Defra project SP1316 - subprojects A & B:
Identifying the soil protection benefits and impact on productivity provided by the access to waterlogged land requirements in cross compliance and exploring the impacts of prolonged waterlogging on soil quality and productivity

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EXECUTIVE SUMMARY

The UK Government is committed to tackling soil degradation threats through sustainable soil management to ensure that agricultural soils continue to provide essential ecosystem services for future generations. Waterlogged soils are sensitive to degradation from farming operations through compaction and erosion; indeed managing access to waterlogged land is critical for sustainable soil management and limiting soil degradation. Furthermore, the wet summer and autumn of 2012, the winter and spring of 2013 and the winter of 2013-14, combined with climate change projections raised concerns that episodes of prolonged waterlogging may become more frequent in the future. There was therefore a need to broaden our understanding of how the management of waterlogged land could affect soil quality, productivity and the delivery of other soil ecosystem services, and to better understand the potential impact of prolonged periods of soil saturation.

The detailed objectives of these studies were to:

i. Collate and review information on the impacts of working waterlogged soils in terms of soil degradation, productivity, water quality, flood mitigation, carbon storage and nutrient cycling.

ii. Assess the cost-effectiveness of measures for preventing soil degradation associated with working waterlogged land, including measures to reduce the duration of waterlogging and measures to alleviate damage caused by accessing waterlogged land.

iii. Assess the effectiveness of current controls on access to waterlogged land and remediation of damage using currently available information.

iv. Collate and review existing information on the impacts of prolonged waterlogging on both soil quality and productivity for a range of farming systems, crops and soil types in England and Wales.

v. Investigate the spatial extent and temporal variability of waterlogging by farming system and soil type under ‘recent’ climatic conditions and under future climate change scenarios.

vi. Consider and assess the adaptations to farming practices that may be required to protect against a more frequent occurrence of prolonged waterlogged conditions, including barriers to adaptation/uptake.

Impacts of working waterlogged soils in terms of soil degradation, productivity, water quality, flood mitigation, carbon storage and nutrient cycling

Waterlogged soils are sensitive to degradation from farming operations through compaction and erosion. Late autumn harvesting and crop establishment are particularly associated with greater structural degradation risks, as soils are more likely to be worked when ‘wet’ or in a plastic state. In medium and heavy soils the main risks are from aggregate dispersion (puddling) and smearing, particularly on slowly permeable soils. In England and Wales, approximately 45% of winter sown crops are grown on these slowly permeable soils which require field drainage to maximise opportunities for field work. In contrast, sandy and light silty soils are more susceptible to compaction through compression if worked in wet conditions. Working ‘wet’ or waterlogged soils can lead to impacts on a number of ecosystem services. Crop yield can be reduced due to restricted rooting and poor water and nutrient uptake, particularly in a wet late/winter spring or dry spring/summer (following soil degradation due to working ‘wet’ or waterlogged land in winter or spring). Reduced macroporosity and the development of coarser soil structure reduces water infiltration and can increase both soil erosion rates and flooding risk, thereby impacting on water quality and soil carbon storage. Finally, soil structural degradation resulting from working waterlogged land can also affect nutrient cycling in terms of organic matter mineralisation rates and soil nutrient uptake.
Cost-effectiveness of measures for preventing soil degradation associated with working waterlogged land, including measures to reduce the duration of waterlogging and measures to alleviate damage caused by accessing waterlogged land

Any measure that reduces the working or trafficking of ‘wet’ or waterlogged land will help prevent soil degradation and reduce the duration of waterlogging through maintaining better soil structure and good drainage.

Drainage installation is very costly and typically requires many years to realise a return on the investment. However, on poorly drained soils, drainage systems enable more flexible field working, provide insurance against very wet years (in which the total loss of production/profit can occur without a drainage system) and could mean the difference between operating a combinable cropping arable system and a less profitable extensive livestock grazing system. Drainage system maintenance is also very costly and may not provide an economic return every year, but can avoid complete loss of production in extremely wet years.

