 heifers for one hour – equivalent to 1,500 LU per hectare - for one hour on two occasions, one week apart) increased WFPS by an average of 27% and 19% respectively, compared with an ‘un-compacted’ control. The mechanical compaction also increased cumulative nitrous oxide emissions by 29% compared with the control (1,215 N\textsubscript{2}O g N/ha cf. 944 N\textsubscript{2}O g N/ha). However, the differences in findings between the two studies are probably due to one investigating the effects of mechanical loosening on nitrous oxide emissions in fields with ‘typical’ levels of soil structural degradation (i.e. alleviating compaction) and the other investigating the effect of tractor compaction and livestock trampling treatments on nitrous oxide emissions (i.e. causing compaction). All sites (ADAS and SRUC sites) had similar initial soil physical conditions, although initial soil BD in the SRUC study was effectively lower at a mean value of 1.06 g/cm\textsuperscript{3} (Hargreaves, pers. comm.). There was also a difference in the amount of N fertiliser applied in the two studies with the SRUC study applying c.165 kg N/ha (over three cuts of silage; as 60 kg N/ha of manufactured N fertiliser and c.35 kg N/ha of slurry readily available N after each cut). The manufactured fertiliser N application rates used at Odstone and Aberbran (40 kg N/ha), while typical for low input grassland in England and Wales, may not have been high enough to detect small changes in nitrous oxide emissions that could potentially result from deeper loosening. On the other hand, the reason for no measurable effect in this study may have been due to the limited effect of mechanical loosening on the internal porosity of soil aggregates in the upper layer of the soil, which, along with aggregate size distribution, inter-aggregate porosity and gas diffusivity, is thought to be an important factor in influencing water filled pore space, denitrification rates and nitrous oxide emissions (Ball \textit{et al}.,
This is supported by the fact that deeper mechanical loosening had no detectable effect on 0-10 cm BD at Odstone and Aberbran in 2010-2012.

One option for future work would be to use N fertiliser rates that are more typical of higher input livestock systems on a site with soils in poor structural condition, but without further intervention through livestock trampling or tractor wheel-to-wheel compaction. This would provide a true indication of whether mechanical loosening can reduce nitrous oxide emissions in 'naturally compacted', 'real world' situations.

8.5.2 Bird foraging plot-scale behaviour discussion

Soil loosening did not appear to have any effect on starling foraging parameters. The model results indicate that there was very little or no impact of any of the loosening treatments on any of the foraging parameters considered in this experiment. Treatment did not have a significant effect on number of "roots" (explorative foraging behaviour), or on total number or percentage of successful roots. The results indicate that starling foraging behaviour was not significantly influenced by mechanical loosening (shallower and deeper) or the introduction of deep-rooting herbs and legumes. There was also no impact of soil penetration resistance on any of the foraging parameters.

This is perhaps surprising, given evidence in the literature that soil loosening can improve the types of soil parameters beneficial to probing birds (decreased penetration resistance, increased prey abundance etc.). It could be that the experimental conditions did not allow the birds to take full advantage of the foraging opportunities (e.g. stress, lack of hunger, small plot size), or it could simply be that the differences between the plots were insufficient for birds to respond accordingly and that the differences in penetration resistance (section 6.2.1; Figure 4) were at deeper depths than would affect foraging by starlings.

8.5.3 Bird foraging field-scale discussion

Soil loosening does not appear to have an effect on insectivorous bird foraging parameters. Birds did not appear to have a preference between loosened and unloosened areas of the 15 fields investigated. This result is not predicted from the literature. However, given only between 5 and 8 months had passed between mechanical loosening and the bird surveys, this may not have provided sufficient time for invertebrate populations to respond, be that positively or negatively. It would be interesting, therefore, in a separate study to see how birds fare in subsequent months and years.

This study did not include any assessments of invertebrate population in the plots – this would be a key requirement of any future studies, before, immediately after and after several months after loosening.

Birds in the current study did not appear to exhibit a preference when presented with loosened and unloosened field plots on which to forage. While this is an interesting result, it is unlikely that the study had sufficient statistical power to reveal any differences, which are likely to be subtle and hard to detect in such a variable data set.
9 General Discussion

9.1 Mechanical loosening

Results from the four field experimental sites have demonstrated that mechanical loosening can give rise to changes in soil physical properties that persist for at least 30 months post-loosening. This corroborates research from other studies, which found that (where changes were observed) the duration of mechanical loosening effects varied from a few weeks to 2 to 3 years (e.g. ADAS, 1984, 1987; Frost, 1988a, b; Burgess et al., 2000; Drewry et al., 2000; Houlbrooke et al., 2005; Cournane et al., 2011).

