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

The alleviation of grassland compaction by mechanical soil loosening

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Executive summary

Soil compaction in grasslands can not only reduce agricultural productivity, but also has implications for flood management and water resources, biodiversity, soil, water and air quality. This report principally reviews research in the UK and the Republic of Ireland (ROI) into the benefits of mechanical alleviation of compaction in UK grasslands and provides guidance on the best methods for mechanical soil loosening in relation to the nature and depth of compaction; an assessment of overseas studies is also included.

The main findings are summarised below:

• There are three main types of grassland soil ‘loosening’ devices, viz:
  – aerators i.e. spikers or slitters working typically at a soil depth of 10 cm.
  – sward lifters working between depths of 20-35 cm of soil.
  – subsoilers working between depths of 35-50 cm of soil.

• Only 5 experimental studies on the benefits of mechanical soil loosening in grasslands in the UK and ROI have been reported in peer reviewed papers or in ADAS Technical Bulletins. Most were conducted 15-25 years ago and evaluated benefits in terms of their effect on grass yields, with only limited measurements of changes in soil physical properties, drainage status or other grassland functions (e.g. biodiversity, gaseous emissions etc).

• Results from UK studies have been variable, with both yield increases and decreases measured. However, these results do suggest 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 rather than increasing productivity, 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 can not 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, if used in appropriate conditions, grassland loosening devices have the potential to alleviate compaction at varying depths, 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 is 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. Recently loosened soil is very sensitive to re-compaction and it is important to allow the newly loosened structure to be stabilised by root activity and natural soil processes. If late growth needs to be utilised it is advisable to graze with sheep rather than cattle and spring growth following loosening 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.

- ADAS Technical Bulletins (ADAS, 1984; 1989) provide clear guidance on the use of topsoil loosening devices and only recommend mechanical loosening devices where there is clear evidence of compaction. The timing of operations is critical. Topsoil loosening in conditions which are too wet can lead to increased damage through smearing and wheel slip. Equally, under dry soil conditions excessive surface heave and root damage can occur. The suitability of soil moisture conditions for successful soil loosening can only be assessed in the field on the day of operation.

- 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 do vary and that depending on a number of factors, soil physical properties and grass yields can be unaffected, slightly improved, or slightly decreased by soil loosening or aeration. In addition, the duration of mechanical treatment effects (where changes have been observed) varied from a few weeks to 2/3 years.
1 Introduction

This document presents a review of:

- the current available methods for mechanical soil loosening.
- UK and Republic of Ireland (ROI) studies on the effectiveness of mechanical soil compaction alleviation.
- Overseas studies on the effects of mechanical loosening of grassland soils.

The review is principally focused on UK and ROI studies that are directly applicable to the specific soil types, agro-climate and grassland systems found in the British Isles. A separate section summarises some of the available international literature to assess whether overseas findings are consistent with those from the UK and ROI, and the range of parameters investigated.

Soil compaction in grasslands can result from both machinery use and livestock grazing and can lead to a coarsening or loss of soil structural units, decrease in soil volume, increase in bulk density, decrease in porosity (particularly macroporosity) and a reduction in hydraulic conductivity of the soil (i.e. reduced water infiltration).

Machinery use can give rise to compaction in the topsoil (0 to 30 cm) and subsoil (typically > 30 cm). Soil physical damage incurred by livestock is often restricted to shallow surface depths (0-15 cm) (MAFF, 1970; Drewry and Paton, 2000; Kurz et al., 2006; Scholefield et al., 1985; Singleton et al., 2000). However, in UK conditions, Scholefield et al. (1986) found that cattle trampling can also result in most compaction at 10 cm depth and below. Compaction risk is generally greater at higher soil moisture contents (MAFF, 1970).

Compaction in the topsoil of managed grasslands has long been recognised as a possible constraint to grassland productivity (ADAS, 1984). In addition, there is growing evidence that soil compaction has important implications for flood management and water resources, biodiversity, soil, water and air quality. Hence, there is a need to improve our understanding of the importance of soil compaction in grasslands and to evaluate mitigation methods that can remediate the negative effects of compaction on grassland biodiversity, flood management and soil quality etc.

Research into the mechanical alleviation of compaction is well developed in arable situations (Spoor, 2006). However, the requirement to minimise sward damage and soil uplift in established grasslands limits the use of arable loosening equipment. National trials work in the 1980’s evaluated the yield effects of compaction alleviation through topsoil loosening (ADAS, 1984; 1987). However, since then there has been a paucity of research into the benefits of compaction alleviation in grasslands and in the development of machinery suited to such a task.
In recent years there have been a number of claims within the agricultural sector that mechanical aeration and sward lifting have the potential to increase grass yields and improve slurry/water infiltration rates. For example, Kingshay have been undertaking field trials evaluating the effects of grassland slitting (i.e. topsoil aeration), with and without gypsum additions, on grassland production and soil quality, and have reported positive benefits from the treatments (www.kingshay.com/kingshay/farmtrials/soilmanagement.html); but no evidence was provided to support their claims.

The aim of this report was to assess the best methods for mechanical compaction alleviation of UK grasslands, including a review of previous research on the benefits of grassland soil loosening.
2 Grassland soil loosening devices

Commercially available machinery for the alleviation of compaction in agricultural grasslands falls into three main groups, viz:

- **Aerators** i.e. surface spikers or slitters working typically at a soil depth of 10 cm.
- **Sward lifters** working between 20 and 35 cm soil depth.
- **Subsoilers** working between 35 and 50 cm soil depth.

Other operations, such as mole drainage, can have a beneficial effect in alleviating compaction. However, their main benefit is in improving the drainage status of soils.

