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SID 5 Research Project Final Report

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Main objectives:

This project aimed to carry out a scoping study to provide information on the predicted geographical extent and severity of soil compaction in grassland landscapes across England and Wales. The impacts of soil compaction are likely to include adverse affects on a number of the objectives of Defra's Environmental Stewardship (ES) Scheme, so this project aimed to bring together current understanding of the impacts of soil compaction on the maintenance of biodiversity and protection of the water and air environments. The project has identified likely causes of compaction in grassland systems, points to potential remediation techniques and provides recommendations for future research

Methods:

This project was desk-based and as such chiefly took the form of an extensive literature review of the causes and impacts of soil compaction. The initial task of mapping the extent of soil compaction was carried out using a simple model of 'vulnerability to compaction' combined with known data on livestock numbers across England and Wales. This produced a map of soil compaction 'risk'.

Available data on the severity of soil compaction is extremely scarce. Information from 12 catchments was used to characterise the nature and degree of compaction in soils, however, the sites are, in no way, representative of the grasslands of England and Wales and so broad conclusions about soil conditions under grassland are ill-advised. For the catchments studied, less than 1% of sites had severe degradation but over 80% were either highly or moderately degraded. The lack of information on the nature and intensity of management systems and grazing in the catchments and at the actual sites visited is a source of uncertainty that limits the scope for analysis of the survey results. It is therefore difficult to draw any further or firmer conclusions from the data that were available.

Findings:

Surprisingly little is know about the extent and severity of soil compaction and its impacts on the vital functions (ecosystem services) supported by soil. We know a little about the impacts of soil compaction on above ground biodiversity, but almost nothing on below ground flora and fauna. Evidence exists to show that soil compaction has the potential to radically increase runoff and flood risk, enhance nutrient and soil loss from field and effect greenhouse gas emissions. Given that an average 30% of England is under managed grassland and that this figure is much higher for western England and Wales, it is important that compaction and its impacts are better understood. The recommendations for future research have been developed from these findings and by consultation with key experts and stakeholders.

Recommendations for future work:

The priorities for research fall under five principal questions.

1. How extensive and severe is soil compaction, and what is its spatial and temporal distribution?

- 1A. A national survey is required to gather information on the extent, nature and severity of soil compaction under different grassland management systems and climates
- 1B. Research is needed to improve understanding of the nature and importance of different types of soil structural degradation.
- 1C. Research is recommended into the development of more cost-effective methods for measuring and monitoring soil compaction.
- 1D. An initial survey of a number of horse pastures and a review of the extent of horse paddocks is recommended to investigate the scale of compaction resulting from horses.

2. What is the impact of different forms of compaction on soil functionality and therefore biota, water quality and flows, and air quality?

- 2A. A detailed field experiment investigating the response of soil biology, grassland composition and bird species to impacts of grazing and farm machinery use is needed.
- 2B. It is recommended that the physical condition of soils on all relevant experimental sites where biological, hydrological or gas exchange parameters are being measured is monitored according to a consistent methodology.
- 2C. It is recommended that investigation of the extent of soil compaction under grazed grassland sites becomes a regular part of the management regime for such sites where they are designated or identified under an agri-environment scheme.
- 2D. Research should be carried out to determine the influence soil compaction has on catchment-scale river flows and flood risk.
- 2E. Investigations on greenhouse gas fluxes following compaction should be carried out.

3. What is the economic and social cost of compaction and therefore the value of its prevention or remediation?

- 3A. The environmental impacts of soil compaction need to be fully costed so that the full economic impact of soil compaction is known.

4. Do soils recover from particular forms of compaction and if so at what rate and under what circumstances?

- 4A. It is recommended that a programme of small-scale experiments be carried out to investigate the natural recovery potential of a range of contrasting soils under grasslands of differing composition.
- 4B. Similar scaled research into the effectiveness of different soil biology and plants in improving different forms of soil compaction should also be carried out.

5. How is compaction best prevented or remediated in grassland soils?

- 5A. A blueprint for contractors and farmers relating to practices to reduce compaction should be produced. The information needed for this is largely available, but not in one place, and not necessarily easily accessible.
- 5B. The feasibility and cost-effectiveness of a nationwide system to monitor moisture in soils in real-time should be assessed.
- 5C. Trials of products that offer solutions to soil compaction under grassland are needed in areas with existing or potential biodiversity interest, such that probity of techniques and impacts on biodiversity can be determined.

Assessing the spatial extent of grassland compaction has to be the first priority (**Rec. 1A**) and it is suggested that this should proceed immediately. If compaction is anything other than a localised issue, it is difficult to see any alternative to: (a) a major study of the impacts on soil and above-ground biota (**Rec. 2A**) and water flows (**Rec. 2D**) and greenhouse gas fluxes (**Rec. 2E**) at catchment scale ; (b) work on more cost-effective methods of measurement (**Rec. 1C**); (c) commissioning of work for **Rec. 5C**. This should be followed by valuation of the impacts of compaction (**Rec. 3A**), as this will inform decisions on Government investment in further research in response to the other research recommendations above.

Recommendations **2B** and **2C** should be considered for adoption as standard practice. The advisory Blueprint in Recommendation **5A** is seen as a useful extension to other initiatives already in place such as the Guide to Good Soil Structure and the unified Code of Good Agricultural Practice.

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
- the scientific objectives as set out in the contract;
 - the extent to which the objectives set out in the contract have been met;
 - details of methods used and the results obtained, including statistical analysis (if appropriate);
 - a discussion of the results and their reliability;
 - the main implications of the findings;
 - possible future work; and
 - any action resulting from the research (e.g. IP, Knowledge Transfer).

Introduction

In accordance with the project specification, the project aimed to carry out a scoping study to provide information on the predicted geographical extent, severity and environmental impacts of soil compaction in grassland landscapes across England and Wales. The impacts of soil compaction are likely to include adverse affects on a number of the objectives of Defra's Environmental Stewardship (ES) Scheme, so this project aimed to bring together current understanding of the impacts of soil compaction on biodiversity, water and air. The project has identified likely causes of compaction in grassland systems, points to potential remediation techniques and provides recommendations for future research.

The specific objectives of the project were:

1. To identify and, where possible, quantify the causes of soil compaction.
2. To describe and, where possible, quantify the impact of soil compaction on
 - soil flora and fauna, particularly macro-invertebrates
 - plant communities
 - birds (especially waders and other species of conservation concern)
 - diffuse pollution of water and air
 - soil erosion and associated nutrient losses
 - water resources and flood risk
3. To identify potential remediation measures for use in Defra's ES Scheme.
4. To identify, within existing and potential ES options, conflicts and synergies between objectives relating to soil compaction and its remediation and other scheme objectives.
5. To recommend priorities for field-based research and identify appropriate sites for case studies.

The following report will be split into sections in accordance with the overall objective and the specific objectives stated above. Summaries of the work carried out in each section are given here. Full reports, figures, all references, and a glossary of terms are given in the appendices.

Work package 1: Mapping the extent of soil compaction

A staged approach has been used to generate a digital map of the extent of compaction risk in grassland landscapes as a framework for organising available information on the extent of compaction. The term 'grassland landscapes' is taken to mean landscapes dominated by enclosed managed grassland used for livestock or dairy production. Compaction is used to include all forms of soil structural degradation and deformation. Further details are given in Appendix 1.

Stage 1: June Agricultural Census data transposed to a 1 km grid (ADAS *priv comm*) for England but only to a 2 km grid for Wales (source EDINA data library) was used to create a map of grassland landscapes using 40 per cent grass as the qualifier.

Stage 2 Vulnerability to compaction: For this project, a model of soil vulnerability to compaction is needed that is focused on soils under grassland, caters for the climatic ranges experienced by grassland in England and Wales, and uses properties of the soil and of climate that are available in digital form and as spatial data sets covering England and Wales. Most work on compaction has been on tilled soils but Harrod's (1979) Grassland Suitability model assesses the relative vulnerability of soils to compaction from traffic and livestock. This is based on topsoil retained water capacity depth to impermeable horizon and soil wetness class and a further climate moistness factor

Stage 3 Stress factor and risk of compaction: The likelihood of soils becoming compacted is a factor of the land vulnerability of the soil to compaction, as described above, and the aggregate stress resulting from livestock and machinery acting on the soil. A number of options for the construction of a stress factor were considered.

These included combinations of livestock numbers and types, types of grassland and grassland management systems. The suitability of each was assessed on the basis of the level of understanding of their influence on the compaction process and the availability and quality of spatial data. Following this assessment, it was decided to base relative compaction stress on a measure of the overall stocking density and a modified Grazing Livestock Unit (this incorporates sheep and cattle) was employed using 2004 Parish Statistics data. This was then combined with the vulnerability to compaction data set using a decision matrix to derive a three class risk of soil compaction map for all areas of grassland (Figure 1).

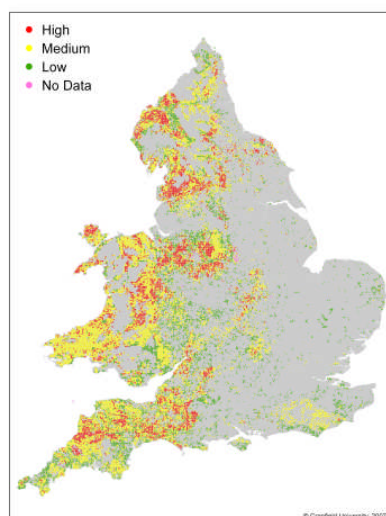


Figure 1. Risk of compaction

Following comments from the Steering Group, the impact of mapping risk on the basis of GLUs per percent grassland per km square was investigated. The resulting compaction risk map indicated higher risk in areas associated with lowland dairying where grass is mixed in with maize and arable cropping and lower risk in the sheep-dominated uplands where grassland is more pervasive. Other than that, the pattern as governed by the underlying soil vulnerability was unaffected. After consideration of factors such as sheep out-wintered as opposed to the winter housing of dairy herds it was decided that the representation of the stress factor simply as number of GLUs offered as good a representation as any other.

Actual extent of compaction: The consistent characterisation of the degree and nature of compaction in soils is challenging as the various forms of structural condition are difficult to measure quantitatively and to describe qualitatively. Work by Palmer (2004) using a technique developed during work on flood-affected catchments in 2000 provides the most significant body of evidence of the extent of compaction but only covers twelve catchments mostly in the south and west of the country (one is from Wales) and the sites cannot be claimed to be representative of the country as a whole. However for the catchments studied, less than 1 per cent of sites had Severe degradation but 21 per cent were placed in the High degradation category with a further 60 per cent in Moderate. Table 1 describes the degradation classes.

Table 1 Degradation classes used in catchment studies (Palmer 2004)

| Class | Description |
|------------------|--|
| Severe | Soil degradation generates sufficient enhanced runoff to cause widespread erosion that is not confined to wheelings/tramelines |
| High (extensive) | Soil degradation generates enhanced runoff across whole field where slopes allow |
| Moderate (local) | Soil degradation generates localised areas of enhanced runoff where slopes allow |
| Low | Insufficient enhanced runoff generation |

The relative proportions of sites in the different categories is variable across the catchments. The data indicate a correlation between vulnerability and actual degradation in so far as low vulnerability soils were found to have predominantly low levels of actual degradation and, conversely, high vulnerability soils were linked to the highest proportion of high degradation sites. Soils under ley grassland may be more susceptible to compaction than those under permanent grassland but it is difficult to draw any further or firmer conclusions from the data. This is based on results from catchment studies made between 2002 and 2007. Ley grass (1-5 years old) can retain features of compaction from previous arable cropping (plough pans; dense, coarse topsoil structures) if remedial measures (which should be part of any good soil/land management) were not put in place PRIOR to establishment of the ley. Ley grassland surfaces are often softer than permanent grass because they do not necessarily have the beneficial effects of dense turf and root mat.