Mechanical loosening had dramatic effects on water infiltration rates in ‘medium’ soils (19-35% clay) with moderate soil structural condition but, at the one site where it was studied (Nafferton), increases in water infiltration rate were accompanied by reductions in earthworm number and biomass that for the shallower loosening treatment persisted into a third year i.e. differences were measured 24-25 months post-loosening. Earthworms help deliver soil fertility and health; so reductions in earthworm numbers and biomass have important implications for the viability of promoting grassland ‘sward lifting’ through incentivised agri-environment or voluntary schemes. However, it is important to note that earthworm numbers and biomass was only measured at one of the four study sites. Nevertheless, there is a substantial quantity of evidence in the literature that mechanical disruption of soil can impact upon earthworm numbers and biomass through disruption of soil macropores and mechanical damage to the invertebrates themselves.

Regular ploughing of arable fields has been shown to result in decreased earthworm populations (e.g. House 1985). However, in some circumstances, tillage can result in an increase in earthworm populations, typically over a six to ten month time frame, particularly if it alleviates soil compaction (Edwards & Lofty 1969), although it may also be related to a temporary increase in energy levels due to mineralisation of previously occluded soil organic matter. As was the case in this study, differences in response to soil disturbance often relate to worm functional group. Certain groups of worms live near the surface of the soil (endogeic worms) while others make deep permanent vertical burrows (anecic worms). Following ploughing, small-bodied endogeic (shallow burrowing) species have been shown to initially decrease but recover quickly, even displaying an increase in numbers as a result of increased food supply (Chan 2001), although time scale is important with a possible subsequent reduction in numbers as food supply reduces to previous levels. In contrast, large-bodied anecic (deep burrowing) species (e.g. Lumbricus terrestris) have been found to be lower in conventionally tilled (ploughed) fields compared to reduced tillage plots, probably due to the destruction of burrows (Wyss et al. 1992, Edwards & Lofty 1982). Therefore, the abundance of the deep burrowing species is likely to decline as a result of mechanical loosening, as was the case in this study, while numbers of shallow burrowing species may stay the same or decrease, depending on the depth and degree of mechanical loosening. Shallower loosening in this study impacted both anecic and endogeic earthworm species.

9.2 Grassland plant community effects

The use of power-harrowing, over-sowing and rolling in this study was effective in improving plant species diversity in agriculturally improved swards, and confirms that such techniques, as recommended by the Rural Development Service (RDS, 2004), can be successfully employed. However, there was no indication that high topsoil bulk density can hinder the establishment of deep rooting herbs and legumes in existing grassland swards or that mechanical loosening of such soils can improve the chances of success. Indeed, there was no evidence to indicate that mechanical loosening should be encouraged as part of strategies to improve plant species diversity in grasslands in England and Wales. Cultivation is the best method for creating microsites for species establishment in grassland (apart from the more intrusive turf-stripping
method; Pywell et al., 2007) but since it had a negative impact on infiltration rate, the effects of other methods such as herbicide and slot-seeding merit further investigation. The introduction of deep-rooting herbs and legumes into existing ryegrass swards, although improving plant species diversity did not have a measurable effect on water infiltration rates. Other studies have shown that monocultures of the species used in the seed mixes (e.g. white clover and chicory) can result in dramatic 15-fold increases in water infiltration rate (e.g. Fychan et al., 2013); so the lack of effect in this study may be more to do with the typical levels of sown species cover achievable in mixed swards than the effectiveness of individual species themselves.

The sown species did, however, increase grass DM yields relative to the original grass sward without N fertiliser. Indeed, at Aberbran and Bicton, DM yields on the seed mix plots were equivalent to those on the uncultivated plots with 80-120 kg N/ha. By contrast, at Odstone manufactured N fertiliser applied at 100 kg N/ha increased grass DM yields by up to 30-40% compared with DM yield increases of c.15% due to the forb and legume seed mix. The forb and legume and seed mix could therefore have a role to play in increasing production per unit area on low output grazing livestock farms while also improving plant species diversity.

9.3 Indicators of soil physical quality

For soil physical property measurements to be useful from a soil functional perspective, it is important that changes in soil structure and function should be measurable by changes in soil physical properties. Yet in this study, while penetration resistance measurements to the depth of loosening were able to detect changes in soil physical properties that corresponded with dramatic increases in water infiltration, soil bulk density (BD) measured at 0-10 cm was not. Furthermore, mid topsoil BD measurements were not able to detect differences in water infiltration rate between treatments in the final year of the experiment. This indicates that BD may not be very sensitive to the type of soil structural changes imparted by mechanical loosening.