The alleviation of compaction relies on breaking through or lifting and breaking the compacted layer. Hence, the depth of compaction dictates the depth of working required. For sward lifters and subsoilers, it is important to make sure that the compacted layer is above the critical working depth of the implement used (NSRI, 2002) and that the working depth of the equipment is 3-4 cm below the base of the compacted layer (MAFF, 1983), Figure 1. Working deeper would increase the horse power requirement and would not improve compaction alleviation.

Examples of the range of grassland soil looseners currently available on the UK market are summarised in Appendix I.

**Figure 1. Loosening a compaction pan with a sward lifter (adapted from NSRI, 2002).**

![Diagram showing the loosening of a compaction pan with a sward lifter.](image-url)

Note: the working depth has to be just below the zone that needs to be broken up.
2.1 Aerators

Aerators are principally designed to increase surface aeration and to improve water/slurry infiltration rates, rather than to alleviate soil compaction *per se*.

All aerators on the UK market follow a similar set of design principles, consisting of a horizontal transverse non-powered rotor, fitted with a series of radial blades or spikes (Figure 2). The machines are conventionally mounted on the rear three point linkage of a tractor (although they can be mounted on front linkages or behind slurry tankers) and depend on either their own weight or additional ballast (Figure 2) to force the blades or spikes into the soil to create a series of short shallow slots as the machine travels forward.

The effect of the slitters is to cut through the turf and matted vegetation into the upper horizon of the topsoil. The working depth is typically around 10 cm, depending on soil conditions, blade configuration, size and applied load. The nature and angle of the blade (or tine) will affect the degree of disturbance caused by the machine, as does forward speed, soil type and soil moisture level at the time of operation. Some machines include provision to adjust the angle of the rotor with respect to the direction of travel. Rotors set at an angle will tend to force the blades sideways and create larger slots than where the axle is at 90 degrees to the direction of travel and the blade cuts cleanly. Significant sward damage can result if the rotors are set at an 80 degree angle to the direction of travel, which can be sufficient to act as partial cultivation in an overseeding operation.

Figure 2. Examples of topsoil aerators

a. ‘McConnel Pasturator’
2.2 Sward lifters

Sward lifters (also known as grassland topsoilers) work at greater depths than aerators, typically in the range 20-35 cm. Although there is greater variation in the configuration and features of individual machines than is the case for aerators, all current UK grassland looseners broadly follow the same design principles. The basic layout has a linkage mounted tool bar, carrying one or more (typically three) vertical legs and disc coulters. Legs may be forward inclined or straight, and may be equipped with chisel type points and optional wings to increase shatter. Depth control and levelling of the finished work is achieved by individual or full width rollers/packers, and legs may be sprung or mechanically vibrated. All machines effectively work as conventional wide-tine topsoilers (i.e. they provide loosening to the full depth and width of the topsoil profile), causing brittle failure of the soil over the leg point and/or wings, and depend on the leading disc and following roller/packer to minimise sward damage (Figure 3). The attachment of wings or leading shallow tines greatly enhances the ability of an implement to produce effective loosening at greater depth (Figure 4).

The horse power (HP) requirement of sward lifters (and subsoilers) is relatively high compared with many other ‘cultivation’ equipment. ADAS experience suggests that the typical minimum power requirement to avoid excessive wheel slip and sward damage is 140-160 HP depending on field conditions.
Figure 3. Grassland sward lifters

a) Opico ‘Sward Lifter’

b) McConnel ‘Shakaerator’

Soil conditions are again critical in determining the performance of the equipment; working at too high a moisture content will result in the leg acting as a narrow tine and simply cutting a slot through the soil, and at too dry a moisture content the degree of sward damage and soil heave will be unacceptable and the power requirement excessive.

The depth of compaction dictates the required depth of working, which should be just (3-4 cm) below the layer that needs to be broken up. It is important to examine the extent of shatter of a trial run and to adjust the equipment if necessary. It is also important to make sure the working depth is above the critical depth of the implement used. As a general rule of thumb, critical depth occurs at approximately six times the individual loosening tine’s width; for example, a tine foot that is 6 cm in width, will have a critical depth of around 36 cm. Operations carried out below critical depth will result in compaction because of the sideways resistance of the surrounding soil.
2.3 Subsoilers

Subsoilers work at depths of typically 35-50 cm and are commonly used in arable fields to relieve deep compaction. The basic layout has a linkage-mounted toolbar (i.e. the equipment is mounted on a three-point hitch or arm connected to the tractor) carrying one or two vertical legs, which may be forward inclined or straight and are usually equipped with wings to increase shatter (MAFF, 1983), Figure 5. However, ADAS experience in grassland use has commonly resulted in unacceptable sward damage due to soil heave, hence, specialist sward lifting equipment (Section 3.2) is favoured.
2.4 Mole drainage

There is a need for adequate drainage to avoid the creation of wet areas following the alleviation of grassland compaction. On suitable soils, moleing has the combined effect of drainage channel creation at depth (typically between 40 and 60 cm) and the shattering of compacted soil above the mole channel. Indeed, on some heavy wet soils, shallow moleing can be used rather than loosening to improve drainage, with a lower risk of sward damage and a wider range of appropriate soil moisture conditions (ADAS, 1989).