The lack of information on the nature and intensity of management systems and grazing in the catchments and at the actual sites visited is a source of uncertainty that limits the scope for analysis of the survey results in this context. It has not been possible to generate a map depicting the extent of actual compaction and the lack of actual data on the extent of compaction is a matter of concern.

Use of the Palmer (2004) method: Bradley (*priv comm*) reported on a meeting of technical specialists held at Silsoe in September 2005 to discuss the field assessment of soil structure. The NSRI methodology was compared with the Peerlkamp and the Visual Soil Assessment method from Landcare New Zealand and also on an ISTRO Working Group F meeting held in France in May of that year at which 10 methods of assessment (but not including the NSRI method) were applied to three different soils. The NSRI method is distinctive in that it assesses conditions at the field scale rather than in a single profile. As well as assessment of soil surface conditions across the field and evidence of run off or erosion, three soil pits are dug for topsoil and subsoil structural assessment at sites chosen to represent the range of surface conditions found within the field. All other methods are focused on topsoil structure assessment at individual sites. While the various soil profile methods use different approaches they are all attempting to measure the nature and level of development of soil aggregation. In the ISTRO comparison study, all methods ranked the three soils similarly.

Work package 2a: The causes of soil compaction

Further details are given in Appendix 2

The underlying cause of compaction is the inability of soil to withstand external pressures applied to it. Soil compaction *sensu stricto* results when the physical structure of the soil is unable to support an applied weight or mechanical stress leading to a coarsening or loss of soil structural units, decrease in soil volume, increase in bulk density, decrease in porosity (in particular macroporosity) and reduction in hydraulic conductivity of the soil. The ability of a soil to support weight or mechanical stress is governed by its strength (Hodgson, 1997: p.57). The structural strength of soil is a dynamic characteristic which for a particular soil varies widely through the year according to soil moisture content and all soils lose structural stability when wet. As a soil wets up pore water pressure increases and friction between particles reduces allowing particles to slide over each other. In the context of this review, we have taken soil compaction to include all forms of soil physical degradation. This includes surface poaching by stock and surface capping although there is little if any work on the effects of capping in grassland soils.

Cementing agents such as organic matter, iron hydroxides and aluminium that stabilise soil structure in some dry and moist soils often dissolve or weaken under wet conditions reducing structural strength. Structural strength is further reduced by the lubricating nature of the water. Clay-rich soils, calcareous soils and soils rich in organic matter tend to have the strongest structural development and at near optimum moisture contents are least susceptible to structural damage. Silt particles are not as strongly attracted to each other as clay-sized particles and silty soils, therefore, are naturally weakly structured. They readily slake under heavy rain forming crusted (capped) surfaces and also readily smear when stocked in wet conditions.

Causes and consequences of compaction in grassland soils have been studied less than in arable soils. Most of the literature covering grassland compaction originates from New Zealand, Australia and the USA with very little direct investigation of grassland compaction in the UK. The existing literature suggests that the pressures most likely to lead to compaction of grasslands, in wetter temperate climate, are untimely agricultural traffic and stocking.

Compaction of grassland by farm vehicles

Agricultural machinery can lead to the compaction of both grazed and silage fields, causing compaction of both surface and subsurface soil. Machinery load, type and dimension of tyres, inflation pressure, vehicle speed, wheel slip and number of passes are all influential. Intensification of agriculture and the use of contractors have brought heavier machinery on to farms, with more than a doubling in wheel loads from the 1980s to 2000 (Van den Akker and Schjønning, 2004).

The wheel-load carrying capacity of subsoil is the maximum stress that can be exerted without exceeding soil strength. The carrying capacity is associated with the specific tyre dimensions and inflation pressure. A wider tyre and lower inflation pressure will result in less compaction for a given axle weight. Compaction of grassland soil can also be a cumulative process. The greater the number of times a location is driven over (trafficked) the more compact the soil beneath becomes. Vehicle intensity on grassland can be double that of arable trafficking (110 to 186 Mg km ha⁻¹ compared to 32 to 88 Mg km ha⁻¹; Douglas, 1994).

Compaction of grassland by livestock

In spring and autumn or on susceptible soils and during wet summers structural damage to the soil surface, termed poaching, can occur. Poaching is the penetration of the soil surface by the hooves of grazing animals, causing damage to the sward and deformation of the soil (Patto *et al.*, 1978). Trampling damage is mainly

restricted to shallow surface depths (0-10 cm; MAFF, 1970; Scholefield *et al.*, 1985; Greenwood *et al.*, 1997). On a weight per unit area basis the pressure caused by the hooves of a standing sheep is approximately 80 kPa, increasing to 200 kPa when the sheep is moving, while for cattle static pressure is 160-192 kPa and this pressure at least doubles when the animal is walking (Willatt and Puller, 1983; Scholefield and Hall, 1986). These pressures exerted by animal hooves compared to 60-80 kPa pressure exerted by an unloaded tractor (Blunden *et al.*, 1994).

Trampling damages the soil in two ways: firstly, at low to medium soil moisture contents, hooves cause compression of the soil; secondly, in a near saturated soil, plastic flow occurs around the hoof homogenising the soil (Scholefield *et al.*, 1985; Drewry, 2006). Poaching is a self-progressive process; the deformation of the soil surface reduces surface porosity, pore space connectivity and infiltration capacity leading to greater potential for surface ponding and increased risk of further poaching (MAFF, 1970; Mulholland and Fullen, 1991; Drewry *et al.*, 1999). Reduced pore space, in particular macropores (reported as either pores > 30 or > 60 µm nominal diameter) can reduce plant growth through restricted delivery of water, nutrients and oxygen (Gradwell, 1965; Cannell, 1977).

Stocking densities have been shown to have a positive relationship with soil compaction (Naeth *et al.*, 1990; Greenwood *et al.*, 1997; Daniel *et al.*, 2002). Daniel *et al.*, (2002) observed that long-term (10 years) livestock grazing increased soil compaction in the top 0-10 cm of soil. With low to high stocking densities (12.5, 25 and 50 cows/ha) all having measurable impact on soil compaction compared to ungrazed control plots, the significance increasing with stocking rate. Compaction damage due to trampling may also be cumulative with time (Kelly, 1985), although this may depend on soil texture (Van Havern, 1983).

Poaching can be widespread in a field under wet soil moisture conditions (Drewry, 2006). However, poaching can also occur in localised areas within a field such as around feeders, water troughs, shelterbelts, gateways and along regularly used tracks where trampling intensity increases (Heathwaite *et al.*, 1990; Cuttle *et al.*, 2006). Intense winter grazing has been reported to lead to increased surface damage (Drewry *et al.*, 1999) and there can be an increase in structural damage under grass due to winter grazing by sheep (Bradley *et al.*, 2000). However, extra grazing cycles in winter under dry conditions may not increase soil compaction (Kurz *et al.*, 2006).

Work package 2b: Impacts of soil compaction

Figure 2 illustrates the damage soil compaction has on the environment as a whole. The following sections will describes these impacts in more detail.

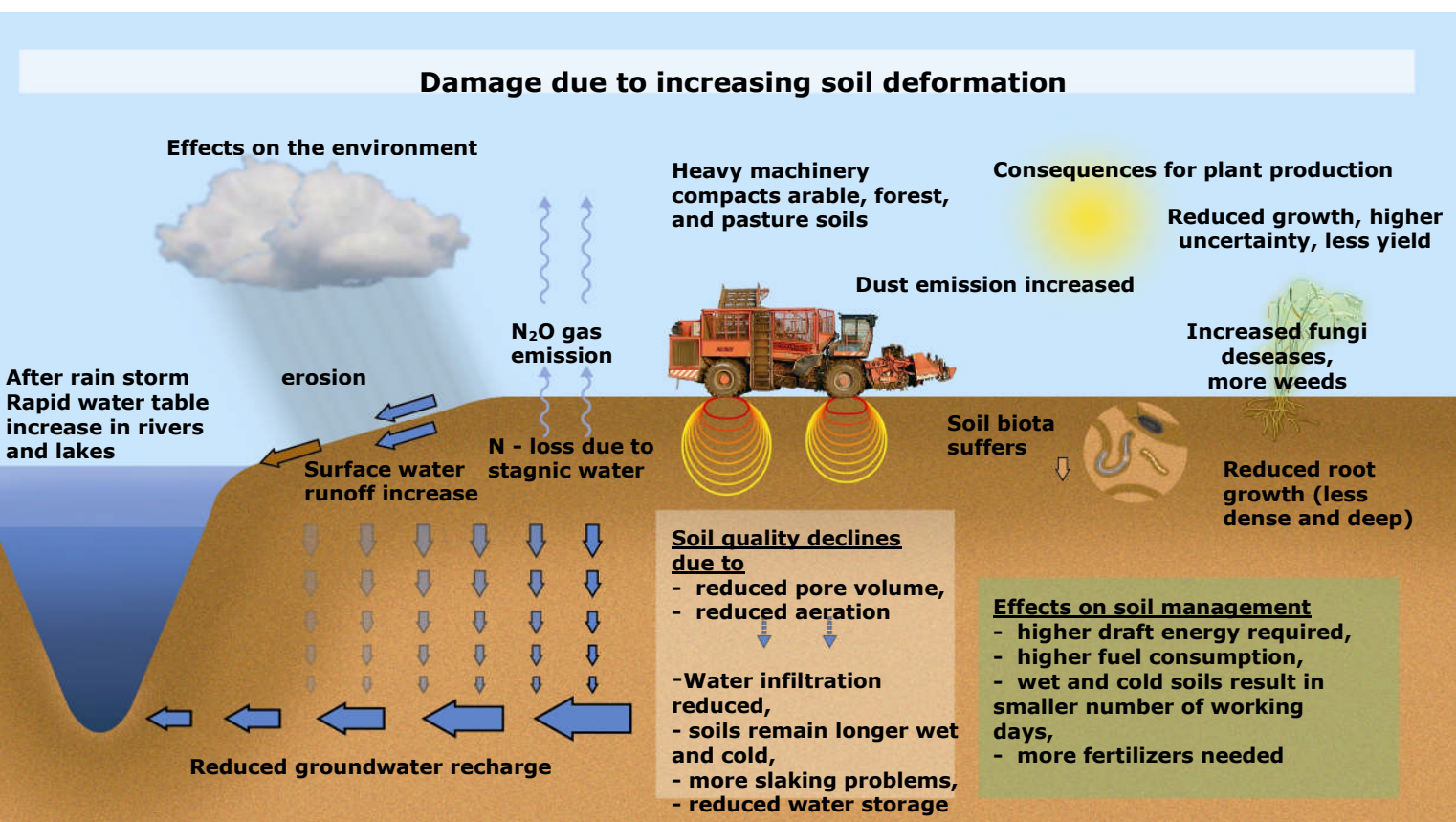


Figure 2. The impacts of soil compaction (taken from 'Trends in Land Degradation in Europe' presentation by L. Montanerella 2006)

1. The impact of soil compaction on soil flora and fauna

Simple measurement of a decrease in the overall porosity of the soil with a reduction in the number of larger pores may mask subtle but important changes in the nature of the pore network including the pore-size distribution and the connectivity and tortuosity of pores. Such factors will, impact on organisms in a variety of ways. The following is a brief summary of soil floral and faunal responses to compaction. See Appendix 3.1 for additional detail on individual studies.