At Odstone in 2013, Visual Soil Assessment (VSA) and Peerlkamp (St) scores were slightly higher on deeper loosened plots where water infiltrations were also higher than on other treatments. However, only small increases in VSA and St score were measured (21.2 cf. 18.3 for VSA; and 6.7 cf. 6.0 for St score) that did not necessarily reflect the dramatic increases in water infiltration rate measured in years 1 and 2 of the study. It may be that by 2013 soil structural condition had declined again and that if visual assessments had been carried out in 2011 and 2012, scores would have been higher on the deeper loosened plots to match the large differences in water infiltration rate. Alternatively, it may be that the mechanical loosening did not have a major effect on the overall soil structural condition, but did create vertical fissures connecting surface water with the subsoil and thereby improving soil drainage overall. Notably, the small increases in visual score on the loosened plots were not sufficient to have an effect on grass DM yield in the years studied, despite increases in root length density in the lower topsoil as a result of mechanical loosening. This is supported by Mueller et al. (2006) who found that on experimentally manipulated silt loam and sandy loam arable soils in Germany and Canada there was a significant increase in cereal grain yield of 300-350 kg/ha per unit of ‘St’ score; for mean ‘St’ scores ranging from 3 to 7.5. There was no data for grassland soils, but the arable data indicated that improving the ‘St’ score from 5 to 7.5 can result in a statistically significant increase in biomass production. By year 3 in this study the differences in St score due to mechanical loosening in 2010 were less than one unit of St on average; so it is unlikely that DM yield differences would have resulted. The greater proliferation of roots in the lower part of the topsoil in the mechanically loosened treatments corresponded with better visual scores at Odstone and Nafferton. The findings indicate that mechanical loosening results in vertical fissuring that can help increase water infiltration rates, but which does not necessarily result in measurable or large
changes in bulk density or the size and angularity of soil structural units as quantified by visual evaluation scores.

9.4 Bird foraging and soil invertebrates
Soil loosening did not appear to affect insectivorous bird foraging parameters in either the plot or field scale experiments (see sections 6.9 and 7). Foraging behaviour was not significantly influenced by mechanical loosening (shallower or deeper) or by the introduction of deep-rooting herbs and legumes. Given the significant impact loosening treatments were found to have on earthworms (a major insectivorous bird resource) at Nafferton, this is a somewhat surprising result.

In the plot scale experiment, the reasons for this are likely to be multi-fold: i) it is possible that experimental conditions did not allow the birds to take full advantage of foraging opportunities (e.g. stress, lack of hunger, small plot size). However, as the method employed by this project has proved successful in a number of other studies (e.g. Devereux et al., 2006) this is unlikely to be the primary cause; ii) birds may have primarily foraged on prey other than earthworms. Indeed, in the majority of cases, birds appeared to consume small prey items. While it was rarely possible to identify prey items from the video recordings, the number of large worms observed (e.g. L. terrestris) was very small (as anecic earthworms are primarily nocturnal foragers, this was to be expected; Pelosi et al., 2009; Péres et al., 2011); iii) it could be the case that the differences between the plots were insufficient for birds to respond accordingly; iv) vegetation characteristics of the sward may have precluded differential foraging. Soil probing birds have been shown to forage preferentially in short swards (Devereux et al., 2004, 2006; using a similar caged bird technique) and potentially in those with a higher percentage of bare ground (Whittingham and Devereux, 2008). While sward height differences were observed between the plots (longer on shallower loosened plots) these differences were far smaller than those identified as affecting foraging preference in previous work (a 10 cm difference in Devereux et al 2004 cf. a ~2cm difference in this study).

In conclusion, there is no evidence from the current study that bird foraging is being limited by soil compaction - birds did not appear to exhibit a preference when presented loosened and unloosened plots on which to forage, either on the small plot scale or the larger filed scale. This result is at odds with the findings of invertebrate sampling which showed a major disruption of earthworm populations in some loosening treatments. While this is an interesting result, further work needs to be carried out, over a longer time period, at different sites, and potentially with some sward manipulations, to determine the true impact of soil loosening on bird foraging parameters.

9.5 Implications for agri-environment policy and delivery
The aims and objectives of agri-environment schemes in England include:

- conserving wildlife including farmland birds (biodiversity)
- protecting natural resources by improving water quality and reducing soil erosion and surface runoff

Agri-environment schemes are used to provide incentives and in many cases advice for farmers to adopt or retain land management strategies that can help deliver a range of environmental objectives. Of the mitigation methods investigated in this study, the introduction of deep-rooting herbs and legumes is already an Entry Level Scheme option (EK21 – Legume- and herb-rich swards) within Environmental Stewardship in England, while mechanical loosening is not currently included as an agri-environment scheme option.

Evidence from this project indicates that legume- and herb-rich swards can be used to improve plant species diversity and increase dry matter yield while also reducing nitrogen fertiliser use in low output grazing livestock systems. However, there was no evidence to indicate that the
species mix used in this study improves soil structure (within the time scale of the project), increases invertebrate numbers, improves bird foraging success or reduces surface runoff. The method can be practically implemented on temporary grassland through standard re-seeding operations, and on permanent grassland through over-sowing, following creation of at least 50 per cent bare ground, although there was some evidence that the cultivation required to create a viable seedbed could increase surface runoff on sloping land. The varying degree of seed mix species establishment between the four sites may also indicate the need for more aggressive control of the existing sward species to encourage greater plant diversity.