Delaying cultivation until soil is in a friable state can have a negative impact on farm profitability if it results in spring rather than autumn cropping. However, in many instances delaying cultivation until field conditions are suitable avoids creating poor seedbeds and soil compaction, which can reduce crop yields; reduce opportunities for field operations; and increase costs due to greater weed/disease pressure. Overall, avoiding cultivation of ‘wet’ soils is more likely to improve yields and reduce costs, resulting in positive impacts on the farm business.

Application of bulky organic materials is generally cost-effective even when farmers have to pay for their nutrient value. Organic materials can increase soil organic matter content, thereby improving soil structural condition, drainage, water holding capacity and resilience to degradation. Better structured soils drain more quickly, reducing the likelihood that they will be trafficked or cultivated when wet.

Low ground pressure (LGP) tyres and tracked machinery can play a role in reducing soil degradation and if used appropriately (i.e. not when soils are ‘wet’), can produce near optimal conditions (in terms of soil bulk density and porosity) for crop establishment and growth. LGP tyres can also reduce fuel use by limiting wheel slip and rolling resistance. Controlled Traffic Farming (CTF) principles can be cost-effective if the land is over-compacted. However, in combinable cropping systems, the practicality and cost of CTF systems has limitations, such as the incompatibility of combine harvester cutting bar widths with the track spacing needed (i.e. greater than 6 m) to achieve significant reductions in trafficked areas. Machinery guidance using Global Positioning Systems (GPS) can result in significant variable cost savings by reducing overlaps (and hence costs) and reducing the trafficked area; benefits exceed the current cost (of lower accuracy systems) for farmed areas greater than c. 200 ha.

Mechanical alleviation, causing fissuring and cracking, can help improve drainage and reduce runoff, erosion and flooding risk. Crop yields can also be improved. The measure is cost-effective when there are clear signs of soil compaction, and sub-soiling and top-soiling is carried out under suitable conditions.

The effectiveness of mitigation measures in helping avoid working waterlogged land is likely to be greater in wetter regions and wetter years. Mitigation measures will also be of benefit if future climate regimes include greater year to year variability and a greater frequency of extreme events such as the prolonged rainfall encountered in 2012-13.

The effectiveness of current controls on access to waterlogged land and remediation of damage using currently available information

A farmer survey carried out as part of Defra project SP1309 indicated that current controls have helped raise awareness of issues associated with accessing waterlogged land. The Soil Protection Review 2010 (SPR10) encouraged some farmers to change the way they accessed
waterlogged land, although the impact on reducing soil degradation was low with only about 12% of respondents making changes to management practices.

The proportion of farmers who accessed waterlogged land was low in 2010-12 (5% of all respondents and 18% of those experiencing waterlogged land). However, the SP1309 survey was carried out before the wet summer/autumn of 2012 and the wet winters of 2012/13 and 2013/14. Working (i.e. cultivating) waterlogged land was not acknowledged as an issue among the 800 farmers surveyed.

There were clear deficiencies in practice when remediating compacted soil as few farmers assessed the extent of the soil damage before taking action. This could be improved through the development of guidance materials, soil management workshops and farm walks.

Mechanical alleviation of soil compaction generally improves drainage and can increase crop yields, particularly on spring crops grown on sandy and light silty soils, but only when there are clear signs of compaction, the machinery is set up correctly and soil conditions are suitable. In general, it is best to delay mechanical alleviation operations until soils are in a friable state, rather than to require that actions are carried out within twelve months of first accessing waterlogged land (in some extreme cases mechanical intervention may be needed while soils are still ‘wet’ to create a channel or pathway for water to drain away). Furthermore, natural restructuring can take place in some soils (>18% clay) and no remediation is then needed. Allowing a degree of flexibility would help farmers take appropriate and timely action. However, improvements are needed in soil management, particularly in soil assessment to determine whether remediation is necessary.

**Impacts of prolonged waterlogging on both soil quality and productivity for a range of farming systems, crops and soil types**

The lack of oxygen in the soil as a result of prolonged surface waterlogging has significant effects on soil chemical and biological processes, and on soil physical structure that can profoundly affect the quality of soil as a medium for plant growth. However, draining and drying a flooded soil can reverse these impacts to some extent.