Figure 6. Mole drainage equipment (adapted from ADAS Leaflet 731 – Mole Drainage; MAFF, 1980)
Mole ploughs may be trailed or linkage-mounted, and fall into two different groups (long and short beam). Both groups employ a slim vertical leg, usually fitted with a replaceable shin to cut a slot through the soil, carrying a ‘bullet’ - effectively a round nosed cylindrical foot shaped like a bullet with slight tapering towards the tail and followed by an expander (a cylindrical plug of slightly larger diameter than the bullet), Figure 6. In grassland machines, the leg is generally preceded by a disc coulter to cut a clean slot in the sward and to reduce tearing and damage. The bullet is designed to initiate the formation of a cylindrical passage through the soil, with minimum draft and to lift the soil above working depth, creating fissuring and some compaction alleviation. Soils need to be sufficiently moist at working depth for the mole channel to be formed through plastic deformation of the soil, but dry enough above working depth to fail through fracture.

Mole drainage is generally used in combination with an effective pipe drainage system, with permeable back fill, such that the mole channels can be drawn (typically at a depth of 40-60 cm) through the backfill, allowing water to percolate through fissures and soil pores to the mole channel and then to the land drain. On soils with sufficient clay content (> 18% clay), moles can remain effective for a number of years (MAFF, 1980); typically in the range 5-10 years. The stability of mole drains will vary according to agro-climate, the amount of sand/silt/clay translocation within the soil, root activity and soil type (the stability of mole drains in ‘dispersive’ or ‘shrink-swell’ soils may be lower than in more ‘stable’ soils).
3 Soil loosening experiments in UK and ROI grasslands

Compared with the number of experimental studies on arable soil loosening, there have been relatively few experimental studies on the effects of grassland soil loosening in the UK and Republic of Ireland (ROI). Most of the grassland loosening studies were conducted around 15-25 years ago. Moreover, the studies evaluated benefits in terms of their effect on grass yields, with only limited measurements of effects on soil physical properties, drainage or other grassland functions (e.g. biodiversity, gaseous emissions etc). A summary of UK and ROI studies on the mechanical alleviation of grassland soil compaction is provided in Table 1.

Table 1. UK and Republic of Ireland studies into the effectiveness of mechanical soil loosening in grasslands.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Years</th>
<th>Location(s)</th>
<th>Soil types*</th>
<th>Machinery used</th>
<th>Parameters investigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADAS</td>
<td>1984-87</td>
<td>Various in England &amp; Wales</td>
<td>Various SL to Clay</td>
<td>Various sward lifters (e.g. Paraplow, Flatlift and Shakaerator) up to 35 cm depth</td>
<td>- Grass yield</td>
</tr>
<tr>
<td>Frost</td>
<td>1983-86</td>
<td>Hillsborough, Northern Ireland</td>
<td>SL, SCL &amp; Clay loam</td>
<td>Paraplow 30-35 cm depth</td>
<td>- Grass yield, Cone resistance</td>
</tr>
<tr>
<td>Douglas et al.</td>
<td>1992-93</td>
<td>Scotland</td>
<td>Clay loam</td>
<td>Bladed aerator 10 cm depth</td>
<td>- Grass yield, N offtake</td>
</tr>
<tr>
<td>Davies et al.</td>
<td>1985-86</td>
<td>Mid Wales</td>
<td>Clay loam</td>
<td>Bladed aerator 10-12 cm depth</td>
<td>- Grass yield</td>
</tr>
<tr>
<td>Fortune et al.</td>
<td>1995-98</td>
<td>9 experimental sites in ROI</td>
<td>Unknown</td>
<td>Bladed aerator up to 20 cm depth</td>
<td>- Grass yield</td>
</tr>
</tbody>
</table>

* SL = Sandy loam; SCL = Sandy clay loam.

ADAS studies reported significant ($P<0.05$) grass yield increases (between 0.8 and 1.8 t/ha dry matter) following topsoil loosening using different sward lifters on three clay textured sites where compaction had been identified (Table 2). However, over all the national trials series the different sward lifters (i.e. paraplow, shakaerator and flatlift) “rarely gave any significant increase in grass yield” (ADAS, 1984; 1987), emphasising the need to target loosening to ‘truly’ compacted soils.
Table 2. ADAS studies 1984-87. Effect of sward lifting treatments on grass yields (t/ha dry matter).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1984</th>
<th>1986</th>
<th>1987</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>6.7^a</td>
<td>12.7^a</td>
<td>11.0^a</td>
</tr>
<tr>
<td>Paraplow*</td>
<td>6.9^a</td>
<td>14.0^a</td>
<td>12.1^b</td>
</tr>
<tr>
<td>Flatlift</td>
<td>7.4^b</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Shakaerator</td>
<td>7.5^b</td>
<td>14.5^b</td>
<td>11.9^a</td>
</tr>
</tbody>
</table>

Column values with the same letter are not significantly different (P>0.05).
1984: Compacted Weald clay, loosened in the autumn
1986&7: Compacted clay soil in Avon, date of loosening not given.
nd: no data
*Parapow no longer commercially available.

Based on the outputs of the national trials series, ADAS Technical Bulletins were produced (Appendix II). The key points from these Technical Bulletins were that:

- Topsoil looseners should not be used unless there are clear signs of soil compaction and the moisture content is suitable
- Topsoil loosening is not recommended in poorly drained soils if there is no drainage system present
- Topsoil loosening should be carried out in the autumn when grass growth is declining
- Equipment should be set up correctly so that the working depth is set just below the zone of compaction
- It is important to make sure the compacted layer is above the critical working depth of the implement used
- Recently loosened soil is very sensitive to re-compaction and it is important to allow the newly loosened structure to be stabilised by root activity and natural soil processes before cattle are grazed or agricultural machinery is run across the surface