The implementation cost is relatively high, mainly due to the cost of seed, which when sown at a rate of 20 kg/ha can be purchased for around £115 per ha (Table 30). The cost of power-harrowing (to create 50% bare soil), seeding and rolling (to improve seed to soil contact) is £80-110 per hectare, depending on whether the operations are carried out by the farmer or a contractor (the latter entails higher cost, but without the time commitment for the farmer/employee). Overall, a deep-rooting herb and legume mix can be established through over-sowing at a cost of £190-230 per ha. The seed mix will persist in improved swards for at least four to five years, although some species such as chicory tend to decline after the second or third year (see section 6.5.2).

**Table 30.** Costs for operations associated with the introduction of deep-rooting herbs and legumes and topsoil mechanical loosening.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cost (£/ha)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power-harrowing (grassland)</td>
<td>40-60</td>
<td>Nix, 2013</td>
</tr>
<tr>
<td>Legume- and herb-rich seed mix</td>
<td>110-120</td>
<td>ADAS / Hurrells Specialist Seeds</td>
</tr>
<tr>
<td>Seeding (Grass broadcasting)</td>
<td>25-30</td>
<td>Nix, 2013</td>
</tr>
<tr>
<td>Rolling (ring – seedbeds)</td>
<td>15-20</td>
<td>Nix, 2013</td>
</tr>
<tr>
<td>Top-soiling (mechanical loosening)</td>
<td>60-65</td>
<td>Nix, 2013</td>
</tr>
</tbody>
</table>

There was no evidence from this project that mechanical loosening can aid in the establishment of deep-rooting herb and legume mixes. Indeed, seed mix establishment was suppressed to a limited extent by the soil surface disturbance caused by mechanical loosening. The survey of soil structural degradation in grassland soils also indicated that soil compaction is not necessarily a limiting factor for semi-improved or species rich swards. Poor soil conditions were not restricted to ‘improved’ grasslands, as a higher percentage of ‘semi-improved’ grassland soils were in poor condition (Appendix 1).

Mechanical loosening can give rise to dramatic increases in water infiltration rates in high bulk density grassland soils in moderate soil structural condition i.e. soils that are typical of grassland in England and Wales. However, the method does not appear to have any effect on bird foraging success and can reduce earthworm number and abundance for around two years post-loosening. There was no effect on grass dry matter yield, although other studies have demonstrated yield increases following mechanical loosening where there have been clear signs of soil compaction (ADAS, 1984). However, even without yield increases there can be clear benefits from topsoil mechanical loosening in terms of improved drainage, reduced runoff risk and increases in the number of grazing days. In wet years, compacted land that has been top-soiled is likely to drain better (Curran Cournane et al., 2011), enabling livestock to be grazed for longer in the autumn and put out to graze earlier in the spring, thereby reducing the housing period and the need to purchase additional bulky fodder or store and spread additional manure/slurry. The additional costs for beef cattle would be around £1/head/day for bulky forage and another £1/head/day for manure spreading not including any cost of additional storage (Newell Price et al., 2011). These economic benefits compare with implementation costs of £60-
65 per hectare (Table 30), although this cost does not include the time needed to assess soils for visual signs of compaction and, where mechanical alleviation is needed, working depth. Based on a stocking rate of 2 livestock units per hectare, an additional week of grazing in the autumn and spring (i.e. 15-16 grazing days) due to improved drainage would more than pay for the cost of mechanical loosening. Given the dramatic increases in water infiltration rate found in this study it is likely that an extra two weeks of grazing could be achieved on many drained medium and heavy textured soils in moderate or poor condition (Catto, 1976; Drewry, 2003; RASE, 2012). There is potential for top-soiling (mechanical loosening) to be included as an agri-environment option to improve water quality and reduce runoff risk, particularly in grassland dominated catchments at high risk of flooding. However, additional evidence is needed to determine the effectiveness of the method in reducing surface runoff on soils in moderate and poor condition. Furthermore, to avoid widespread mechanical loosening where it is not required (mechanical loosening of well-structured grassland soils can do more harm than good), such an option would need to be integrated with an assessment of soil structural condition, perhaps as part of a Farm Environment Plan or soil management plan. A DairyCo/EBLEX funded project due to report in October 2014 aims to develop an industry standard grassland soil assessment tool to aid visual evaluation of grassland soils and link this to management options. The assessment tool will include a cycle of assessing soils (including focus on the ‘limiting’ layer for rooting and water infiltration); linking this to management and any need for mechanical loosening; selecting loosening depth; and then assessing the effectiveness of the operation. Another option would be to provide capital grants for the purchase of top-soiling machinery within machinery rings or co-operatives.
10 Conclusions