Microflora

Changes in microbial community structure and function as a consequence of compaction would be expected, but due to the high levels of complexity (i.e. biodiversity) that prevail in most soils these are unlikely to be simple or consistent in nature. This is borne out by the extant literature where a wide range of biotic responses to compaction have been reported (Appendix 3.1; Table 5).

Microbes [prokaryotes, fungi]: Due to their small size, direct effects of soil compaction on micro-organisms are less likely than indirect effects. Even compacted soils have an extensive pore volume at microscopic scales, providing habitat space for micrometer-sized organisms such as bacteria, archaea and fungi. It is therefore unlikely a compaction event would result in compression-induced death in microbes. Fungal mycelia may be disrupted by such an event, but are well-adapted to regeneration, and are only likely to be impacted with repeated severe disturbance of the soil, for example via heavy tillage or poaching. Indirect effects such as changes in porosity and pore morphology are considered to have the greatest impact upon microbial function.

Effects of compaction on soil microbial communities have been studied most often in the context of forest and arable systems, with few studies specifically in relation to grasslands¹. Compaction in grasslands is often found to have no direct effect on a variety of microbial parameters, such as concentration of bacterial colony-forming units (Kohler *et al.*, 2005), bacterial growth rates (Kohler *et al.*, 2005), microbial biomass (Jensen *et al.*, 1999; Althoff & Thien 2005 but see Peacock *et al.*, 2001) and some biochemical properties of the soil that indicate microbial community structure (Amelung *et al.*, 2001).

Microfauna (see Appendix 3.1, Table 6)

Protozoa: Soil structural effects upon protozoa are thought to be mainly due to indirect mechanisms rather than direct impacts, although there is little research. The effect of a compaction event upon protozoan populations appears to be unknown, but with their small size, it is unlikely that all but the most extreme soil compression events would result in significant mortality.

Nematodes: Soil bulk density appears to affect different species of nematodes in different ways, dependent on their functional roles within the soil such as feeding guilds, i.e. microbivorous, fungivorous, omnivorous, predatory, animal-parasitic, entomopathogenic (Zunke & Perry, 1997). Compaction has no direct effect on the abundances of nematodes within arable soils, but will change the relative proportion of individuals or species within the aforementioned guilds (Bouwman & Arts, 2000) which is suggested to be due to a decrease in habitable pore space for bacterivores and an increased in feeding sites for herbivores, though no direct measure of food availability was made in this study. Nematodes are multi-cellular prokaryotes and show a greater range of body sizes compared to protozoa, with lengths from <0.5 up to c. 5 mm in soils. As such it may be expected that they would show more sensitivity to soil compaction, although this issue is rarely considered (c.f. Ritz & Trudgill, 1999).

Mesofauna (see Appendix 3.1, Table 7)

Collembola, mites and enchytraeids are the most abundant invertebrates found in grassland systems (Black *et al.*, 2002) and therefore are most pertinent when considering compaction impacts in grassland systems. Note that no information on the impacts of compaction were found for the Symphyla, Diplura and Protura.

Collembola: play an important role in plant litter decomposition processes and in forming soil microstructure. Collembola species vary considerably in their ecomorphological life forms and feeding guilds, with a range of functional roles in ecosystems (Rusek & Marshall, 2000). There has been little research completed in terms of soil compaction effects in grassland systems on collembola, with the majority of research done in arable systems assessing the effect of agricultural traffic and tillage practices on collembola abundance and diversity. In general, compaction effects due to tillage practice caused a reduction in total collembola abundance (Heisler & Kaiser, 1995; Schrader & Lingnau, 1997; Heisler *et al.*, 1998; Dittmer & Schrader, 2000) but species specific responses were more variable (Heisler, 1991; Larsen *et al.*, 2004).

Acari (mites): Mites represent a major arthropod group, often occurring in densities as high as 1×10^6 individuals m^{-2} (Rusek & Marshall, 2000) and are commonly the most abundant invertebrate taxa found in grassland ecosystems (Creamer *et al.*, 2005). There is inadequate data relating soil compaction studies (with bulk density data) to mite abundance or species richness in grassland systems.

¹ Web of Knowledge search [Jun 2007] using (microb* + soil + compaction) returns 123 outputs, and adding the further term 'grass*' returns 23 publications. Most of the latter do not involve studies where compaction is explicitly addressed.

Enchytraeidae (Potworms): Enchytraeids serve a similar ecological role to the earthworms. They are important in soil microstructure development and the incorporation of organic material into the soil (Didden, 1993; Marinissen & Didden, 1997). They tend to be dominant in acid soils where earthworms are infrequently found (Standen, 1980). Within arable systems soil compaction has been shown to significantly reduce numbers of Enchytraeids, and affect their vertical distribution and burrowing activity (Schrader *et al.*, 1997; Rohrig *et al.*, 1998; Langmaack *et al.*, 1999b).

Macro-invertebrates (see Appendix 3.1, Table 8)

Lumbricidae (Earthworms): Soil compaction generally has a negative impact on the Lumbricidae, with decreases of up to 86 per cent in earthworm density and biomass recorded in grassland systems (Pearce, 1984; Cluzeau *et al.*, 1992; Radford *et al.*, 2001; Althoff & Thien, 2005). However, susceptibility to the effects of compaction varies between the three main ecological types which results in changes in the composition of earthworm communities. The greatest impact is on the surface-dwelling, litter-feeding epigeic species (Pearce, 1984; Pizl, 1992). These species are particularly vulnerable to the direct effects of crushing, and the indirect effects of reduced vegetation cover, which increases exposure and degrades food resources (Aritajat, Madge & Gooderham, 1977; Cluzeau *et al.*, 1992; Radford *et al.*, 2001). The deep-burrowing, surface-feeding anecic earthworms, and the geophagous endogeics are less susceptible to crushing, but their fitness is reduced by the extra energy required to move through the compacted soil (Rushton, 1986; Kretzschmar, 1991; Söchtig & Larink, 1992). This limits the time available for activities such as feeding and reproduction (Söchtig & Larink 1992; Binet, Hallaire & Curim, 1997). Mean burrow length has been shown to decrease and burrow systems become fragmented (Rushton, 1986; Langmaack *et al.*, 1999a; Jegou *et al.*, 2002). This has implications for the many other organisms (including plant roots) that use earthworm burrows, as well as soil hydrology, gaseous exchange and nutrient cycling.

Coleoptera (Beetles): The extent of beetle utilisation of the soil environment varies with species and may also depend on developmental stage (Cooter, 1991). For most species utilising the soil compaction is likely to reduce movement within the soil of larval stages (Ellsbury *et al.*, 1994; Ellsbury, Exner & Cruse, 1999). This inhibition of free movement is also likely to affect the dung beetles (Scarabaeidae), potentially important drivers of soil processes in grasslands that influence the breaking down and reincorporation of above ground organic matter in the form of dung from domesticated animals (Strong, 1992; Finn & Gittings, 2003). The impact of soil compaction on beetles may also extend to species that do not directly utilise the soil during any stage of their life history. For example, the impact of soil compaction on above ground plant biomass could impact on some phytophagous beetles (Althoff & Thien, 2005).

Diptera (Flies): Where flies have larval stages present in the soil (McAlpine *et al.*, 1981-1989), compaction has been shown to reduce their movement within the soil, and as a result will also reduce pupation depths in some cases (Hennessey, 1994; Alyokhin *et al.*, 2001).

Lepidoptera (Butterflies and Moths): The use of the soil environment by the Lepidoptera is principally as a pupation site for larvae. There has been little research conducted on the direct effects of soil compaction on Lepidoptera. However, there is some evidence that soil compaction may reduce emergence rates of soil pupating larvae (Roach & Campbell, 1983).

Hymenoptera - Aculeates (Bees, wasps): Relatively little research to date has directly assessed the impacts of soil compaction on aculeate Hymenoptera.

Hymenoptera - Formicoidea (Ants): Ants contribute to the soil structure by redistributing soil mineral and organic matter during nest construction and food accumulation (Lobry de Bruyn & Conacher, 1990; Cammeraat *et al.*, 2002; Dostal *et al.*, 2005). The movement of soil can be considerable (King 1981) and as a result ant nests may impact on infiltration rates (Cammeraat *et al.*, 2002). There is evidence of the impact that soil compaction has on the distribution or abundance of ants.

Isopods and Myriapods (Woodlice, Millipedes and Centipedes): Woodlice may occur in large numbers in grassland ecosystems, and are important components of the detritivore system (Paoletti & Hassall 1999). Whilst there appears to have been no research into the impacts of soil compaction on isopods and myriapods in grassland systems, the diversity and abundance of woodlice has been shown to decrease under intensive grassland management (Paoletti & Hassall, 1999; Souty-Grosset *et al.*, 2005).

2. The impact of soil compaction on plant communities

The composition of grassland plant communities can respond markedly to soil compaction. Impacts of compaction can be mediated by the availability of water, nutrients and air to the roots, direct mechanical factors and the consequences of interspecific competition. These are summarised below: (See also Appendix 3.2)

Variation in species response

Within species-rich grassland, there is substantial variation in species' ability to grow on compacted soil (Godefroid & Koedam, 2004). This modifies plant community composition, with compacted soils tending to

support less diverse assemblages than those on better structured profiles (Roovers *et al.*, 2004; Moore and Gowing, 2007). Compacted soil affects the relative competitiveness of species both via the direct influence of soil strength restricting root growth and via the indirect effects of changed soil hydrology resulting from an altered pore-size distribution. The relative contributions and therefore importance of these factors in determining plant-community composition has not been researched. The impact of soil compaction on natural vegetation has been most widely considered in forestry systems (e.g. Kozłowski, 1999) and more widely considered with respect to amenity paths (Andres-Abellan *et al.*, 2005; Kutiel & Zhevelev, 2001; Adkison & Jackson, 1996; Cole, 1995; Sun & Walsh, 1998) and military training grounds (Althoff & Thien, 2005; Whitedcotton *et al.*, 2000) than with respect to semi-natural grasslands (Clary, 1995; Kaufman *et al.*, 2004). It is also noticeable that the research base in this area is rather sparser for the UK (e.g. Charman & Pollard, 1995; Hirst *et al.*, 2003) than for either North America (Adams & Atkhar, 1994; Beebe *et al.*, 2002; Clary, 1995; Kaufman *et al.*, 2004) or Continental Europe (Godefroid & Koedam, 2004; Roovers *et al.*, 2004; Andres-Abellan *et al.*, 2005.)

The best quantitative data found, which illustrates the variation in species' tolerance to soil compaction are from Luten and Roozeboom (1976; Figure 3), in which agronomic assessment of yield was undertaken. No record of an equivalent ecological experiment on experimentally manipulated soil was found though a recent article has recognised the importance of manipulating soil compaction as an ecological variable (Kyle *et al.*, 2007).