In general, clay soils are more susceptible to waterlogging than sandier soils, although the extent and duration of waterlogging depends on a range of factors including climate, soil water regime, topography, cropping and land management. The main practices to limit the impacts of waterlogging on any soil type are to maintain and improve soil structure, and facilitate drainage by:

1) Maximising soil surface protection in the form of vegetation, crop residue or mulch.
2) Maximising surface roughness to reduce capping risks.
3) Avoiding compaction pressures such as trafficking and poaching, through reduced cultivations or by smarter timing of field operations.
4) Alleviating soil compaction where appropriate.
5) Increasing soil organic matter content by the addition of bulky organic materials such as farmyard manures and compost
6) Maintaining or improving field drainage.

Impacts on crops growing under waterlogged conditions are predominantly a consequence of oxygen deprivation. The overall effect on plant growth is related to the duration of waterlogging, soil temperature and the stage of crop development at which waterlogging occurs. There is strong evidence from a range of studies that waterlogging reduces yields of cereal crops, oilseed rape, grass, legumes and roots. The overall economic impact of waterlogging is likely to be greatest for cereals because they are widely grown on most soil types, although the consequences for potato farmers who experience complete losses of this high value crop could be very significant.

The analysis of the duration of the impacts of waterlogging indicated that all farm types should be prepared to deal with short-term waterlogging, although longer-term waterlogging was more likely to be a problem for livestock farmers. The greatest flood risk is normally from heavy clay
soils that have been traditionally under drained and used to grow arable crops. Effective drainage of clay soils has been shown to reduce the risk of waterlogging.

The timing of waterlogging is the key to the impacts of waterlogging on farm practices. Autumn waterlogging can affect winter drilling/establishment while winter waterlogging has minimal impacts, apart from possible delays to some spray/fertiliser applications. Spring waterlogging can delay spring drilling, chemical and fertiliser applications, whilst summer waterlogging can lead to reduced grain fill. All of the above effects can affect crop yield, although the spring to summer period is key to determining the degree to which crops can ‘recover’ from earlier setbacks and ultimately yield. Adaptations to prolonged waterlogging include changing the crop rotation in favour of spring crops, changing cultivation method to suit the soil conditions, installing farm tracks to combat livestock poaching, installing drainage systems or more proactive management of existing drainage systems.

There are a number of issues which may need to be addressed by farmers and growers following periods of prolonged waterlogging including drying out of the soil, dealing with soil structural issues caused by waterlogging (e.g. compaction, capping and slumping), correcting loss of soil fertility, dealing with crop damage or loss and animal health issues.

**Spatial extent and temporal variability of waterlogging by farming system and soil type under ‘recent’ climatic conditions and under future climate change scenarios**

The modelling component of this study aimed to assess the severity and past frequency of events similar to those experienced in 2012/13 and the likely future impacts of climate change on the degree of waterlogging. The analysis was undertaken using regression models driven by MORECs data, which enabled an assessment of the spatial extent and temporal variability of waterlogging by farming system, soil type and season. Projections of annual and summer average rainfall were combined with existing regression models that estimate the duration of field capacity from seasonal rainfall totals. These were then used to predict changes in the duration of field capacity for the UKCP09 low, medium and high future emission scenarios (forecast to 2020, 2050 and 2080). This was done at a 25 by 25 km grid resolution to calculate the duration of waterlogging associated with each grid square for each of the 9 future climate scenarios.

Future UKCP09 climate scenarios predict an increase in winter rainfall and a decrease in summer rainfall. This would lead to a later return to field capacity and a fall in the number of field capacity days and the duration of waterlogging. This supports other studies (e.g. Defra project SP1104), which reports that the number of field capacity days will decrease (on average) in the period 2020-2080 under three future climate scenarios. Although the degree of waterlogging changed over time under the different climate scenarios, the geographical distribution of waterlogging severity did not change significantly, highlighting the importance of soil type in determining the degree and duration of waterlogging.

The predictions also indicated that the area of soils at risk of prolonged waterlogging may reduce under all climate change scenarios. However, in some regions under the 2020 scenarios, the increase in winter rainfall outweighed the decrease in summer rainfall, leading to some short-term increases in the high waterlogging risk categories.