Frost (1988a) studied the effects of soil compaction (by machinery traffic) and soil loosening (using a paraplow at 30-35 cm depth) on ryegrass yields at 10 sites in Northern Ireland. The soils were predominantly clay loam textured (15-24% clay), but crucially showed no visible compaction (as assessed by the researchers) at the outset of the experiments. Soil loosening reduced soil strength (as measured by the cone penetrometer to 35 cm depth) on the zero-traffic treatments at all sites, but only over the short-term (6-12 months following loosening). In 1983, loosening in late spring (after first cut) reduced (P<0.05) overall grass yields by c.1.2 t/ha on both the zero-traffic and trafficked treatments (receiving 1-3 passes of a tractor and slurry tanker prior to loosening), Table 3. The yield decreases were attributed to sward disruption and root severance caused by the paraplow. Autumn loosening in 1983 also reduced first cut yields in spring 1984 (by c.20%), but resulted in yield increases in subsequent cuts (by 8-15%) particularly on the heavily trafficked treatments, with an overall yield increase (P<0.05) of 1.0 t/ha across the whole season (Table 3).
Table 3. Effect of topsoil loosening using a paraplow on grass yields (t/ha) at 10 sites in Northern Ireland (taken from Frost, 1988a;b).

<table>
<thead>
<tr>
<th>Year</th>
<th>Control</th>
<th>Loosened</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Autumn</td>
<td>Spring</td>
<td></td>
</tr>
<tr>
<td>1983</td>
<td>7.7</td>
<td>nd</td>
<td>Average yield from 5 sites, with 3 cuts per site; $P&lt;0.05$</td>
</tr>
<tr>
<td>1984</td>
<td>9.2</td>
<td>10.2</td>
<td>Average yield from 5 sites, with 4 cuts per site; $P&lt;0.05$</td>
</tr>
<tr>
<td>1985</td>
<td>10.2</td>
<td>9.2</td>
<td>Average yield from 3 sites, with 3 cuts per site; $P&lt;0.05$</td>
</tr>
<tr>
<td>1986</td>
<td>9.0</td>
<td>9.0</td>
<td>Average yield from 1 site, with 3 cuts; $P&gt;0.05$</td>
</tr>
</tbody>
</table>

Note: results are given for the 'heavily' trafficked treatment (3 passes of a tractor & slurry tanker prior to loosening).

A second study by Frost (1988b) in Northern Ireland (soils with 18-21% clay and again no visible signs of compaction) also measured first cut yield reductions ($P<0.05$) in 1985 as a result of soil loosening with a paraplow in autumn 1984, which persisted to second cut (albeit at a lower level) and gave an overall yield reduction of 1 t/ha (Table 3). In 1986, Frost (1988b) measured no grass yield differences ($P>0.05$) as a result of loosening in the previous autumn and spring (Table 3). Soil strength (as measured by the cone penetrometer) decreased with loosening, but again only persisted for 6-12 months following loosening.

The studies of Frost (1988a;b) showed that soil loosening (using a paraplow) can cause grass yield reductions in subsequent harvests and over the whole growing season, despite measured decreases in soil strength (penetration resistance). These results were most probably due to the lack of compaction at the outset of the experiments and sward damage caused by the paraplow. Moreover, Frost (1988b) suggested that the study soils were 'resistant to compaction' and that disruption to the sward and root system caused by loosening had a much greater impact on yields than any of the induced compaction treatments. These results support ADAS guidelines for grassland soil loosening (ADAS, 1984; 1987) i.e. soil loosening should only be considered where there are clear signs of soil compaction and that autumn loosening is potentially more beneficial than spring loosening in terms of grass yield responses; see Appendix II.

Douglas et al. (1995) evaluated the effects of topsoil aeration (using a bladed aerator to create ‘slits’ c.10 cm deep) on grassland yields and N offtakes on a clay loam textured site in Scotland, which had been subjected to differential compaction treatments. While the use of machinery with low pressure tyres significantly enhanced grass yields (by 13%) compared with the conventional management treatment, soil slitting had no effect ($P>0.05$) on annual grass yields in both 1992 and 1993. Visual assessment showed that the slits were readily closed up by subsequent traffic and any improvement in soil aeration was short-lived. Crawford and Douglas (1993) speculated that mechanical soil
aeration could also be used as a means of reducing surface runoff from grassland by improving water infiltration, but no data were presented.

In comparison, Davies et al. (1989) measured (surprisingly) large increases in net herbage yields and nitrogen uptakes as a result of soil slitting on a clay loam soil that was severely compacted at 10-12 cm depth, due to high stocking rates of dairy cattle over the preceding 26 years. An aerator was used to create slits up to 14 cm deep in spring (April), with the plots continuously grazed from April to October in the following two years. Herbage accumulation (kg/ha/day) was measured by protecting the plots for eight 16 day periods during 1985 and 1986 (the rest of the field was grazed continuously). The average dry matter accumulation rate on the aerated treatments was 4 and 2-fold greater than on the untreated control in 1985 and 1986, respectively (Table 4). Slitting increased the weight of roots at 10-20 cm depth, but there was no difference in root weight over the whole topsoil (0-20 cm depth), with most roots in the untreated control concentrated in the top 10 cm (i.e. above the compacted layer).

Table 4. Effects of topsoil aeration (slitting) on average herbage dry matter accumulation rates (kg/ha/day DM) and nitrogen uptakes (kg/ha/d) on a heavily compacted soil in Wales. Taken from Davies et al. (1989).