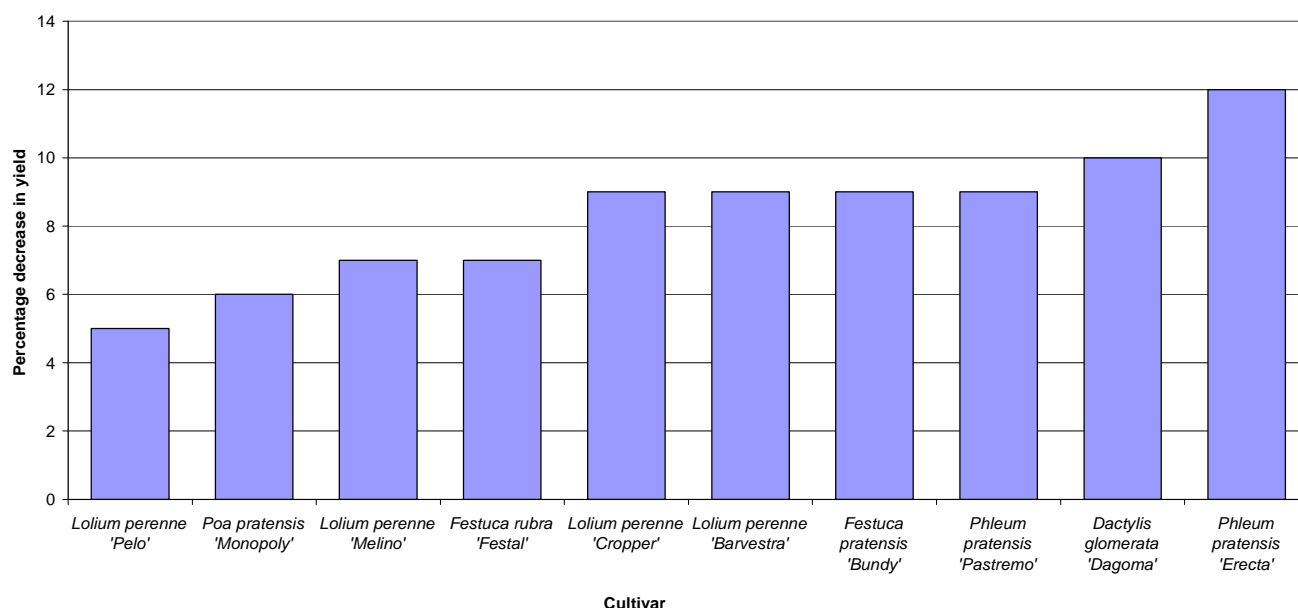


Figure 3. The loss of yield in 10 grass cultivars in response to increased soil compaction caused by experimentally-controlled trafficking.

Water regime

A database of the water-regime requirements of grassland plant communities (Gowing *et al.*, 2002) allows the impacts of soil compaction on the soil's water regime to be estimated and thence its effect on plant-community composition deduced. Such deduction has to assume that soil aeration is the major mediating factor (Adams & Akhar, 1994). As part of this project, a modelling approach was used to demonstrate the potential impact of soil compaction on plant community composition. A recorded water-regime in a soil of known pore-size distribution and from a site supporting a species-rich floodplain-meadow community was assessed in terms of its imposition of potential aeration stress on the vegetation (see Gowing *et al.*, 2002 for approach.) This assessment was performed both in the case of its current pore-size distribution and in the case of a modified distribution based on observed alterations to pore-size measured in response to a soil compaction episode (Whalley, 2007). The results revealed that as a result of compaction, the aeration stress would increase to such an extent that the soil would no longer be likely to support a species-rich community (on the basis of its observed water-regime requirements), but rather a species-poor inundation grassland instead. No evidence of experimental manipulation of soil compaction under grassland to observe such an alteration in water-regime and hence in vegetation composition could be found in the current literature, so this modelled prediction requires validation in the field.

Although water stress is the most intensively-researched physical stress to root growth, field data show that it may not always be the most critical stress. Various physical stresses may act in combination to limit root elongation. This problem has received more attention in the soil science literature than it has in the plant science community. Hypoxia, water stress and mechanical impedance to root growth will change with the water content of the soil and their relative importance will depend upon the degree of soil compaction.

Remediation

It is well-known that roots do change soil structure, either by the act of root penetration or by water extraction (and shrinkage), but there is insufficient data to generalize this understanding. Reports of soil bulk density being

reduced in response to increased root biomass do occur in the literature (e.g. Beebe *et al.*, 2002), but the subsequent effects on species composition are not documented.

Data, such as those illustrated in Figure 3 above, are not only important for predicting yield (Luten & Roozeboom, 1976; Whalley *et al.*, 2006) and competitive ability, but also for indicating which species are likely to be effective at ameliorating damaged or compacted soil (Whalley *et al.*, 1995). To date there has been very little systematic comparison of the ecological responses of different species to compacted soil, however, there is evidence that plants can be used to improve the structure of damaged soil (Douglas *et al.*, 1992). Recently, wax-layer root-penetration screens, developed for use on rice (Clark *et al.*, 2002), have been applied to species of pasture grass (Crush *et al.*, 2002). Unpublished data (BBSRC project BB/D010683/1; Figure 4) confirms the view that some grasses are much better at penetrating strong soil than others. To date, there has been little effort to exploit this variability to relieve compaction or to manage the landscape (Macleod *et al.*, in press), which is in part due to the need to improve our mechanistic understanding of how roots and soil interact with each other. Currently this understanding is limited to the root scale (a few millimetres) (Whalley *et al.*, 2004, 2005; Hallet *et al.*, 2002) and it needs to be extended to the catchment scale.

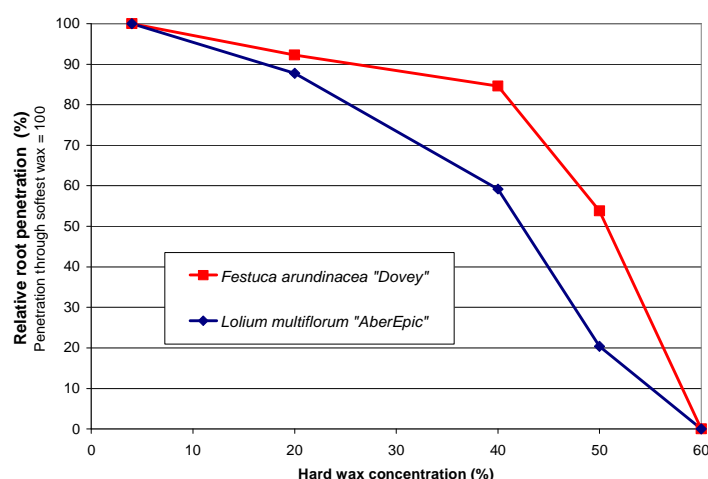


Figure 4. The ability of grass roots from two separate species to penetrate a wax layer of increasing hardness.

There is need to develop measurement approaches that give quantitative data on soil physical characteristics relevant to root growth and soil structure. In a recent review of progress (Clark *et al.*, 2005), it was concluded that technologies for measuring soil properties at the field scale were under-developed. While it is possible to measure localised soil conditions, such as penetrometer pressure and soil water status, which can then be related to root growth (Whalley *et al.*, 2007), there were fewer options for providing quantitative assessments of soil condition at the catchment scale. Methods to give a rapid and quantitative assessment of soil structure at the catchment scale would be a powerful tool in any attempt to use grasses to ameliorate damaged soil and manage soil physical properties. The extension of geophysical tools to landscape management is likely to be a productive route but is still in its infancy.

Indicator species

The use of ecological indicator species in grassland to assess soil compaction has been mooted (Bosch & Kellner, 1991), but it is likely to be a complex issue because the effect of soil compaction on plant competition can be mediated by a number of different factors (e.g. water availability, oxygen availability, concentration of toxins (e.g. Fe^{2+} , Mn^{2+}), soil resistance to root elongation.) Therefore it is unlikely to be possible to identify a single suite of species that are able to indicate degree of soil compaction in a way that is transferable between sites, even within a specified vegetation type such as grassland, because the soil structure and the local water regime will be strong modifying factors. The interaction between species' tolerance of soil compaction and their tolerance to trampling (Cole, 1995) also need to be resolved. Nevertheless, it is clear that some species increase their competitive advantage when soil is compacted (Godefroid & Koedam, 2004) and therefore an indicator score system may be worth further exploration.

3. The impact of soil compaction on birds

In the last 25-30 years, many farmland birds that were once common in Britain have exhibited widespread population declines and range contractions. Growing evidence links these declines to changes in farm management practices associated with agricultural intensification (e.g. Newton, 2004). The management and productivity of lowland grassland has been transformed during the last 50 years and these changes have undoubtedly played an important role in farmland bird declines (Vickery *et al.*, 2001), but the mechanisms are poorly known. Although soil compaction may be a consequence of several changes in management, the impact of soil compaction on birds is poorly understood.

Three criteria were used to assess the level of the potential risk of compaction to grassland bird species: (i) impact of compaction on (a) the abundance and (b) the accessibility of invertebrate prey, (ii) existing evidence that food abundance/accessibility limits productivity, survival and/or distribution (iii) conservation status. Thus a species considered to be at greatest potential risk would be one for which compaction reduces the abundance and accessibility of important prey items, food shortage has been shown to limit productivity, survival or distribution and it is considered of high conservation concern (e.g. due to population decline). Detailed consideration of all these four criteria are presented in Appendix 3.3. Here we present the key findings for the most vulnerable group of widespread grassland species – namely those that feed to a large extent on below ground invertebrates.

The summary presented in Table 2 suggests that a number of species are potentially at relatively high risk from soil compaction. Thrush species feed extensively on earthworms and Tipulid larvae. The abundance and accessibility of these invertebrates is a key determinant of foraging distribution and productivity in farmland and the invertebrates will be negatively affected by soil compaction. Song Thrush and Starling may be particularly vulnerable species among this group. Many declining species of wader show a heavy reliance on soil dwelling invertebrates. The distribution and accessibility (determined by soil penetrability) of prey determines the suitability of grassland as foraging habitat and influences the distribution of waders between and within habitats. Many of these species are of high conservation concern due to declining populations and should be considered at relatively high risk in terms of potential negative impact of compaction.

The risk of soil compaction impacting on birds depends not only on the impact *per se* but on the likelihood of exposure to that impact. A key initial step to assessing exposure is to examine the broad scale relationships between bird distributions and abundance and degree of compaction risk. This was carried out for five bird species identified as 'at risk' in the above section and representing the range of foraging techniques typical of the 'at risk' species in grassland: Song Thrush, Blackbird Starling, Lapwing and Rook (for full details see Appendix 3.3). Data on the distribution and abundance of birds were used for 1,279 grassland Breeding Bird Survey (BBS) in England and Wales 1-km squares for which there is information on the risk of compaction. The results suggest a broadly consistent pattern across these five species. About 55% of BBS squares reporting each of the five species occurred on medium risk grassland squares. A further 15-18% of BBS squares reporting each of the five species were on high risk grassland 1-km squares.

Table 2. Potential risk of compaction on grassland bird species in relation to conservation status, impact of compaction on prey abundance and evidence of food limitation on demography or distribution. Species for which potential risk is greatest are highlighted.

| Species | | Conservation status | Reduced abundance of important prey | Evidence of food limitation |
|--------------|----------------------------|---------------------|-------------------------------------|-----------------------------|
| Starling | <i>Sturnus vulgaris</i> | Red, FaBI | Yes | Yes |
| Song Thrush | <i>Turdus philomelos</i> | Red, BAP | Yes | Yes |
| Blackbird | <i>Turdus merula</i> | Green | Yes | Yes |
| Rook | <i>Corvus frugilegus</i> | Green, FaBI | Yes | Yes |
| Jackdaw | <i>Corvus monedula</i> | Green, FaBI | No | |
| Carrion Crow | <i>Corvus corone</i> | Green | No | |
| Snipe | <i>Gallinago gallinago</i> | Amber | Yes | Yes |
| Lapwing | <i>Vanellus vanellus</i> | Amber, FaBI | Yes | Yes |
| Redshank | <i>Tringa tetanus</i> | Amber | Yes | Yes |

Conservation Status: Red, Amber, Green refers to the listing under Birds of Conservation Concern (The State of the UK's Birds 2005), BAP refers to a species for which a Biodiversity Action Plan has been developed (Anon 1995) FaBI refers to birds included in the Farmland Bird Index (Vickery *et al.*, 2004). Reduced abundance of important invertebrate prey: 'Yes' indicates that prey recorded as being important in the diet (rather than just present) are likely to be reduced in abundance by compaction. Evidence of food limitation: 'Yes' indicates that published evidence exists indicating that demography or distribution is limited by food availability. See also Appendix 3.3.