Mechanical loosening (or ‘top-soiling’) is a practical method for alleviating compaction in grassland soils through lifting the soil, causing fractures and fissures, and thereby resulting in dramatic increases in water infiltration rate and enhanced rooting within the topsoil. The method may therefore be effective in reducing surface runoff and improving resilience to re-compaction (and possibly drought) through more extensive rooting at depth. The method was not effective in improving grass yield or quality; reducing nitrous oxide emissions; enhancing the establishment of deep-rooting herbs and legumes; or affecting bird foraging behaviour or success. On the single site assessed, loosening also had a negative impact on earthworm numbers and biomass that persisted for two years post loosening. Mechanical loosening is therefore effective in increasing water infiltration and rooting in grassland soils, with little impact on yield and possible damage to soil biological function. However, it should only be carried out where there are clear signs of compaction. Mechanical loosening of well-structured soils is likely to do more harm than good; and so any introduction of the method as an agri-environment scheme option would have to be aligned with a form of visual soil evaluation or soil management plan.

Deeper loosening (to c.30-35 cm depth) resulted in greater increases in water infiltration rate than shallower loosening (to c.20 cm). Earthworm biomass and number also recovered more quickly from deeper loosening than from shallower loosening and there were indications that grass dry matter yield was negatively affected by shallower loosening compared with deeper loosening. Overall, it is concluded that deeper loosening is a more effective treatment than shallower loosening in improving grassland soil structural condition and function.

The introduction of deep-rooting herbs and legumes was introduced into the agri-environment Entry Level scheme in January 2013. The method can be practically implemented at reasonable cost (c. £200/ha) and can be effective in diversifying agriculturally improved swards and increasing grass yield in low input livestock systems. However, it had no effect on water infiltration rates, bird foraging or the number and biomass of earthworms. The cultivation effect of power-harrowing (required to create establishment niches for the seed mix) reduced water infiltration rates in the first two years post-cultivation. The introduction of deep-rooting herbs and legumes can provide a useful contribution to production within low output grazing livestock systems and can also increase plant species diversity, but probably has a limited role to play in resource (particularly water) protection or improvement of soil structure, at least in the short term.

The results indicate that moderate levels of soil structural degradation (i.e. high bulk density soils in moderate condition) are not limiting for plant species diversity or for biodiversity in general (e.g. invertebrates and farmland birds). Mechanical loosening of high bulk density soils in moderate condition did not aid the establishment of deep-rooting herbs and legumes, and in the survey there were as many soils in moderate or poor condition under semi-improved and species rich swards as under improved swards.
11 Options for future work

11.1 Flooding risk
Water infiltration rate measurements provide a good indication of the relative effects of mechanical loosening on soil hydrology, but can only provide an indication of the effect of mechanical loosening on surface and subsurface runoff volumes. However, the use of Gerlach traps and tipping buckets in sloping grassland soils could help determine the effect of mechanical loosening on overall flooding risk. This work should be targeted at grassland soils in poor structural condition and should include some soils with higher clay content (i.e. <27% clay).

11.2 Provision of food (grassland production)
Grass dry matter yield measurements at the four field experimental sites indicated that mechanical loosening on ‘medium’ textured high BD soils did not have a significant effect on grass production. However, previous research has shown that mechanical loosening can result in both yield increases and yield decreases (e.g. Frost, 1988; Shah et al., 2004), although the relationship between soil structural condition, soil type and the impact of mechanical loosening was not clear. Further work is needed to identify the specific circumstances in which mechanical loosening can be used to improve grass dry matter yields and increase water infiltration rates, thereby contributing towards the goal of sustainable intensification.

11.3 High risk catchments
To date, the effect of soil compaction mitigation methods has been investigated on high bulk density soils in moderate structural condition. Soils in moderate condition represent around 50-65% of managed grassland soils at the national (England and Wales) scale, while c.10% of managed grassland soils are in poor condition (Newell Price et al., 2013). However, in some catchments the proportion of grassland soils in poor condition may be more significant than this (e.g. Collins et al., 1997; Palmer 2004) with important implications for grassland productivity and flooding risk. It is therefore important to assess the effect of soil compaction mitigation methods on productivity and water regulation in soils in poor structural condition.

In England, more than 5 million properties are at risk of flooding (nearly 1 in 6 homes). As a response to the devastating flooding in 2007, the Pitt Review provided a series of recommendations for improving the way flood risk is managed. The review advised that “Defra, the Environment Agency and Natural England should work with partners to establish a programme through Catchment Flood Management Plans to achieve greater working with natural processes” such as using farmland to slow the progress of water to sub-catchment outlets and to minimise runoff. Grassland can be a significant source of runoff and sediment (Collins et al., 2010) and there is a need to better understand the implications of using mechanical loosening to increase water infiltration in grassland soils and potentially reduce peak flow in catchments with a recognised flooding and erosion problem.