<table>
<thead>
<tr>
<th>Year</th>
<th>Untreated control</th>
<th>Aerated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DM yield</td>
<td>N uptake</td>
</tr>
<tr>
<td>1985</td>
<td>14</td>
<td>1.2</td>
</tr>
<tr>
<td>1986</td>
<td>36</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Fortune et al. (1999) conducted a comprehensive evaluation of the effect of grassland spiking, using a ‘Tranco Aerway Pasture Aerator’ operating at 20 cm depth, at 9 experimental sites in ROI over the period 1995-1998. Fields had either been cut or grazed, with some sites having historic compaction treatments. Treatments included autumn (October) or spring (April) spiking, and once-only compared with annual spiking. Over the 4 year period, a total of 21 separate comparisons were made. The majority of the measurements showed no yield effects ($P>0.05$) at individual cuts or over the whole growing season from the spiking treatments (Table 5). Where there was a positive yield response to spiking (4 occasions), this was only measured at one or two cuts during the season. Conversely, there were 10 occasions where a negative yield response was measured at one or two cuts. There were no consistent differences between the autumn and spring spiking treatments, or between once-only and annual spiking. Indeed, Fortune et al. (1999) concluded that while differences were measured, these were small and inconsistent, and advised that the routine spiking of grassland was unlikely to produce any consistent yield benefits.
Table 5. Effect of topsoil spiking (to 20 cm depth) on the annual grass dry matter yields at 9 experimental sites in the Republic of Ireland (collated from Fortune et al. (1999)).

<table>
<thead>
<tr>
<th>Site: management</th>
<th>Date</th>
<th>Annual grass yield (t/ha)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>Spiked in spring</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Once</td>
<td>Annually</td>
</tr>
<tr>
<td>1. Kilmaley: Grazed</td>
<td>1995</td>
<td>15.5</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>1996</td>
<td>14.5</td>
<td>14.4</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>16.5</td>
<td>16.9</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>12.5</td>
<td>12.9</td>
</tr>
<tr>
<td>2. Kilmaley: Cut</td>
<td>1995</td>
<td>15.4</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>1996</td>
<td>14.8</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>16.0</td>
<td>15.9</td>
</tr>
<tr>
<td>3. Kilmaley: Compacted</td>
<td>1995</td>
<td>2.9</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>1996</td>
<td>17.1</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>8.9</td>
<td>7.8</td>
</tr>
<tr>
<td>4. Knockbeg: Cut</td>
<td>1995</td>
<td>3.5</td>
<td>3.3</td>
</tr>
<tr>
<td>5. Knockbeg: Grazed</td>
<td>1995</td>
<td>2.9</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>14.2</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>13.2</td>
<td>13.5</td>
</tr>
<tr>
<td>7. Oak park 2: Cut</td>
<td>1997</td>
<td>14.0</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>14.0</td>
<td>13.7</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>15.3</td>
<td>15.4</td>
</tr>
<tr>
<td>9. Solohead: Grazed</td>
<td>1997</td>
<td>20.5</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>12.8</td>
<td>11.8</td>
</tr>
</tbody>
</table>

*Annual grass yields from 3-9 cuts, with the grazed sites cut at c.3 weekly intervals to correspond with the grazing periods. Sites 4 & 5 and site 3 in 1995 were only cut once.

bSpring spiking usually carried out in April

cAutumn spiking usually carried out in October
4 Overseas studies

To assess overseas studies on the impacts of mechanical loosening of grassland soils, scientific literature was reviewed using combinations of keywords in the ‘ScienceDirect’ database and search facility, and the ‘Soil Use and Management’ Index (Volumes 1-25, 1985-2009). Relevant papers and documents were scrutinised for information on the effectiveness of mechanical aeration and sward lifting in alleviating grassland soil compaction. Papers were identified from New Zealand and North America.

4.1 New Zealand

As in the UK and ROI, research into the mechanical alleviation of soil compaction in New Zealand grasslands showed that the benefits of loosening/aeration can be soil type dependent and related to the degree of loosening achieved, with some soils quickly reverting back to their original state shortly after mechanical treatment (Curran Cournane, 2011).

In Waikato Region, North Island, Burgess et al. (2000) reported that sward lifting as silt loam, dairy grassland soil initially decreased bulk density and penetration resistance, and increased hydraulic conductivity, total porosity and macroporosity compared to an un-loosened soil. However, the improvements only persisted for 10 months. Pasture herbage yields, botanical composition and root length were unaffected (P>0.05) by loosening, but loosening increased (P<0.05) root dry weights and decreased bare ground. Also in Waikato Region, Houlbrooke et al. (2005) showed that the mechanical aeration of grassland increased surface infiltration rates and reduced the loss of farm dairy effluent in surface runoff compared with non-aerated soil.

In Southland (South Island), Drewry et al. (2000) showed that sward lifting (25-30 cm) a compacted, fine-textured, silt loam, grassland soil increased macroporosity, saturated hydraulic conductivity and air permeability, and decreased bulk density. Improvements persisted for up to 30 months post-loosening. Pasture dry matter production from the loosened treatment was variable, with no difference (P>0.05) in total production compared with the un-loosened control.

In North Otago (South Island), Curran Cournane et al. (2011) used a sward lifter (‘Clough panaerator’) to mechanically loosen a silt loam, dairy grassland soil to a depth of 20 cm. Within six months of loosening, but before cattle grazing had re-commenced, there were no differences in soil physical properties between loosened and un-loosened treatments, i.e. any differences in soil physical properties such as macroporosity were short-lived. The lack of treatment differences continued after grazing and were largely attributed to the re-settling of the unstable and poorly structured soil studied. Flow-weighted mean concentrations and annual loads of dissolved reactive P (DRP) from the loosened soil (2.24 kg DRP/ha) were approximately double those from the un-loosened control treatment (1.20 kg DRP /ha) (P=0.05). However, there were no differences in total P and suspended sediment losses.
between treatments, which was thought to reflect the similar soil physical conditions between treatments within six months of loosening.