Despite a likely reduction in the duration of waterlogging, it is possible that projected increases in winter rainfall in future could increase the severity of waterlogging due to larger rainfall volumes overwhelming drainage systems.

The return period of the 2012-2013 winter was determined by comparing the calculated duration of field capacity for that year to the individual annual values for each grid square from 1962 to 2013. This showed that from September to December 2012 the duration of field capacity was longer than normal, with some areas experiencing durations with a return period of more than 1 in 50 years. However there were exacerbating factors in 2012 in that the summer period was unusually wet, with soils in some key areas reaching field capacity from
mid-July onwards and across large areas of the country by early September. Even in the driest areas in the east of England, field capacity was reached much earlier than usual. The combination of the wet summer and continued wet conditions in the autumn will have considerably increased the impact on farming operations, and increased the potential for soil damage both during harvest and from livestock grazing. In contrast, the period from January to April 2013 was close to average.

Additional analyses were undertaken to compare daily rainfall totals against drainage design rates (the amount of rainfall a field drainage system can evacuate from the soil) to investigate both the severity of waterlogging during the period when it occurred and the impact of drainage deterioration. This analysis showed that some areas, most notably the south west of England, experienced rainfalls in excess of the field drainage capacity that would only be expected once in 50 years or more. Reduction in the capacity of mole drains to evacuate water from the soil profile (by failure to renew moles) was shown to increase the area where 1 in 50 year return period conditions were exceeded. It is likely that the capacity of other types of drainage systems has been reduced due to poor ditch and outfall maintenance, such that the impact demonstrated for mole drainage will have been replicated elsewhere.

Adaptations to farming practices that may be required to protect against a more frequent occurrence of prolonged waterlogged conditions, including barriers to adaptation/uptake

Farming adaptations that improve soil drainage, maintain or enhance organic matter levels and produce better structured soils will help to mitigate against waterlogging and will generally benefit the farm business, although economies of scale are an important consideration and significant changes to cultivation systems, such as the adoption of controlled traffic farming (CTF) can have practicality and cost limitations. Adaptations include:

- Replacing and maintaining field drainage systems on slowly permeable soils
- Applying bulky organic manures to improve soil resistance and resilience
- Visual assessment of soils combined with timely use of sub-soilers and top-soilers, where appropriate
- The use of low ground pressure tyres and satellite guidance systems in suitable field conditions
- The use of more efficient machinery to establish crops more rapidly, particularly on larger farms

Conclusions and policy implications

Working waterlogged soils

Working waterlogged land can have a significant effect on crop productivity, water quality (particularly sediment and associated phosphorus losses), flood mitigation (due to increase surface runoff), carbon storage (mainly related to erosional losses) and nutrient cycling (mineralisation rates and crop uptake can be reduced, and nitrous oxide emissions increased).

Any measure that helps avoid working or trafficking waterlogged land will help prevent soil degradation and reduce the duration of waterlogging through maintaining better soil structure and good drainage. Cost-effective measures to which economies of scale apply include drainage installation and maintenance, the use of LGP tyres/tracked machinery and the use of CTF principles through GPS guidance systems. Measures that can be used on any farm include delaying cultivation until soil is in a friable state, the application of bulky organic manures and mechanical alleviation to create fissuring and cracking in compacted soils. Drainage installation and maintenance is very costly and cannot be justified economically on all imperfectly to poorly drained soils or in all farming systems.

Current controls (i.e. SPR10) have helped raise awareness of the issues associated with accessing waterlogged land and have encouraged some farmers to change the way they accessed waterlogged land. However, in a survey carried out in spring 2012 (Defra project SP1309), farmers did not acknowledge that land on their farm was ever worked (i.e. cultivated)
when waterlogged. Furthermore, there was clear evidence of deficiencies in practice when remediating compacted soil as few farmers assessed the extent of the soil damage before taking action. Improvements are needed in soil management, particularly in soil assessment to determine whether remediation is necessary. This is an area of current interest for many farmers within all farming systems. There is therefore an opportunity to raise awareness and improve soil management skills through the development of guidance materials, and knowledge exchange through soil management workshops and farm walks. These could include discussion of mitigation measures and adaptation strategies and demonstration of soil visual evaluation techniques and how these should be carried out at various points in a year/cropping cycle to assess variability in soil condition and management requirements.