National data on bird abundance (2003-2006) and population trends (1994-2006) was used to investigate whether there is any relationship between these variables and compaction risk (Table 3). There is evidence of lower abundance of Song Thrush, Blackbird, Rook and Starlings on 1-km squares where the risk of compaction is higher, although the differences were only significant for Blackbird and Rook. No clear relationship between Lapwing abundance and compaction risk was found. In the case of population trends, the decline of Starlings was significantly greater on sites where there was a higher risk of compaction (an approximate 10 per cent decrease in growth rate compared to the growth rate where compaction risk is low). During the same period Song Thrush and Lapwing both increased to a greater degree on sites where compaction risk was higher and there were no consistent patterns for the remaining species. Differences in soil type such as between well and poorly drained soils that are coincident with patterns of compaction risk may explain some of these results.

It is important to note that these findings are only correlations and must be interpreted in relation to longer-term population trends of these species. The BBS has been in operation for a relatively short time period over which to examine population change. We know for example that Starling has shown continued decline since the mid-1960's to the present including the period covered by the BBS, whilst for Song Thrush the BBS period represents a period of slow population growth following large declines during the 1970's and 80's.

Table 3. Occurrence of birds in 1km squares with high risk of compaction and patterns of abundance (2003-06) and population trend (1994-2006) in relation to compaction risk

| Species | | % occupied BBS squares in high risk areas | Abundance and increasing compaction | Population trend and increasing abundance |
|-------------|--------------------------|---|-------------------------------------|---|
| Starling | <i>Sturnus vulgaris</i> | 15.8 | -ve (ns) | -ve *** |
| Song Thrush | <i>Turdus philomelos</i> | 13.7 | -ve (ns) | +ve * |
| Blackbird | <i>Turdus merula</i> | 16.2 | -ve *** | = |
| Rook | <i>Corvus frugilegus</i> | 15.2 | -ve *** | =a |
| Lapwing | <i>Vanellus vanellus</i> | 18.8 | = | +ve (ns) |

% occupied BBS squares: raw counts of BBS squares reporting the species in each 'compaction risk' category.

Abundance/population trend and increasing compaction: --ve = abundance/population growth declines with increasing compaction risk, * $p < 0.05$, *** $p < 0.0001$. a Rook shows higher population growth at high risk 1km squares but lower at medium risk (relative to low risk squares)

Therefore, based on foraging ecology and conservation status, five grassland bird species are considered to be at potentially greatest risk from soil compaction: Song Thrush, Starling, Lapwing, Snipe and Redshank. Two common and stable or increasing species are also potentially at risk Rook and Blackbird. Many of these species feed on below ground invertebrates, the numbers and accessibility of which will be reduced by compaction. The distribution of 5 species (Song Thrush, Lapwing, Rook, Starling and Blackbird) was examined in relation to soil compaction. In each case 15-19 per cent of 1km squares where these species occurred were classified as high compaction risk. Four species showed decreasing abundance with increasing compaction risk (two significantly) and one species, Starling, showed significantly greater population declines in high risk compared with low risk areas.

4. The impact of soil compaction on water resources and flood risk

Further details are given in Appendix 3.4

Soil compaction and infiltration

Livestock exert a significant pressure on soil. Under the shallow water tables common in many upland or poorly drained soils under grassland, compaction by livestock is likely. The problem is compounded by the fact that many of our grass growing regions are in areas of high rainfall, and economic pressures have extended the grazing season which leads to greater poaching and sealing of the soil. Fieldwork in the Yorkshire Ouse, Severn, Uck and Bourne catchments following the severe flooding of that autumn of 2000/01, showed significant proportions of grassland soils having soil structural degradation (Holman *et al.*, 2003). In many cases, this was manifest in extensively poached soil surfaces and topsoil compaction leading to extensive areas of standing water and marked vertical wetness gradients. However, in some ley grassland sites, soil degradation was sufficient to cause extensive rill erosion.

Early work by Holtan and Kirkpatrick (1950) clearly showed the effect of land cover and management on soil infiltration rates (Figure 5). In general, grassland soils and in particular those under long established permanent pasture have a higher infiltration rate than arable soils - especially during periods of the year when the latter are bare or crusted (Holtan and Kirkpatrick, 1950). Experimentation by Heathwaite *et al.*, (1990) with a rainfall simulator and runoff plot monitoring in the Slapton Catchment in South Devon showed that heavy grazing of permanent grassland resulted in an 80 per cent reduction in infiltration capacity. Clark (1997) showed significant differences between the saturated hydraulic conductivity of topsoils under grassland and woodland in the Upper Brue catchment, Somerset (Figure 6). Similar results are reported in Clark (1987) and Clark (2005).

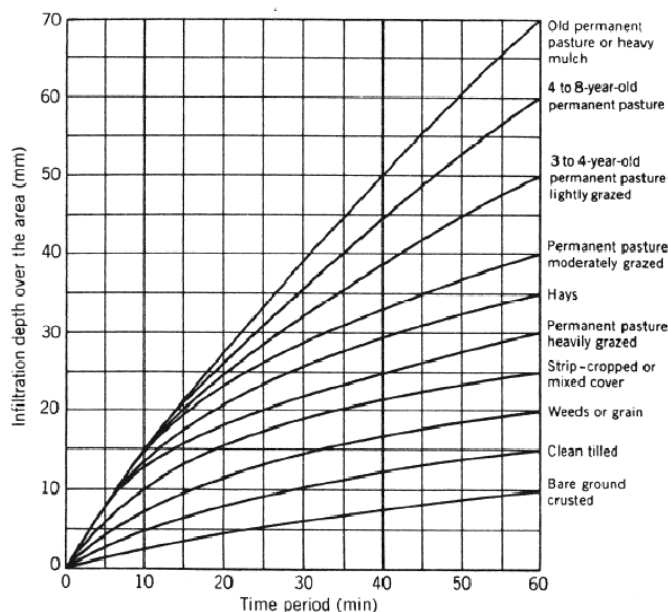


Figure 5 Typical mass infiltration curve (from Holtan and Kirkpatrick, 1950)

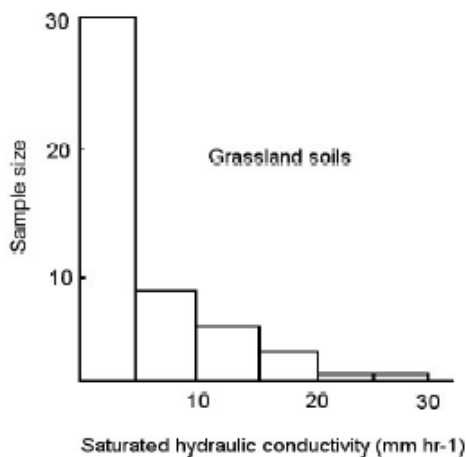
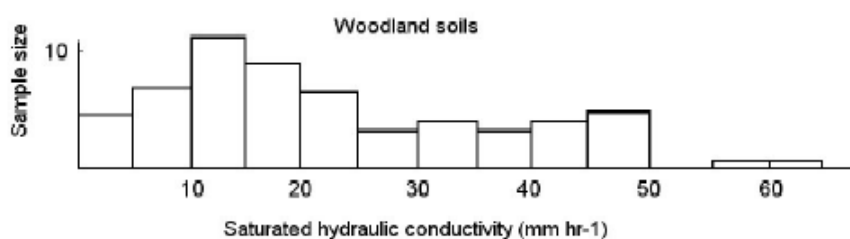


Figure 6 Saturated hydraulic conductivity of grassland and woodland soils in the Upper Brue catchment (from Clark, 1997)



Runoff generation

Measurements by Heathwaite *et al.* (1989) showed that surface runoff from heavily grazed permanent pasture in Devon was 53 per cent of total rainfall compared to 7 per cent from ungrazed land. Poaching or severe trampling of grassland around feeding troughs and in gateways are point sources of surface runoff. Poaching by livestock promotes the occurrence of overland flow in some circumstances in the view of Leinweber *et al.* (2002). Heathwaite *et al.* (1990), using a rainfall simulator and runoff plot monitoring in the Slapton catchment in South Devon, showed that surface runoff from overgrazed permanent grassland was double that from lightly grazed areas, and at least twelve times that from ungrazed areas.

Samson (1996) suggests that "sheep may be causing enough loss of vegetative cover and serious poaching of the soil surface to lead to increased runoff rates and thus to an increase in the likelihood of serious floods". The analysis presented by Samson (1996) makes a reasonable case for stocking densities of sheep to have an effect on flood runoff production but is not backed up by a quantitative analysis (O'Connell *et al.*, 2004).

Indicative assessment of hydrological Impact of grassland soil compaction

Two methods have been previously used to provide preliminary quantification of the hydrological effects of agricultural land management in the UK. The Curve Number method has been used by Godwin and Dresser (2003) and Holman *et al.* (2003), and the Hydrology of Soil Types (HOST) by Packman *et al.* (2004). Packman *et al.* (2004) proposed revised Standard Percentage Runoff (SPR) values for each HOST class by assigning an appropriate analogue HOST class to represent the degraded soil. The rationale for the proposed changes is that soil structural degradation, in the form of topsoil and upper subsoil compaction or seasonal 'capping' and sealing of soil surfaces, causes a reduction in the effective soil storage, which in turn results in increased surface runoff. Increased surface runoff on a specific HOST class will give an increased SPR value, assuming that there is no change in the proportion of the surface runoff that is transferred from the fields to the surface water network i.e. that the effects of landscape connectivity remain unchanged.

An indicative assessment of the potential hydrological impact of grassland soil compaction has been carried out using a modification of Packman *et al.* (2004). Packman *et al.* (2004) suggests that the degraded SPR values are applied to all of a catchment's area under cereal and lowland grass cover. Rather than assume a 'worst-case' scenario in which all grassland soils are degraded, a revised catchment-average SPR has been calculated, assuming that (1) all non-grassland areas and grassland in Poaching Risk class 1 have a 'normal' SPR as given in Boorman *et al.* (1995), according to the HOST Class; (2) all grassland of Poaching Risk class 3 have a 'degraded' SPR given by their analogue HOST class in Packman *et al.* (2004) owing to their high risk to compaction due to high livestock numbers and vulnerable soils and (3) all grassland of Poaching Risk class 2 have been allocated a SPR which is midway between those given in Boorman *et al.* (1995) and Packman *et al.* (2004). A similar indicative assessment has been made on the potential impacts on groundwater water resources through using the Base Flow Index (BFI), the second key hydrologic parameter provided by the HOST class (Figure 7).

Figure 7 shows that the indicative absolute increase in SPR is less than 6 per cent with the area of generally greatest increases being in the south west. Figure 5 shows that the largest increases in SPR are generally found in the catchments with SPR's according to Boorman *et al.* (1995) of 25 – 45 per cent. Catchments with low SPR's (i.e. less than 25%) are generally found in chalk, sandstone and limestone landscapes, where the well drained soils, relatively dry climate and arable dominated farming systems limit the potential for compaction of grassland soils. The catchments with the highest SPR's in Fig. 5 which show little impact from grassland soil compaction represent upland catchments with little managed grassland due to wet soil conditions.

The small absolute increases in SPR represents relative increases of less than 13 per cent in most catchments, although a number (mostly in the south west) show indicative increases of 13 - 41 per cent (Figure 7). However, the relative increases in SPR are much lower than those reported in plot studies (e.g. Heathwaite *et al.*, 1989, 1990) representing the moderating effects of landscape connectivity. As would be expected, the spatial patterns in the change in Base Flow Index (Figure 7) is similar to that for SPR, as increased runoff to surface water is reflected in reduced infiltration and recharge. Indicative changes in catchment BFI are less than 8 %, which represents a small reduction in groundwater resources and summer surface flows but which may be significant in catchments with limited water availability.