The authors suggested that one reason for the observed increase in DRP losses from mechanical treatment could be that loosening exposed a greater soil surface area to P desorption, which may have been enhanced by a prolonged period of saturation during storm events once the soil had re-settled. Another possible explanation is that soil aeration may have liberated P from the microbial biomass which has been reported to be sensitive to disturbance (Sparling et al., 1987).

4.2 North America
Research in North America has mainly been focused on the use of mechanical aerators (i.e. spikers/slitters) to improve infiltration and alleviate compaction.

In Canada (Nova Scotia), Gordon et al. (2000) used a mechanical aerator immediately before and after spreading dairy slurry, but found no beneficial effects in reducing ammonia emissions or increasing forage yields. However, studies in British Columbia showed that using a trailing hose spreader to apply slurry directly over aeration slots as a single operation, reduced ammonia and odour emissions, and increased grass yields compared with surface broadcasting using a splash plate (Bittman et al., 2005; Lau et al., 2003).

In West Virginia, USA (Shah et al., 2004) and Georgia, USA (Butler et al., 2008; Franklin et al., 2007), use of a mechanical aerator on well-drained grassland soils decreased surface runoff volumes and dissolved reactive phosphorus (DRP) and total phosphorus (TP) losses compared with non-aerated soil. Decreases in surface runoff volumes and P losses were attributed to the increased infiltration of rainfall and binding of P with soil minerals. Effects on grass yields were inconsistent with some yields unaffected, some slightly increased and some slightly decreased. In a similar study in Arkansas, Pote et al. (2003) reported that concentrations of soluble P in surface runoff following poultry manure application were reduced \((P<0.05)\) where the poultry manure was partially incorporated using an aerator (surface slitter) as opposed to surface-applied without mechanical slitting.

In contrast, on poorly drained soils in Georgia, USA, soil aeration increased surface runoff volumes (4.8 mm/runoff event) and losses of DRP (0.25 kg DRP/ha per runoff event) and TP (0.25 kg TP/ha per runoff event) when compared to the non-aerated soil treatment (Franklin et al., 2007). The authors concluded that mechanical soil aeration of the poorly drained soils, prone to episodes of wetness as a result of soil compaction (the aeration had no effect on compaction), stimulated reducing and oxidising conditions and DRP loss in runoff, and that the effect of aeration on P loss is likely to vary depending on soil drainage status.

The above studies from New Zealand and North America indicate that mechanical loosening and aeration can benefit soil properties, but not in all
circumstances, with results varying in relation to soil type, drainage status and the degree of loosening achieved. In most cases, benefits were only reported where soils were compacted prior to mechanical treatment and the duration of benefits (where they occurred) varied between a few weeks and 2-3 years.

Table 6. New Zealand and North American studies into the effectiveness of mechanical soil loosening of grasslands.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Years</th>
<th>Location(s)</th>
<th>Soil type</th>
<th>Machinery used</th>
<th>Parameters investigated</th>
</tr>
</thead>
</table>
| Drewry et al.     | 1992-94| Southland, New Zealand   | Silt loam          | Sward lifter (James aerator) | - Macroporosity  
|                   |        | (maritime temperate)      | (Brown Earth)      |                                        | - Hydraulic conductivity  
|                   |        |                           |                    |                                        | - Air permeability  
|                   |        |                           |                    |                                        | - Bulk density  
|                   |        |                           |                    |                                        | - Grass yields  |
| Burgess et al.    | 1996-98| Hamilton, Waikato, New    | Silt loam          | Sward lifter (James aerator) | - Bulk density  
|                   |        | Zealand (maritime        |                    |                                        | - Cone resistance  
|                   |        | temperate)               |                    |                                        | - Hydraulic conductivity  
|                   |        |                           |                    |                                        | - Macroporosity  
|                   |        |                           |                    |                                        | - Grass yields  
|                   |        |                           |                    |                                        | - Root length  
|                   |        |                           |                    |                                        | - Root dry weight  
|                   |        |                           |                    |                                        | - Botanical composition  |
| Curran Cournane et al. | 2008-10| North Otago, New Zealand| Silt loam          | Sward lifter (Clough panaerator) | - Bulk density  
|                   |        | (maritime temperate)      |                    |                                        | - Hydraulic conductivity  
|                   |        |                           |                    |                                        | - Macroporosity  
|                   |        |                           |                    |                                        | - P fractions  
|                   |        |                           |                    |                                        | - Suspended solids  |
| Gordon et al.     | 1996-97| Nova Scotia, Canada       | Unknown            | Bladed aerator           | - Grass yields  
|                   |        | (mid-temperate continental) |                |                                        | - Ammonia emissions  |
| Bittman et al.    | 2000-01| British Columbia, Canada  | Silt loam          | Bladed aerator           | - Grass yields  
|                   |        | (subtropical)             |                    |                                        | - N uptake  
|                   |        |                           | & Sandy loam        |                                        | - Ammonia emissions  |
| Lau et al.        | 1999-2000| British Columbia, Canada  | Unknown            | Bladed aerator           | - Odour from manure applications |
|                   |        | (subtropical)             |                    |                                        | |
| Shah et al.       | 2000-01| West Virginia, USA        | Well drained       | Bladed aerator           | - P losses  
|                   |        | (humid subtropical)       |                    |                                        | - Grass yields  |