**Prolonged waterlogging**

Prolonged surface waterlogging can profoundly affect soil chemical and biological processes (mainly due to lack of oxygen), soil physical structure and the quality of soil as a medium for plant growth. The overall effect on plant growth is related to the duration of waterlogging, soil temperature and the stage of crop development at which waterlogging occurs. All farming systems are affected, but our analysis of the duration of the impacts of waterlogging indicated that longer-term waterlogging was more likely to be a problem for livestock farmers.

Modelling assessments in this study using UKCP09 climate projection scenarios (2020s, 2050s and 2080s with low, medium and high emissions) predicted a later return to field capacity and a reduction in the number of field capacity days, the duration of waterlogging and the area of soils at risk of prolonged waterlogging. However, it is possible that the severity of waterlogging where it occurs may be greater than at present because larger winter rainfall daily volumes may overwhelm drainage systems. For example, in some regions under the 2020 scenarios, the increase in winter rainfall outweighed the decrease in summer rainfall, leading to some short-term increases in the high waterlogging risk categories. Nevertheless, based on UKCP09 climate projections, the risk of prolonged waterlogging is likely to reduce in future.

Farming adaptations that improve soil drainage, maintain or enhance organic matter levels and produce better structured soils will help to mitigate against waterlogging and will generally benefit the farm business, although economies of scale are an important consideration. The adaptations and mitigation measures mentioned above can help improve efficiency of production, increase productivity and increase the resilience of farming systems to prolonged rainfall. They form a natural progression towards more efficient farming systems, helping increase productivity while minimising impacts on the environment, particularly reducing flooding risk and improving water quality through reductions in sediment and associated phosphorus losses. However, ensuring appropriate adoption of these practices requires an on-going programme of advice, demonstration and research activities. For example, the impacts on flooding risk of mechanical alleviation of soil compaction (sub-soiling of arable land and top-soiling of grassland soils) is still poorly understood.
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1. INTRODUCTION

The Natural Environment White Paper, The Natural Choice, sets a goal that by 2030 all soils in England should be managed sustainably and degradation threats tackled successfully, in order to improve the quality of soils and to safeguard their ability to provide essential ecosystem services and functions for future generations (Defra, 2011). The impact of soil degradation on ecosystem services in England and Wales has been estimated to cost between £0.9 and £1.4 billion per year (Graves et al., 2011). Within this context and considering related concerns for sustainable production and environmental protection, the management of waterlogged agricultural soils in England and Wales presents a challenge to Government and to land managers.

This report investigates the issues of working waterlogged land and the impact of prolonged waterlogging on soil quality under current climatic conditions, under future possible climate change scenarios and in relation to the effects of degraded drain function. Mitigation measures that reduce the risk of working ‘wet’ or waterlogged land or alleviate the soil degradation caused by working waterlogged land were also considered, as were adaptation measures to cope with possible increases in the occurrence or intensity (quantity of rainfall within a defined period) of prolonged waterlogging in the future.

Working or accessing waterlogged land can lead to rapid soil degradation. Management of waterlogged land therefore plays a key role in maintaining soil quality and delivering essential ecosystem services. Soils can degrade rapidly if they are cultivated or trafficked when waterlogged, so managing access to waterlogged land is a critical part of sustainable soil management. Furthermore, the wet period from summer 2012 to spring 2013, the wet winter of 2013/14 and climate change projections have raised concerns that episodes of prolonged waterlogging may become more frequent in the future. There was therefore a need to broaden our understanding of how the management of waterlogged land impacts on productivity and the other ecosystem services provided by soils; and to evaluate the impact of increased rainfall quantity and degraded drain function on the spatial extent and temporal variability of waterlogging in England and Wales.

The specific aims of the project were to investigate the:

- **Impacts of working waterlogged soils in terms of productivity, soil degradation and ecosystem services – section 2.** Literature was systematically reviewed to assess the effects of working waterlogged soils on ecosystem services across a range of farming systems, crops and soil types. A summary is provided in section 2 with a more detailed review in Appendix 1.