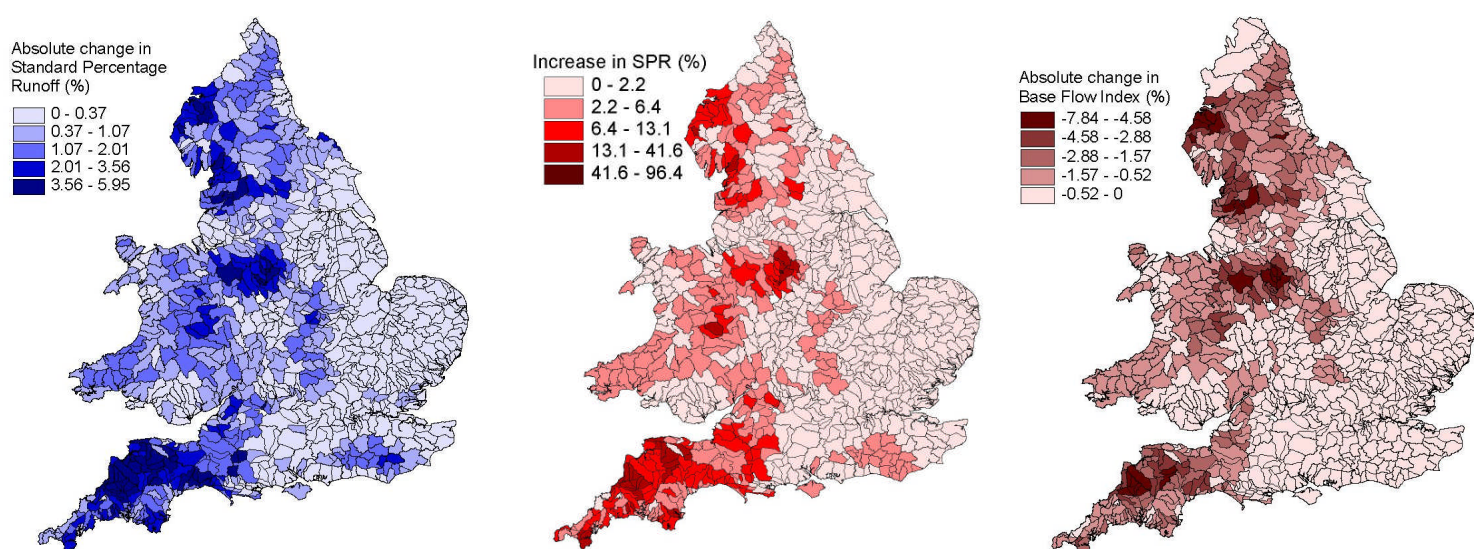


Figure 7 Effects of grassland soil compaction on runoff and water resources – (left) indicative absolute increase in Standard Percentage Runoff (SPR); (centre) relative increase in SPR and (right) absolute decrease in Base Flow Index

5. The impact of soil compaction on diffuse pollution of water, soil erosion and associated nutrient losses

Background

Changes in soil hydrology due to compaction increase the risk of soil erosion, movement of nutrients and carbon, and propensity to flooding on susceptible soils (see Water resources and flood risk section of this report, Eckelmann *et al.*, 2006). On-site impacts of these processes include immediate adverse effects on crop productivity and a deterioration of soil health indicators, such as soil organic carbon content and soil biota. Reversing these degradation processes is extremely challenging, and virtually impossible in the short term. Off-site, water resources are at greater risk of diffuse pollution, with detrimental effects on aquatic flora and fauna. Financial costs associated with soil erosion alone are estimated at £205 million (EA, 2002; Table 16, Appendix 3.5).

Changes in soil porosity due to compaction will change soil hydrology at both local and catchment scales. Degraded soil structural conditions caused by compaction will lead to increased field-scale runoff (O'Connell *et al.*, 2004). In particular, compaction reduces soil porosity, as a result of re-arrangement of soil particles and aggregates, and increased bulk density. Infiltration capacity and rate are reduced, so hindering the ingress of rainfall into the soil, causing the generation of overland flow. This surface runoff is able to entrain, transport/mobilise and deposit diverse pollutants (such as sediment, agrochemicals, nutrients, heavy metals and pathogens) from many diffuse origins in grassland landscapes (Table 17, Appendix 3.5). In any one area, the load and concentration of pollutants may be small, but collectively, over a catchment, their impacts can be damaging.

Diffuse pollutants in runoff may be in soluble and particulate form. For soluble pollutants, the degree of mobilisation from the soil into runoff is related to the differential in pollutant concentrations between the soil-water and that in the overland flow running over the soil surface (Miller, 2004). Particulate pollutants are adsorbed onto the surface of individual soil particles and aggregates, especially colloids and fine particles as these have large specific surface areas, and higher adsorption capacities (Newman *et al.*, 1994; Beckett & Chittleborough, 1994). Pollutants are mobilised when these particles/aggregates are eroded (detached, entrained and transported) by surface and sub-surface hydrological processes, such as rain splash impact, subsurface flow (both horizontal and vertical), and overland flow. Thus where farming practices generate soil erosion, detachment of sediment-associated P at the soil surface is encouraged (Kronvang, 1990; Chambers *et al.*, 2000).

The energy of the rain drop impacting the soil and the shear velocity of the overland flow will determine the amount of detachment, entrainment and transport of sediment-adsorbed pollutants. The velocity of the flow and calibre of the sediment will also determine at what point deposition of soil/sediment (and associated pollutants) will take place (Hjulstrom, 1935). However, Krueger *et al.* (2007) point out that our perceptual understanding of phosphorus, sediment and colloid transfers from intensive grasslands is far from perfect (Bilotta *et al.*, 2007; Gimbert *et al.*, 2007; Granger *et al.*, 2007; Haygarth *et al.*, 2006).

When the pollutants reach water bodies, the consequences include:

- groundwater and surface water contamination and degradation, and the subsequent need for treatment of drinking water resources
- microbiological contamination of water supplies
- smothering of fish spawning gravels
- nutrient enrichment leading to oxygen depletion and eutrophication
- toxicity to plant and animal life, including endocrine disruption in fish.

If the pollutants are re-deposited on land further down slope, this can cause soil contamination, with subsequent damage to the environment, such as damage to crops and habitats. There may be enrichment of pollutants at these sites of deposition as sediment originating from a larger area is concentrated at the point of deposition.

The following section reviews the relationships between soil compaction and different diffuse pollutants.

Sediment

The relationship between soil compaction and sediment production is complex. It is expected that the higher runoff volumes associated with compacted soils (see Water resources and flood risk section of this report) will lead to higher rates of soil erosion. However, this may be off-set by the fact that compacted soils have a higher bulk density, which in turn is associated with a higher shear strength (Zhang *et al.*, 2001), making the soil less erodible / more resistant to the shearing forces of raindrop impact and overland flow (Cruse and Larsen, 1977). Also, there is a stronger relationship between soil erosion rates and runoff velocity (rather than volume) (Morgan, 2005).

Changes in soil properties caused by cattle treading on grassland soils can increase the susceptibility of soil to erosion processes, and thus transport of associated pollutants. First, the loss of sediment (and particulate P) has been shown to be related to the reduction in macroporosity caused by compaction (McDowell *et al.*, 2003). Also,

cattle movements break up soil aggregation and structure, and damage vegetation, so reducing effective soil cover and root density which would otherwise help reduce erosion rates (McDowell *et al.*, 2003). Thus erosion rates can be related to the degree of treading and associated compaction.

Soil erosion models can be used to estimate the amount of soil loss in runoff. These include WEPP (based on the hydrological model CREAMS - Ascough *et al.*, 1997; Rudra *et al.*, 1985), EUROSEM (based on the hydrological model KINEROS - Kalin & Hantush, 2006; Mati *et al.*, 2006) and the Morgan, Morgan and Finney model (Morgan, 2001). However, these models were not developed specifically for compacted soils, although they do allow for variable input data relating to soil compaction / bulk density, mainly because they recognise the effect of bulk density on runoff generation. Another limitation of these models is that although they may be reliable predictors of total sediment load and/or concentration for any given runoff event, modelling the dynamics of pollutant adsorption onto sediment and thus mobilisation by sediment is still poorly understood (Miller, 2004). There have been attempts to quantify the relative contribution of different particle size fractions in transporting P in agricultural runoff from grassland soils (Heathwaite *et al.*, 2005).

Agrochemicals (pesticides, herbicides)

The risk of mobilisation by runoff is greatest following application of agrochemicals, especially when application rates are excessive, or the application coincides with high rainfall events. If agrochemicals are mobilised in the runoff, a) they are removed from the intended target, representing a waste of agricultural inputs (incurring costs to the farmer) and b) they present an environmental threat to downstream ecosystems.

Nutrients (including nitrogen, phosphorus, potassium)

The risk of mobilisation by runoff is greatest when nutrient loadings on the land are high. This may be due to excessive application rates of fertilisers, manures and animal feeds, and/or high density of livestock (often related to the pastoral system – whether it be enclosed permanent grassland, ley grassland or grazing on forage crops). Haygarth *et al.* (1998b) estimated that for phosphorus alone, unless the import of P to agricultural land is modified, the soil P reservoir may double in the next 30 years. This build up of soil P increases the potential for off-site movement of P, because the solubilisation of P from soil surfaces and soil biota into soil water increases with increasing soil P (Heckrath *et al.*, 1995). The risk of nutrient mobilisation is dependent on soil type and hydrology, and is increased when high nutrient loadings coincide with significant rainfall events. If the nutrients within fertilisers are mobilised in the runoff, a) they are removed from the intended target, representing a waste of agricultural inputs (incurring costs to the farmer) and b) they present an environmental threat to downstream ecosystems.

The degree of nutrient losses depends on the farming system deployed. For example, fattening pigs on pasture carries a high risk of nutrient loss, so it might be that the most environmentally acceptable way of keeping them on pasture involves a combination of reduced dietary N intake, reduced stocking rate and seasonal rather than round the year production (Eriksen *et al.*, 2006). The literature demonstrates that changing land management practices on grassland (such as converting rough grazing to fertilised temporary and permanent pastures) can increase the risk of nutrient losses in runoff and soil loss (Johnes *et al.*, 1996). These effects are compounded by an associated increase in stocking rates of cattle and sheep, which can increase the amount of nutrients exported from a catchment.

Haygarth and Jarvis (1999) outline three ways in which P is mobilised – via solubilisation, physical detachment (on soil particles moved via the process of soil erosion) or direct transfer of recent P amendments ('incidental transfer'). The actual processes of phosphorus transfer from diffuse agricultural sources is complex (Krueger *et al.*, 2007) not least because particulate P transport varies with the calibre of sediment removed during erosion processes (Heathwaite *et al.*, 2005). Also, the ability of a soil to retain or release P is related to soil processes such as microbially mediated mineralisation or immobilisation, and chemically controlled sorption-desorption and precipitation reactions (Heathwaite *et al.*, 2005). Livestock wastes (such as dairy, swine or poultry manure and dairy slurry) are a major source of diffuse P reaching surface waters (Haygarth *et al.*, 1998). For the UK, estimates of annual P transfer rates from grassland soils are of the order of 2-3 kg P ha⁻¹ (Haygarth and Jarvis, 1997; Haygarth *et al.*, 1998). Preedy *et al.* (2001) showed that losses of this magnitude can occur within a few hours where heavy rainfall follows application of manures or inorganic fertilisers on grasslands.