17
Table 6 (cont.). New Zealand and North American studies into the effectiveness of mechanical soil loosening in grasslands.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Years</th>
<th>Location(s)</th>
<th>Soil types</th>
<th>Machinery used</th>
<th>Parameters investigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butler et al.</td>
<td>2004-06</td>
<td>Georgia, USA (humid subtropical)</td>
<td>Sandy loam over clay loam</td>
<td>Bladed aerator ('Aerway')</td>
<td>- Surface runoff</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- P losses</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Sediment</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Grass yields</td>
</tr>
<tr>
<td>Franklin et al.</td>
<td>1995-03</td>
<td>Georgia, USA (humid subtropical)</td>
<td>Well drained to poorly drained</td>
<td>Bladed aerator ('Aerway 80Q') 10-12 cm depth</td>
<td>- Surface runoff</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- P losses</td>
</tr>
<tr>
<td>Pote et al.</td>
<td>1999-00</td>
<td>Arkansas, USA (humid subtropical)</td>
<td>Silt loam</td>
<td>Bladed aerator</td>
<td>- Surface runoff</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Grass yields</td>
</tr>
</tbody>
</table>

Note: The New Zealand studies were from maritime temperate/oceanic climates similar to the UK and ROI, while the North American studies were carried out in dry summer subtropical (British Columbia), humid subtropical (e.g. Georgia and West Virginia) and mid-temperate continental climates (Nova Scotia).
Discussion

Results from the limited number of studies evaluating the effects of grassland soil loosening in the UK, ROI and overseas have been very variable, with many measuring no annual yield benefits, along with some yield increases and some decreases. Where yield increases were measured these were generally at sites where there was evidence of compaction at the outset. Where yield decreases were measured these were generally at sites where there was little (or no) evidence of compaction at the outset of the experiment and loosening resulted in sward and root damage.

Frost (1988a; b) observed a reduction in soil strength (as measured by the cone penetrometer to 35 cm depth) as a result of loosening with a paraplow. However, this loosening effect only persisted for 6-12 months, most probably due to ‘re-settling’ of the soils when livestock and machinery returned to the field. The short-term effect of loosening may also have been due to the fact that these light to medium textured soils showed no visible compaction (as assessed by the researchers) prior to loosening and so they soon returned to their consolidated, but ‘un-compacted’ condition after mechanical loosening. Frost (1988b) also suggested that the study soils were ‘resistant to compaction’ and that this may be due to “the organic matter content and stone content of the soils, together with the use of perennial ryegrass and high rates of fertiliser”. It is certainly possible that soils with higher organic matter content may be more resistant to compaction than low organic matter soils.

The above results suggest that both sward lifters and aerators 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. Sward lifters will be more effective where compaction is below the surface 10-12 cm, while aerators can also be effective where compaction is identified within 10-12 cm of the soil surface. ADAS studies (1984; 1987) showed that the use of sward lifters could result in grass yield increases where compaction was identified. Equally, Davies et al. (1989) measured some large increases in net herbage yield as a result of soil slitting on a clay loam soil that was severely compacted at 10-12 cm depth. By contrast, other researchers (Frost 1988; Douglas et al. 1995; and Fortune et al. 1999) reported negative or inconsistent effects of mechanical loosening on grass yields where soils were not compacted (or an attempt was made to induce compaction) prior to loosening. This suggests that the negative effect of the soil compaction needs to be greater than the negative effect of sward damage (resulting from the use of aerators or sward lifters) if mechanical soil loosening is to have a positive effect on yield. The working depth of loosening also needs to be set just below the compacted layer and any mechanical loosening should only be carried out in moist to dry conditions. Clearly, if soils are not compacted prior to loosening or soil conditions are not suitable (soils are either too wet - resulting in excessive wheel slip and soil smearing - or too dry - resulting in excessive power requirement, soil heave and sward damage), mechanical soil loosening in grasslands is likely to be a waste of time and money.
Notably, the above UK and ROI studies focused on the effect of grassland soil loosening on herbage yields. Only one study from UK and ROI (Frost, 1988a;b) investigated soil physical properties and none of the UK studies considered the effects of compaction and soil loosening on flood management and water resources, biodiversity, water and air quality. The overseas studies show that mechanical loosening can influence a number of soil properties and that the degree and direction of change can vary according to soil type, drainage status, degree of loosening etc.. This highlights the need to investigate the effects of modern topsoil loosening equipment on soil functions and ecosystem services at ‘compacted’ soil sites in England and Wales.
5 Conclusions

Where used in appropriate conditions, grassland looseners (e.g. sward lifters) have the potential to alleviate compaction at varying depths, and where compaction is evident, responses in herbage yields are likely. However, increased yields and improvements in soil physical properties may be short-lived (up to 12 months).

Where the aim is to improve surface aeration and water/slurry infiltration rates, aerators (i.e. surface spikers or slitters), working typically at a soil depth of 10 cm, should be used. However, aerators are principally designed to increase surface aeration, rather than to alleviate soil compaction per se.

The best option for alleviating compaction in the middle and lower parts of the topsoil is a sward lifter or ‘grassland topsoiler’, working between 20 and 35 cm soil depth. This equipment typically consists of a set of leading discs followed by vertical legs or tines (sometimes ‘winged’) and a full width roller/packer to control depth and level the surface.

ADAS Technical Bulletins (ADAS, 1984; 1987) provide clear guidance on the use of topsoil loosening equipment, based on outputs from a national trials series undertaken in the 1980’s (see Appendix II). Soil loosening devices should only be used when there is clear evidence of compaction. Also, the timing of operations is critical; use in conditions that are too wet will potentially lead to soil damage through smearing and wheel slip, and use in conditions that are too dry will most likely result in excessive soil surface heave and root damage leading to sward death.

Recently loosened soil is very sensitive to re-compaction and it is important to allow the newly loosened structure to be stabilised by root activity and natural soil processes before livestock are returned or machinery is used on the land. If late growth needs utilising it is advisable to use sheep rather than cattle to minimise re-compaction damage. Equally, in the spring following soil loosening it is advisable to cut and conserve grass rather than graze with livestock.