- **Cost-effective measures for preventing damage to soils due to working waterlogged land (including measures to prevent waterlogging) and remediating damage after it has occurred – section 3.** The costs and effectiveness of measures to prevent waterlogging and to alleviate damage caused by accessing or working waterlogged land were separately assessed using model farms at appropriate scales, evidence in the literature and expert opinion.

- **Soil protection benefits and impact on productivity provided by the 2010-14 controls on access to waterlogged land and remediation of damage – section 4.** The impact on soil protection and productivity of 2010-14 controls on access to waterlogged land was assessed using outputs from Defra project SP1309 and considering a range of farming systems and soil types.

- **Impact of prolonged waterlogging on both soil quality and productivity – section 5.** Literature was systematically reviewed to better understand the impact of prolonged surface waterlogging on soil quality and productivity, for a range of farming systems, crops and soil types. A summary is provided in section 5 with a more detailed review in Appendix 2.
• Extent of waterlogging in England and Wales under ‘normal’ climatic conditions and how this might change in the future – section 6. A modelling approach was used to assess the spatial and temporal extent of waterlogging under current and projected climate scenarios to inform policy on the management of waterlogged land. Meteorological datasets were also used to assess how unusual the weather patterns were in 2012-2013 in terms of the duration and extent of waterlogging in England and Wales.

• The impact of degraded drain function on the spatial extent and temporal variability of waterlogging in England and Wales – section 7. A modelling approach was used to provide insight into the potential impact of degraded drain function on the spatial extent and temporal variability of waterlogging in England and Wales.

• Possible adaptations to farming practices that may be required to protect against a possible future scenario of more frequent episodes of prolonged or intense waterlogging – section 8. The farming practice adaptations that may be required to protect against a more frequent occurrence of prolonged waterlogging were reviewed in terms of their benefits, approximate costs and barriers to uptake using a literature review approach including consultation with practitioners and consideration of a range of farming systems.
2. IMPACTS OF WORKING WATERLOGGED LAND

- This section summarises the impacts of working waterlogged soils in terms of productivity, soil degradation and ecosystem services. A more in depth assessment is provided in Appendix 1.

2.1 Introduction

- Waterlogged soils are sensitive to degradation from farming operations through compaction and erosion. Factors that increase the likelihood of waterlogging include soil compaction (and subsequent reduction in water infiltration and drainage), periods of excessive rainfall and the deterioration (or lack) of drainage systems on impermeable/slowly permeable soils. (Harris and Catt, 1999).
- Managing waterlogged land plays a key role in maintaining soil quality and the delivery of essential ecosystem services including crop production, flood mitigation, carbon storage and nutrient cycling.

2.2 Physico-chemical and bio-physical effects of working waterlogged soils

2.2.1 Cultivation and soil moisture

- Cultivation carried out when soils are ‘wet’ can result in soil structural damage. The degree of damage caused relates to the direction of force and pressure applied and the frictional and cohesive strength of the soil at any given soil moisture content.
- Soils are most workable at moisture contents within the friable range between the shrinkage limit and the lower plastic limit (Spoor, 1975). When soil is in a plastic state (between the lower and upper plastic limits) soil clod and bearing strength declines, resulting in increased wheel slip, rolling resistance and sinkage/compression. The risk of structural damage increases with increasing soil moisture content to a ‘sticky point’ where bulk shear strength falls and soil sticks to cultivation machinery, resulting in significant puddling (aggregate dispersion) and smearing (spreading of soil by sliding pressure).
- Soils at field capacity (start of drainage) are prone to compaction through compression as soil moisture approaches the lower plastic limit and coarser pores (i.e. greater than 0.05 mm) are still mainly air-filled and able to reduce in volume (Spoor, 1975).
- Clay and medium textured soils tend to be at greatest risk of structural damage due to the longer periods of time during which the soil is in the plastic state following prolonged or heavy rainfall. Recently cultivated soils that are mechanically weak are also more liable to damage than well-structured soils in stubbles or under grassland.