Pathogens

Grasslands, loaded with livestock waste may present a potential surface store of microbial pathogens. Oliver *et al.* (2005) consider the contamination of surface waters by the pathogenic microorganisms found in livestock wastes, including bacteria, viruses and protozoa. This is recognised as an area of growing importance in the context of diffuse agricultural pollution. In their review, Oliver *et al.* (2005) found that runoff from grassland systems may be a particularly important hydrological pathway for the transfer of these pathogens in the environment. Assuming they survive long enough to be transported to first order streams, these pathogens may impact the quality and ecological balance of watercourse, and cause significant health problems to water users. As demonstrated in the previous sections, compacted soils are likely to generate greater volumes of runoff, along with any associated pathogens. Mawdsley *et al.* (1996) suggested that on impermeable heavy clay soils, a

greater proportion of pathogens would be lost in surface runoff than for a more permeable soil. This could be interpreted as an analogy for compacted and non-compacted soils respectively.

Considering grassland soils, Oliver *et al.* (2005) do acknowledge that as well as surface pathways, pathogens may be transported by subsurface transfer routes in highly permeable soils (i.e. non-compacted soils) and soils with field drainage. The degree and speed of transfer through the soil profile is influenced by a) soil properties (including those affected by compaction, such as pore size and distribution (Young & Ritz, 2000), soil moisture content and hydraulic conductivity) and b) the size, persistence and motility of the microorganisms present.

Oliver *et al.* (2005) make no direct comment on compacted soils and admit that “we have no proof that overland flow, once started actually delivers materials to streams and primary water systems”. Research gaps are identified, including uncertainties of the hydrological connections between the source of pathogens (surface applied wastes) and aquatic receptors. Gaining understanding of these processes is hindered by the heterogeneity and hydrological complexity of agricultural catchments. The role of hydrology (both surface and/or subsurface pathways) is highlighted as “the key component in governing pathogen emergence in receiving waters”. As seen in sections above, compaction has a direct influence on these hydrological processes.

6. The impact of soil compaction on diffuse pollution of air

Soil compaction in grasslands can result in changes in the exchange of trace gases between the soil and the atmosphere. In general, compaction results in decreased grass yield, increased denitrification, increased emissions of nitrous oxide (N₂O) and ammonia (NH₃), decreased uptake (oxidation) of methane (CH₄) (and occasionally net emission of CH₄), decreased emission of NO_x and reduced respiration and emission of carbon dioxide (CO₂). However, it should be noted that the processes responsible for trace gas exchange are often characterised by high spatial and temporal variability. In grazed grasslands, the influence of compaction is compounded by the important influence of dung and urine deposition by animals. To date, there appears to have been little or no attempt to estimate the implications of changes in compaction for gas exchanges at the landscape scale. In the context of increased concerns over the potential global impact of greenhouse gas emissions, there is an urgent need to quantify all significant sources and sinks. Such an exercise is beyond the scope of this document but should be considered as a longer-term topic for investigation.

A schematic summary of the direction and approximate magnitude of changes which have been observed in trace gas fluxes as a consequence of grassland soil compaction is illustrated in Figure 8. A summary containing some relevant data from different studies can be found in Table 4. A more complete review can be found in Appendix 3.6.

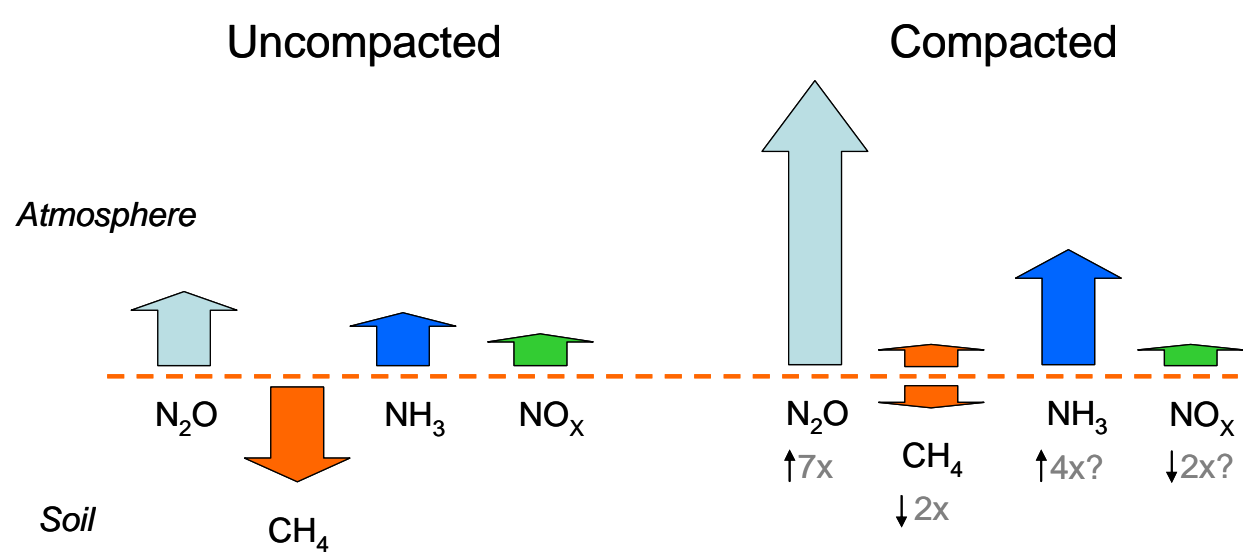


Figure 8. Schematic summary of the direction and approximate magnitude of changes which have been observed in trace gas fluxes under grassland soil compaction.

Note that arrows are not drawn to scale and are illustrative only, and also that the processes represented are highly variable, both spatially and temporally – such that the actual result of compaction will be site specific and dependent on transient conditions such as moisture content and the timing and magnitude of fertiliser inputs. In the case of CH₄, the direction of the flux is generally from the atmosphere to the soil.

Table 4. Summary of selected studies with relevant data comparing gas fluxes in compacted and non compacted soils. Note that the units vary between studies.

| Type | Uncompacted | Compacted | Units | Reference |
|---|-------------|-----------|---|------------------------------------|
| N₂O | | | | |
| <i>Grazed</i> | 153 ± 9 | 557 ± 107 | g N ha ⁻¹ d ⁻¹ | Clayton <i>et al.</i> (1994) |
| <i>Experimental</i> | 1.55 % | 2.92 % | % of urine applied | van Groenigen <i>et al.</i> (2005) |
| <i>Urine only vs Urine + compaction</i> | 0.83 % | 6.86 % | % applied @ 119 mg N kg ⁻¹ | van Groenigen <i>et al.</i> (2005) |
| | 0.72 % | 5.48 % | % applied @ 237 mg N kg ⁻¹ | van Groenigen <i>et al.</i> (2005) |
| | 1.13 % | 5.73 % | % applied @ 474 mg N kg ⁻¹ | van Groenigen <i>et al.</i> (2005) |
| | 1 % | 1.7 % | % applied @ 949 mg N kg ⁻¹ | van Groenigen <i>et al.</i> (2005) |
| <i>Various treatments on ungrazed grassland</i> | | 4.4 x | | Yamulki and Jarvis (2004) |
| <i>Vehicle compaction</i> | 1.12-4.37 | 2.62-61.7 | kg N ha ⁻¹ over 3 months | Bhandral <i>et al.</i> (2007) |
| <i>Cattle over-wintering area</i> | 39 | 241.4 | Average µg N ₂ O-N m ⁻² h ⁻¹ | Hynst <i>et al.</i> (2007) |
| NO | | | | |
| <i>Grazed</i> | 5.8 | 9.1 | ng N m ⁻² s ⁻¹ | Walker <i>et al.</i> (2002) |
| CH₄ | | | | |
| <i>Arable rotation rich in ley/legumes</i> | -9.7 | -4.85 | mg CH ₄ m ⁻² | Hansen <i>et al.</i> (1992) |
| <i>Various treatments on ungrazed grassland</i> | 29.8 | 132.2 | g C ha ⁻¹ d ⁻¹ | Yamulki and Jarvis (2004) |
| NH₃ | | | | |
| <i>Grazed</i> | 2 | 4.3 | ng N m ⁻² s ⁻¹ | Walker <i>et al.</i> (2002) |
| CO₂ | | | | |
| <i>Potato field</i> | 0.24 | 0.15 | G CO ₂ -C m ⁻² d ⁻¹ | Ruser <i>et al.</i> (2006) |

Work package 3: Potential remediation measures for use in Defra's Environmental Stewardship Scheme.

The following suggestions provide potential measures that could be used within existing ES schemes in England and Wales for remediating soil compaction.

- **Match machine operations to the nature and condition of the soil:** This is a major management tool for preventing soil compaction and reducing unnecessary traffic especially on wet soils, for example, by using umbilical systems to spread slurry in spring (Van den Akker & Schjønning, 2004).
- **Adjust tyres, inflation pressures and loads:** Soil stresses in the subsoil can be decreased by decreasing tyre inflation pressures, wheel loads and rut depths and by using wider, larger and more flexible tyres. For sustainable soil management only field traffic with wheel loads lower than the carrying capacity of the subsoil can be allowed (Van den Akker & Schjønning, 2004)
- **Loosening of soil:** Moderate compaction of surface layers may be eliminated by shallow loosening of the soil when the soil is dry enough. More severe cases may require ploughing and re-seeding. The use of slotting to improve grassland soil conditions and yield on shallow soil compaction has been shown to work well by Davies *et al.* (1989). However, Douglas *et al.* (1995) suggest that slotting may be less effective on grassland where compaction extends throughout the depth of the topsoil.
- **Guidelines to prevent compaction occurring:** It is difficult to generalise about dates for operations or specific stocking rates, therefore, the best approach to guidance should be similar to "if the tractor wheel or hoof sinks by more than x cm on average, then stop the operation" – such guidelines would obviously need a period of development, but the principle of leaving an informed decision to the operator rather than trying to set a list of general prescriptions is likely to be the best approach. An example of this is that schemes currently require some operations such as hay making to be conducted each year for a certain level of grazing. However in a year like 2007, the manager should have the option not to follow the prescription on the basis of potential damage to soil, without risking a penalty.
- **Maintenance of good surface drainage:** One of the most effective measures to increase soil strength is by improving drainage. Improving soil drainage will both reduce the risk of compaction and extend the time frame over which the land can be used as pasture or driven on. This can be as simple as clearing out ditches or installing subsurface drainage. In heavier clay loam soils shallow moling below the depth of compaction may be possible. The current HLS guidelines appear to discourage drainage work, (HK6 stipulates "no new drainage") but maintenance of good surface drainage infrastructure is also important in many ways for biodiversity and should be actively encouraged by the ES schemes. because it is also beneficial in terms of preventing compaction and therefore a win-win situation.

- **Biodiversity monitoring and responsive management:** If an area of a field begins to lose its plant diversity as a result of heavy trafficking, then a plan should be developed to limit the damage either by reducing the traffic, or failing that to restrict it to a defined area.
- **Adaptive management where compaction has occurred:** If soil wetness is being managed under an HLS scheme, it would be necessary to offset the lowered hydraulic conductivity of the soil either with closer-spaced grips or similar features or via tighter control of water levels in water courses (particularly relevant to grazing marsh options).
- **Reduce or prevent treading damage:** Suggested strategies for reducing or preventing treading damage include: reducing treading intensity (Drewry, 2003; Drewry & Paton, 2000), excluding animals (Greenwood *et al.*, 1998; Stephenson & Veigel, 1987), removing animals for several rotations and using the pasture for silage (Drewry & Paton, 2000), when soils are wet, the numbers of livestock per unit area or the time spent on the field should be reduced, reducing stocking densities by either increasing grassland area or reducing livestock numbers (Mulholland & Fullen, 1991).
- **Use of plant species:** Plants with desirable rooting characteristics can enhance the structure of soils (e.g. Macleod *et al.* (in press))
- **Use water management to encourage soil shrink-swelling leading to re-structuring:** e.g. Spoor *et al.*, 2000
- **Remediation of diffuse pollution from compacted grasslands:** This can be tackled using 3 approaches: controlling sources, restricting pathways and/or protecting potential receptors.