Notably, given the medium/high horse power requirement of sward lifting machinery and relative infrequency of use of such equipment, compaction alleviation on grassland farms are most likely to be carried out by contractors, who will have large enough tractors (140-160 horse power is the typical minimum requirement) to power the machinery and can spread the capital costs over a number of farm users.

Overseas studies have shown that sward lifting/aeration can improve soil physical properties and affect surface runoff and associated sediment and nutrient losses from grassland soils, although results have been variable. Overall, research from the UK, ROI and other parts of the world confirms the need to investigate the effects of modern topsoil loosening equipment on soil functions and ecosystem services at ‘compacted’ soil sites in England and Wales.
7 References


Appendix I

UK market equipment (not exhaustive)

Aerators

Browns Agricultural Machinery, Grovebury Road, Leighton Buzzard, LU7 4UX,
- **Slitmaster.** 1.5m to 6m adjustable rotor aerators. Built in weight frame, optional depth control / levelling roller on smaller models. Max depth 20 cm.

David Ritchie (Implements) Ltd. Carseview Rd. Forfar, DD8 3BT
- **Grassland Aerator.** 10 degree adjustment of shaft angle, 4 boron steel blades per rotor ring, optional ballast tanks.

K-Two Sales, Fowler’s Field Farm, Station Road, Haddenham, Aylesbury, HP17 8DD
- **Aeravator Grass Slitter.** 3m and hydraulic folding 8m machines with weight frame or integral ballast tanks. 5 blades per rotor ring, adjustable off-set headstock.

Glenside Group Ltd. Throsk, Stirlingshire, FK7 7XY
- **OxyGenerator Super Six.** Fully galvanised 6m folding slitter with boron steel blades and shaft. Integral slurry splashplate and drop tubes for use with umbilical system. Racked plastic ballast tanks for additional weight.

Sward lifters/topsoilers/subsoilers

Opico Ltd. Cherry Holt Road, Bourne, Lincs. PE10 9LA.
- **Sward Lifter.** Sprung loaded leading disc coulters, slightly inclined leg with replaceable shin and shearbolt breakback, chisel pointed foot, depth control by sprung corrugated 4 ring press wheel.

David Ritchie (Implements) Ltd. Carseview Rd. Forfar, DD8 3BT
- **Actisol grassland top-soiler.** Leading disc coultor, 30mm thick sprung forward inclined leg with chisel point and optional wings. Depth control by 450mm diameter crumbler roller. 2.9m frame, available in 3, 4 or 5 leg configurations.

F W McConnel, Temeside Works, Ludlow, Shropshire SY8 1JL
- **Grassland build Shakaerator.** Sprung loaded plain leading disc coulter, slim 600mm vertical leg with replaceable shin and slightly winged inclined shoe. PTO driven vibration unit to reduce draught requirement and increase shatter. Depth control by depth wheels or full width flat roller. 2m or 2.5m frame with 2 or 3 legs.
Sumo UK Ltd, Redgates, Melbourne, York, YO42 4RG
• Grassland Subsoiler. Linkage-mounted subsoiler with leading discs, full width depth control roller and comb harrow. Forward inclined leg and foot with wings.
Terrington Machinery, Market Lane, Terrington St Clement, Kings Lynn, Norfolk. PE34 4HR
• Badalini grassland subsoiler.

Mole ploughs
Suppliers and manufacturers of mole ploughs are becoming scarce. However, the following manufacturers do still supply them:

• Hunton Legg (Running Gear) Lt, Bridge Works, Bruisyard, Saxmundham, Suffolk. IP17 2DT
• Michael Moores Hi-Rider Mole Ploughs.

A number of other machinery manufacturers and engineers will build mole ploughs to order from their old catalogues, or as bespoke variations of subsoilers.
Appendix II

Guidelines for the use of topsoil looseners in UK grassland

Adapted from ADAS Technical Briefing notes (ADAS, 1984; 1987):

1. **Do not use topsoil looseners unless there are clear signs of soil compaction, and the moisture content is suitable:**
   - Examine the soil by digging holes to find out the nature and depth of any compacted layers, as well as the moisture content and friability of the soil.
   - Topsoil loosening in dry conditions is likely to lead to the formation of large clods, sward tearing and excessive surface heave giving an uneven surface finish.
   - Topsoil loosening in conditions which are too wet will potentially lead to increased soil damage through smearing and wheel slip.

2. Topsoil loosening is **not recommended in poorly drained soils** if there is no drainage system present, as this is likely to cause excessive wetness in low lying areas which will potentially be at further risk of poaching and re-compaction. In these situations, and on heavy textured soils, moling may be more effective in improving the soil drainage status than topsoil loosening.

3. Topsoil loosening should be carried out in the autumn when grass growth is declining. If carried out in the spring or summer when grass is growing rapidly and is often under moisture stress, disturbance to the root system can lead to severe sward death.

4. **Use the appropriate equipment and set it up correctly.** The depth of compaction will dictate the depth of working required - make sure the compacted layer is above the critical working depth of the implement used and examine the extent of shatter of a trial run, adjusting the equipment if necessary.

5. **Recently loosened soil is very sensitive to re-compaction** and it is important to allow the newly loosened structure to be stabilised by root activity and natural soil processes:
   - Cut or graze the site immediately before treatment.
   - Avoid grazing after loosening and conserve rather than graze in the first spring after treatment.
   - If late growth needs utilising, use sheep rather than cattle to minimise re-compaction damage.
   - Do not spread slurry on recently loosened fields.