2.2.2 Cultivation methods

- When soils are ‘wet’, ploughing is often the preferred option, since the mechanical disturbance drains and aerates a greater depth of soil than reduced cultivation. However, repeated ploughing over a number of years can create a ‘plough pan’ in the upper subsoil or ‘transition layer’, which can give rise to further compaction in the future (Batey, 2009).
- Secondary cultivations involving the use of flexible tines, power-rotated tines or discs are particularly high risk operations for soil structural damage in ‘wet’ conditions. Tines lift the soil and in wetter conditions are likely to be least damaging, whereas discs and power harrows tend to smear the soil (Shepherd et al., 2002). Rainfall following power harrowing can cause the soil to ‘slump’ into a compacted, unstructured 10-15 cm layer, with reduced permeability increasing the risk of prolonged waterlogging over winter (Davies et al., 1972).

2.2.3 Impacts of working waterlogged soils

- Working waterlogged soil can reduce macroporosity by 10-60% (Singleton et al., 2000; Drewry et al., 2008); reduce water holding capacity and available water capacity; increase
bulk density; re-orientate clay particles; reduce aggregate stability; increase the size, angularity and platy nature of soil structure; reduce water infiltration rates; reduce continuity of pores and links to any drainage systems; damage swards; and increase the percentage of bare soil in grassland (Brady and Weil, 2008).

- When soils are cultivated in a plastic state, compaction results from reduced pore size and continuity due to compression and soil smearing, often causing an impenetrable layer to plant/crop roots (Forbes and Watson, 1996). Root growth can be impacted by physical restriction, through reductions in pore size and increases in penetration resistance (Whitmore et al., 2010).

- Prolonged waterlogging can give rise to degradation of leaf chlorophyll, purpling of leaves and emissions of ethylene, which can facilitate the development of adventitious roots, increasing root surface area within the waterlogged zone and once soils have dried out partially compensating for the reduced ability of roots to explore the soil below any compacted layer (Kozlowski, 1984; see section 5). However, at later growth stages ethylene production can accelerate leaf senescence (Brady and Weil, 2008). Continuing microbial activity in the absence of oxygen can quickly lead to products that are damaging or toxic to plant roots e.g. ammonia, sulphides, ferrous-iron, and methane (Brady and Weil, 2008).

- Aggregate structure and surface conditions as a result of tillage are influenced heavily by soil water content (Watts et al., 1996). The consequences can be decreased aggregate stability which can lead to increased risk of surface crusting and erosion (Bullock et al, 1988; Schjonning et al., 1997; Munkholm and Schjonning, 2004).

- The compaction caused by wheels may reduce water infiltration rates and impede the growth and extension of roots (Smith et al., 2013). When soils are ‘wet’ and very plastic, the use of machinery and lifting of root crops can result in deeply rutted ground with an almost complete loss of macropores (Shepherd et al., 2002).

- Where soil compaction means that roots cannot push soil aside or compress the soil, they grow laterally along the upper surface of the compacted layer until they can find a vertical pore or fissure to grow into the soil below (Batey, 2009). Rooting patterns of this kind are commonly found above compacted layers and also branching or forking of tap roots in crops such as oilseed rape and sugar beet (Shepherd et al., 2002). Such rooting patterns developed during the winter and spring can result in significant impacts on yield, especially if rainfall amounts in the subsequent spring and summer are low (Allen and Scott, 2001; O’Sullivan, 1992).

- The effect of soil structural damage on crop performance depends on the depth and extent of compaction, the crop type (spring crops tend to be more susceptible) and subsequent weather conditions (drought or extreme ‘wet’ conditions are unfavourable). Cereals are mainly susceptible to soil conditions that delay or inhibit secondary roots, but are generally tolerant of a range of tilth and soil conditions, as is grassland.

2.2.4 Working waterlogged land within different soil types/farming systems

- Rainfall in the UK is relatively evenly distributed over the course of the year. However, it is more likely for waterlogging to occur in winter months when evapotranspiration rates are lower (e.g. Varapertian and Jackson, 1987; Dickin et al., 2009).