Controlling sources – reduce concentration / loading of pollutants in the environment

- reduce chemical inputs
 - An alternative to conventional farming is organic farming that eliminates or greatly reduces chemical usage
 - Changing livestock diets
- Control sediment production at source – agronomic measures (use of vegetation), soil management (conservation tillage, non-inversion tillage) and engineering structures (berms, bunds, surface and sub-surface drainage)

Control pathways – reduce overland flow and subsequent soil erosion (detachment and transport)

- Improve soil structure - McDowell *et al.* (2003) showed the importance of maintaining macro porosity to control sediment and P losses.
- Increase surface roughness to reduce runoff velocity and sediment transport capacity
 - Use of tillage techniques to create a rough tilth
 - Use of crop residues / mulches to increase surface roughness
- Drainage (reduces runoff)
 - However, surface drainage may concentrate flow and mobilisation locally
- Sub-soiling (reduces runoff)
 - May increase leaching losses of nutrients and agrochemicals

Protect receptors – avoid ingress of runoff loaded with diffuse pollutants

- Install across slope buffer strips at field edges, mid-field and on levees,

Work package 4: Conflicts and synergies within existing and potential ES options, between objectives relating to soil compaction and its remediation and other scheme objectives

Appendix 4 details the existing ES schemes that are available and Table 19 provides existing ES options and their impacts on soil compaction.

- **Lack of flexibility:** Currently a lack of flexibility in some ES schemes can be seen as presenting conflicts for soil compaction. For example, windows of opportunities for farmers to correct soil problems may conflict with payment schemes. Fixed timing limits for grazing species-rich grasslands can also be a problem in years with extreme weather conditions.
- **Impact of wetting up grassland:** The wetting up of grassland for wet meadows can result in compaction/poaching and loss of soil fauna. This process needs careful management to get the right balance and may demand pre-remedial treatment before going into the scheme so that soils are well structured at the outset.
- **Above ground biodiversity vs below ground biodiversity:** Agri-environment schemes are focussed on above ground biodiversity. To remove conflicts and create greater synergies the schemes need to better recognise soil fauna interests and Soil Management Plans need a wider focus and greater status.
- **Archaeology options:** Measures to protect archaeological/heritage sites such as restricting subsoiling, can have antagonistic effects if the soils become compacted.

- **‘Real’ stocking density:** If stocking density is calculated on a total farm basis it may hide the fact that certain fields are more intensively grazed.
- **Impact of field margins:** Margins are promoted for improving diversification but they are often very compacted from preferential trafficking with restrictions for subsoiling. In-field strips may be better for biodiversity than margins. Compacted buffer strips can also create a problem with increased run-off and associated nutrient loss.

A well structured soil delivers a range of environmental benefits. Many existing ES options are synergistic with improving soil structure and therefore further enhancing biodiversity, however, it is important to note, that some of these options and potential remedial measures could have adverse knock on effects on biodiversity. For example, silage is, generally, a less attractive foraging habitat for birds than grazed pasture. Decisions about management techniques designed to alleviate compaction must be taken in the context of broader conservation objectives.

Work package 5: Recommended priorities for field-based research and appropriate sites for case studies

Priorities for field-based research

Surprisingly little is known about the extent and severity of grassland soil compaction and its impacts on the vital functions (ecosystem services) supported by soil. Given that 30% of England is under managed grassland and that this figure is much higher for western areas it is important that the causes and effects of compaction are better understood. Future research is justified and the priorities are categorised under five principal questions.

1. How extensive and severe is soil compaction and what is its spatial and temporal distribution?

The general causes of compaction are reasonably well understood but new developments in soil mechanics could be applied to better understand the shear deformation of structured soil. Questions at the project workshop were raised about the general condition of artificial drainage systems including tile/pipe systems and arterial ditches and the impact of their deterioration on soil water regimes. We recognise that loss of drainage infrastructure is a critical issue with respect to soil compaction in grasslands. Further comments were made about the impact of the growing numbers of horses in certain areas and the impact that cross compliance has had on soil compaction.

There is very little information on the extent, nature and severity of soil compaction under different grassland management systems and climates and on different soils and a national survey is required to generate such information (**Recommendation 1A**). There is a lack of clarity over the nature of soil structural degradation under grassland and the relative importance of different forms of degradation - surface condition, immediate near surface structure and deeper compaction. Any future survey needs to be designed so as to improve understanding of these different forms. Consideration should be given to integrating soil structural condition in all its forms into any future national soil monitoring activities (**Rec. 1B**).

Systems of visual soil inspection are currently the only reliable method for properly measuring and characterising soil structure and compaction although they can be augmented by geophysical techniques to interpolate between point observations. Research is recommended into the development of more cost-effective methods for measuring and monitoring soil structure and compaction (**Rec. 1C**). These may include acoustic methods, as well as the use of plant and soil-microbial indicator species and parameters. The aim should be to develop one or more rapid and more cost-effective methodologies for detecting and quantifying soil structure.

Attendees at the stakeholder workshop recommended a study of the nature and scale of compaction resulting from horses. An initial survey of a number of horse pastures and a review of the extent of horse paddocks is recommended (**Rec. 1D**).

2. What is the impact of different forms of compaction on soil functionality and therefore biota, water quality and flows, and air quality?

Few studies have directly measured the impacts of soil compaction on above- or below-ground biota., Very little is known other than anecdotal evidence of negative impacts on feeding birds and only preliminary evidence is available for reduced species richness in swards. In relation to water movement and quality, and for greenhouse gas fluxes, the underlying processes are better researched. However, understanding of impacts at larger spatial scales is lacking.

A replicated multi-site field experiment investigating the response of soil biota, sward composition (where relevant) and bird species to different levels of grazing and farm machinery use is needed (**Rec. 2A**). Amongst other things, this research should extend the earlier work of Godefroid & Koedam (2004) to assess the susceptibility of grassland species to soil compaction both through manipulation of compaction within a controlled environment and through observation in the field. The impact of grazed as opposed to conservation (i.e. silage) grassland management requires investigation as part of this study. The size of the treatment plots within such a field experiment will need to be appropriately large if the study is to include responses of farmland birds to compaction. Potentially valuable further work could be carried out on birds in relation to compaction by extending

the analysis of population changes further into the past and using bird trend data from 1970s (i.e. before the onset of major declines in bird populations). To underpin this work on the responses of the higher trophic levels, e.g. birds, it will also be necessary to quantify the impacts of compaction on not only soil macrofauna (e.g. earthworms), but also to place these impacts within the wider context of the soil food webs as a whole.

It has not been possible to explore the potential offered by some of the longer term experimental sites in England and Wales to address these questions but it is recommended that the physical condition of soils is monitored according to a consistent methodology on all experimental sites where relevant biological, hydrological or gas exchange parameters are being measured (**Rec. 2B**). Investigation of the extent of soil compaction under grazed species-rich grassland sites could yield valuable information about its impact on species composition and it is recommended that this becomes a regular part of the management regime for such sites where they are designated or identified under an agri-environment scheme (**Rec. 2C**).

There is evidence that soil compaction can dramatically increase run-off. Once the extent and distribution of compaction is better understood (Rec 1A) a project should be established to research the influence that this is having on catchment-scale river flows and flood risk. (**Rec. 2D**).

With regard to greenhouse gas fluxes, little is known regarding the nature and impact of secondary soil processes following compaction. Most studies of gas exchange have been conducted at laboratory or small plot scale with little or no attempt to extrapolate to landscape scale. It is recommended that this be attempted following on from project 1A (**Rec. 2E**).

3. What is the economic and social cost of compaction and therefore the value of its prevention or remediation?

Evidence of the impact of soil compaction on grass yields can be translated into economic terms but the environmental impacts of soil compaction represent a further set of costs to the public good that have not yet been valued. Once these impacts are better understood and quantifiable, they should be fully costed so that the full economic impact of soil compaction is known (**Rec. 3A**).

4. Do soils recover from particular forms of compaction and if so at what rate and under what circumstances?

Stakeholders at the workshop recommended research into the rate at which soils recover from compaction and the factors that influence this process. It was also recommended that the influence of soil biota (e.g. earthworms) and particular plant species is investigated. It is recommended that a programme of plot-scale experiments be carried out to investigate the natural recovery potential of a range of contrasting soils under grasslands of differing composition (**Rec. 4A**). Similar scaled research into the efficacy of different soil biota and plants in remediating different forms of soil compaction should also be conducted (**Rec. 4B**).

5. How is compaction best prevented or remediated in grassland soils?

Prevention is better than cure, and stakeholders at the project workshop recommended production of a blueprint for contractors and farmers relating to practices to reduce compaction. The availability of such advisory material should be reviewed and any gaps filled (**Rec. 5A**). This information is largely available but not easily accessible and not in one place. Many texts deal only with arable systems, although some (e.g. Davies *et al.*, 1972; and The Guide to Better Soil Structure) do briefly discuss grassland. The need is for practical advice specific to each grassland system (sheep, dairy, silage etc.) and should demonstrate how to identify the different types of compaction and the measures needed to alleviate the consequences.

Real-time systems for monitoring of the moisture state of soils and therefore their vulnerability to compaction are a reality and are being used to support daily decisions on land management in other contexts. It is recommended, if compaction is widespread (outcome of work under Rec. 1A), that the feasibility and cost-effectiveness of a nationwide system is assessed (**Rec. 5B**).

Conventional treatments for compaction in tilled soils such as autumn subsoiling disrupt swards, so threatening buried archaeological assets and creating hazards to grazing stock. Decisions about management techniques, for instance switching to zero grazing and tramline harvesting of forage for fully housed stock that are designed to alleviate compaction on vulnerable soils need to be reviewed in the context of broader conservation objectives over and above the maintenance of high yields. 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 in areas with existing or potential biodiversity interest, such that their impacts on biodiversity can be established (**Rec. 5C**). 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.

Summary of recommendations for research

Assessing the spatial extent of grassland compaction has to be the first priority (**Rec. 1A**) and it is suggested that this should proceed immediately. If compaction is anything other than a localised issue, it is difficult to see any

alternative to: (a) a major study of the impacts on soil and above-ground biota (**Rec. 2A**) and water flows (**Rec. 2D**) and greenhouse gas fluxes (**Rec. 2E**) at catchment scale ; (b) work on more cost-effective methods of measurement (**Rec. 1C**); (c) commissioning of work for **Rec. 5C**. This should be followed by valuation of the impacts of compaction (**Rec. 3A**), as this will inform decisions on Government investment in further research in response to the other research recommendations above.

Recommendations **2B** and **2C** should be considered for adoption as standard practice. The advisory Blueprint in Recommendation **5A** is seen as a useful extension to other initiatives already in place such as the Guide to Good Soil Structure and the unified Code of Good Agricultural Practice.

Case study sites discussed at the stakeholder workshop are detailed in Appendix 5. Generally speaking, however, the sites chosen must be representative of grassland across England and Wales and have specific management issues that can be investigated during a pilot study. The specific sites will depend on the particular research recommendation being addressed.

References to published material ---

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

All references cited are listed in the appendices.

No other published material has been generated by this project as yet.