11.4 Earthworm sampling
Earthworm populations in this study showed significant declines in some treatments, and recoveries and even increases in others. However, as discussed previously in the report, these results are limited by both time (two years) and space (one site). If soil loosening is to be promoted as an effective grassland management tool it is essential to determine its impact on earthworm populations. To do this effectively, sampling would need to be carried out at a number of sites of differing soil types and monitored over a number of years, in fields or areas of fields in receipt of “typical” soil loosening schedules. Additionally, given that earthworms have been shown to enhance soil drainage (Capowiez et al., 2009; Sharpley et al., 1979), future studies should seek to explore medium and long-term impacts of loosening on infiltration rates with respect to earthworm densities.
11.5  *Bird foraging*

As discussed in Section 9.4, foraging behaviour of soil probing birds is influenced by sward structure e.g. length of sward, density of plant growth and percentage of bare ground. At the bird foraging study site, there was no significant difference between treatments in the sward structure parameters relevant to birds such as starlings. It may be possible to incorporate some sward manipulation (e.g. sward length) experiments into future soil loosening trials to determine the impact this may have on foraging behaviour. It may be the case that sward manipulations could be employed to aid bird foraging and help mitigate for reductions in earthworm numbers and biomass. A wider approach investigating the factors that make different agricultural soils more or less attractive to foraging birds, could also be employed, as could an exploration of the impacts of longer-term establishment of diverse swards on bird foraging and other soil functions explored in this project.
12 Acknowledgements

We would like to acknowledge the funding provided by the Department for Environment, Food and Rural Affairs (Defra), the management provided by Natural England and the advice provided by the Defra project BD5001 Steering Group. We would also like to thank all the farmers that participated in the survey of grassland soil condition with particular thanks to those that hosted the four field experiments. The hard work of the ADAS and Newcastle University field teams and site managers is also gratefully acknowledged.
13 References


between soil penetrability and the abundance of yellow wagtails (Motacilla flava) in arable fields. Biological Conservation 141 (12): 3116-3126.


The OPAL Soil and Earthworm Survey. Imperial College London http://www.opalexplorenature.org/Earthwormguide (last accessed 07/01/2014).


## Appendix 6  Field experiments operations diary

The following table shows the sequence of field experimental activities from July 2010 through to March 2014:

<table>
<thead>
<tr>
<th>Activity</th>
<th>Nafferton(^1)</th>
<th>Odstone</th>
<th>Aberbran</th>
<th>Bicton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field plots marked out - 24 m x 16 m blocks; 3 treatments and 4 replicates</td>
<td>21/07/10</td>
<td>20/07/10</td>
<td>02/08/10</td>
<td>19/07/10</td>
</tr>
<tr>
<td>Soil sampling completed on each replicate block and dispatched to the laboratory</td>
<td>21/07/10</td>
<td>06/09/10</td>
<td>02/08/10</td>
<td>19/08/10</td>
</tr>
<tr>
<td>Botanical recording completed on all plots</td>
<td>30/07/10</td>
<td>23/07/10</td>
<td>06/08/10</td>
<td>23/07/10</td>
</tr>
<tr>
<td>Treatments 4 to 9 power harrowed to create ≥ 50% bare soil</td>
<td>18/08/10</td>
<td>6/09/10</td>
<td>27/08/10</td>
<td>02/09/10</td>
</tr>
<tr>
<td>Seed mix applied to treatments 7, 8 and 9</td>
<td>20/08/10</td>
<td>06/09/10</td>
<td>27/08/10</td>
<td>02/09/10</td>
</tr>
<tr>
<td>All plots lightly rolled</td>
<td>25/08/10</td>
<td>06/09/10</td>
<td>04/09/10</td>
<td>02/09/10</td>
</tr>
<tr>
<td>Soil loosening applied to treatments 2, 3, 5, 6, 8 and 9</td>
<td>02/09/10</td>
<td>18/9/10</td>
<td>13/09/10</td>
<td>08/09/10</td>
</tr>
<tr>
<td>Molluscide applied to control slugs - <em>Timing related to slug pressure, seedling emergence and weather.</em></td>
<td>17/09/10</td>
<td>-</td>
<td>-</td>
<td>18/11/10</td>
</tr>
<tr>
<td>Nitrous oxide measurements started (at Odstone and Aberbran) – post loosening.</td>
<td>N/A</td>
<td>18/09/10</td>
<td>13/09/10</td>
<td>N/A</td>
</tr>
<tr>
<td>Soil compaction levels measured on each plot</td>
<td>04/01/11</td>
<td>10/11/10</td>
<td>19/11/10</td>
<td>18/11/10</td>
</tr>
<tr>
<td>Sheep introduced to plots</td>
<td>13/01/11</td>
<td>11/01/11</td>
<td>11/12/10</td>
<td>11/12/10</td>
</tr>
<tr>
<td>Sheep removed from plots</td>
<td>25/01/11</td>
<td>25/01/11</td>
<td>16/12/10</td>
<td>14/12/10</td>
</tr>
<tr>
<td>Activity</td>
<td>Nafferton¹</td>
<td>Odstone</td>
<td>Aberbran</td>
<td>Bicton</td>
</tr>
<tr>
<td>-------------------------------------------------------------------------</td>
<td>-----------</td>
<td>---------</td>
<td>----------</td>
<td>---------</td>
</tr>
<tr>
<td>Water infiltration measurements completed on every plot</td>
<td>10/03/11</td>
<td>16/2/11</td>
<td>24/03/11</td>
<td>22/02/11</td>
</tr>
<tr>
<td>Molluscidide applied in early spring.</td>
<td>N/A</td>
<td>N/A</td>
<td>02/03/11</td>
<td>21/02/11</td>
</tr>
<tr>
<td>N fertiliser applied to all plots excluding the areas where the ‘nil N’ N₂O chambers are placed (plus P₂O₅,K₂O and SO₃, according to RB209).</td>
<td>N/A</td>
<td>28/02/11</td>
<td>14/03/11</td>
<td>29/03/11</td>
</tr>
<tr>
<td>Nitrous oxide measurements started (at Odstone and Aberbran) – post N fertiliser applications</td>
<td>N/A</td>
<td>01/03/11</td>
<td>15/03/11</td>
<td>N/A</td>
</tr>
<tr>
<td>Grass height assessments</td>
<td>12/04/11</td>
<td>06/04/11</td>
<td>12/04/11</td>
<td>12/04/11</td>
</tr>
<tr>
<td>Grass topped and removed</td>
<td>16/04/11</td>
<td>06/04/11</td>
<td>14/04/11</td>
<td>14/04/11</td>
</tr>
<tr>
<td>Botanical recording completed on all plots</td>
<td>30/05/11</td>
<td>26/05/11</td>
<td>31/05/11</td>
<td>19/05/11</td>
</tr>
<tr>
<td>Silage cut for yield measurements</td>
<td>7-8/06/11</td>
<td>02/06/11</td>
<td>w/c 27/06/11</td>
<td>25/05/11</td>
</tr>
<tr>
<td>Total above ground biomass yield, total above ground dry matter and D-value measured on every plot (36 yield measurements per site)</td>
<td>7-8/06/11</td>
<td>02/06/11</td>
<td>w/c 27/06/11</td>
<td>25/05/11</td>
</tr>
<tr>
<td>Nitrous oxide measurements completed (at Odstone and Aberbran) – post loosening and post N fertiliser applications.</td>
<td>N/A</td>
<td>28/02/12</td>
<td>13/03/12</td>
<td>N/A</td>
</tr>
<tr>
<td>Young stock grazed on plots as grass growth permitted</td>
<td>Jul-Oct 2011</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Soil compaction levels measured on each plot</td>
<td>24/01/12</td>
<td>21/12/11</td>
<td>13/12/11</td>
<td>20/12/11</td>
</tr>
<tr>
<td>Sheep introduced to plots (young cattle at Odstone)</td>
<td>01/12/11</td>
<td>05/03/12</td>
<td>08/10/11</td>
<td>Dec-11</td>
</tr>
<tr>
<td>Activity</td>
<td>Nafferton¹</td>
<td>Odstone</td>
<td>Aberbran</td>
<td>Bicton</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------------</td>
<td>-------------</td>
<td>-------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Sheep removed from plots (young cattle at Odstone)</td>
<td>23/01/12</td>
<td>12/05/12</td>
<td>26/10/11</td>
<td>Dec-11</td>
</tr>
<tr>
<td>Water infiltration measurements completed on every plot</td>
<td>01/03/12</td>
<td>16/03/12</td>
<td>06/04/12</td>
<td>14/03/12</td>
</tr>
<tr>
<td>Molluscicide applied in early spring.</td>
<td>-¹</td>
<td>-</td>
<td>w/c 23/04/12</td>
<td>-</td>
</tr>
<tr>
<td>N fertiliser applied to half plots of treatments 1, 2 and 3 (plus P₂O₅, K₂O and SO₃, according to RB209).</td>
<td>N/A</td>
<td>03/04/12 and 09/05/12</td>
<td>20/04/12</td>
<td>21/04/12</td>
</tr>
<tr>
<td>Botanical recording completed on all plots</td>
<td>18/05/12</td>
<td>18/05/12</td>
<td>25/05/12</td>
<td>18/05/12</td>
</tr>
<tr>
<td>Silage cut for yield measurements</td>
<td>01/06/12</td>
<td>26/05/12</td>
<td>w/c 18/06/12</td>
<td>07/06/12</td>
</tr>
<tr>
<td>Total above ground biomass yield, total above ground dry matter and D-value measured on every plot (36 yield measurements per site)</td>
<td>08/06/12</td>
<td>26/05/12</td>
<td>w/c 18/06/12</td>
<td>w/c 11/06/12</td>
</tr>
<tr>
<td>Young stock grazed on plots as grass growth permitted</td>
<td>Jul-Oct 2012</td>
<td>N/A</td>
<td>N/A</td>
<td>Rotational paddock grazing</td>
</tr>
<tr>
<td>Soil measurements completed on <em>each plot</em></td>
<td>11/04/2013</td>
<td>05/12/2012</td>
<td>14/03/2013</td>
<td>07/02/2013</td>
</tr>
<tr>
<td>Sheep introduced to plots (young cattle at Odstone and Aberbran)</td>
<td>Dec 2012</td>
<td>26/06/2012</td>
<td>August 2012</td>
<td>Rotational paddock grazing with dairy cattle</td>
</tr>
</tbody>
</table>

¹ Note: N/A indicates not applicable or not available.
<table>
<thead>
<tr>
<th>Activity</th>
<th>Nafferton&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Odstone</th>
<th>Aberbran</th>
<th>Bicton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheep removed from plots (young cattle at Odstone and Aberbran)</td>
<td>Feb 2013</td>
<td>27/06/2012</td>
<td>October 2012</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>August 2012</td>
<td></td>
<td></td>
</tr>
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<td></td>
<td>11/09/2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water infiltration measurements completed on every plot</td>
<td>11/04/2013</td>
<td>18/02/2013</td>
<td>26/04/2013</td>
<td>02/04/2013</td>
</tr>
<tr>
<td>N fertiliser applied to half plots of treatments 1, 2 and 3</td>
<td>N/A&lt;sup&gt;1&lt;/sup&gt;</td>
<td>March-August 2013</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Botanical recording completed on all plots</td>
<td>w/c 20/05/2013</td>
<td>w/c 13/05/2013</td>
<td>w/c 07/05/2013</td>
<td>w/c 07/05/2013</td>
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<tr>
<td>Grassland management – summer 2013</td>
<td>Grazed</td>
<td>1 cut then grazed</td>
<td>Grazed</td>
<td>Grazed</td>
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<tr>
<td>Soil measurements completed on each plot</td>
<td>November 2013</td>
<td>November 2013</td>
<td>November 2013</td>
<td>November 2013</td>
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<tr>
<td>Water infiltration measurements completed on every plot</td>
<td>February 2014</td>
<td>February 2014</td>
<td>February 2014</td>
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</tbody>
</table>

<sup>1</sup> Field under organic production
N/A: Not applicable
Appendix 7 Bird foraging trials details

The identification numbers, sex and age of Starlings used in field trials. The identification numbers of the two companions birds used in each trial the trials completed by each bird. M = Male, F= Female, A = Adult, FW = First winter.

<table>
<thead>
<tr>
<th>Focal Bird ID</th>
<th>Sex</th>
<th>Age</th>
<th>Companions</th>
<th>Treatments completed</th>
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<tbody>
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<td>2011</td>
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</tr>
<tr>
<td>1</td>
<td>F</td>
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<td>2</td>
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<td>A</td>
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<tr>
<td>3</td>
<td>M</td>
<td>FW</td>
<td>4 &amp; 12</td>
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<td>4</td>
<td>M</td>
<td>A</td>
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<td>F</td>
<td>FW</td>
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<tr>
<td>6</td>
<td>M</td>
<td>FW</td>
<td>7 &amp; 3</td>
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<tr>
<td>7</td>
<td>M</td>
<td>A</td>
<td>10 &amp; 2</td>
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<tr>
<td>8</td>
<td>M</td>
<td>A</td>
<td>13 &amp; 4</td>
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<td>9</td>
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<td>6 &amp; 5</td>
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<td>F</td>
<td>FW</td>
<td>11 &amp; 14</td>
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<td>12</td>
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<td>FW</td>
<td>10 &amp; 6</td>
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<td>M</td>
<td>A</td>
<td>9 &amp; 7</td>
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</tr>
<tr>
<td>14</td>
<td>M</td>
<td>FW</td>
<td>8 &amp; 12</td>
<td>1,2,3,4,5,6,7,8,9</td>
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<tr>
<td>2012</td>
<td></td>
<td></td>
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<tr>
<td>15</td>
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<td>26 &amp; 17</td>
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<td>M</td>
<td>FW</td>
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<td>A</td>
<td>28 &amp; 18</td>
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<tr>
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<td>M</td>
<td>A</td>
<td>17 &amp; 23</td>
<td>1,2,3,4,5,6,7,8,9</td>
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<tr>
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<td>F</td>
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<td>22 &amp; 19</td>
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<td>F</td>
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<td>FW</td>
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</tbody>
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