- The return to ‘field capacity’ date varies across England and Wales according to rainfall, evapotranspiration, cropping and soil type (including, for ‘impermeable’ soils, whether or not an effective underdrainage system is in place); and marks the date after which there are limited opportunities to access and work the land with machinery without causing soil structural damage (Morris et al, 2010).

- The risks of causing soil structural damage will vary between farming systems and crop rotations according to the specific sequences of harvesting and establishment dates, and
differences in competing activities at key times of the year. Crop rotations that include late harvested crops are at particularly high risk.

2.2.5 Soil type

Heavy and medium soils

- Heavy and slowly permeable soils remain ‘wet’ for longer periods than other soil types (Morris et al., 2010) and have a higher saturated moisture content, a lower percentage of drainage water and a greater available water capacity than light sand soils.

- Heavy soils have lower bearing strength when wet and are therefore more susceptible to compaction and smearing during trafficking, grazing or cultivation than soils with lower clay content (Holman et al., 2003). However, heavy soils are also better able to recover from compaction, mainly due to the shrink-swell properties of many clay minerals and generally higher organic matter content than lighter textured mineral soils (Gregory et al., 2009).

Sandy and light silty soils

- Soils with high silt contents or those with low organic matter content, are more susceptible to surface crusting and slaking (Ramos et al, 2003). On sandy and light silty soils there is an increased risk of surface capping where rainfall or cultivation of ‘wet’ soils can displace silt particles leading to slaking and the formation of an impermeable cap up to 10 mm thick (NSRI, 2002). This in turn can lead to reduced infiltration and increased surface runoff.

Shallow soils over chalk and limestone

- Shallow calcareous soils tend to have a silty clay loam texture that can be susceptible to slaking and capping. However, high base saturation provides resilience in terms of the ability to restructure and resist compaction and a permeable substrate allows good drainage and a greater number of workable days in spring and autumn than on heavier soils (Defra, 2005).

Peaty soils

- Peaty soils are most susceptible to degradation when they are overgrazed or dry out (Foulds and Warburton, 2007) and can suffer irreversible shrinkage. Lowland peaty soils are susceptible to severe poaching when ‘wet’, but can be quite resilient to short-lived episodes of trafficking or grazing in such conditions due to their high organic matter content and ability to recover rapidly from compression.

2.2.6 Farming systems

- Soil management is important particularly in the post-harvest period in order to minimise the risks of soil degradation, erosion and associated pollutant losses (SP1315). Compaction is often more likely to occur when harvesting crops such as maize, potatoes and sugar beet as they are harvested later, often under wetter field conditions and require the use of heavy machinery (Defra, 2005; Shepherd et al., 2002).

Winter combinable cropping

- Winter combinable cropping rotations tend to dominate on heavy soils and deep clay soils with a slowly permeable layer, on which workable days in autumn and spring are limited compared with lighter textured soils.

- In years with wet summer and autumn periods there are risks of trafficking or cultivating soils when they are ‘wet’, particularly following late-harvested cereals. Harvest may be delayed in such years and may result in soil structural damage, and there may not be an opportunity to alleviate soil compaction before establishment of the next crop.

Roots and combinable cropping

- Roots and combinable cropping rotations tend to dominate on ‘sandy and light silty’ and medium soils that are well drained and provide flexibility in terms of the timing of field
operations. Autumn and spring workable days are more numerous than on heavier soils, providing greater opportunity to access land for harvest, cultivation etc.

- The best drained soils can be accessible within twenty four hours (or less) of heavy rainfall. Nevertheless, the risk of working waterlogged soils within such rotations are high due to the late harvest of crops such as potatoes, sugar beet, carrots and cauliflowers, the heavy machinery used to establish and harvest crops, and the pressures on growers to provide a steady supply of produce to contract through the late autumn and winter months. These late-harvested crops represent the ‘high risk points’ within the rotation as far as soil structural damage is concerned.

**Grassland systems**

- The risks of working, trafficking or trampling waterlogged soils in grassland systems are mainly associated with growing forage crops such as maize, strip grazing forage crops, re-seeding grassland, harvesting cut grass and early or late season grazing of grassland.

- Soil structural degradation can occur as a result of grazing animals under ‘wet’ soil conditions (e.g. Bell et al., 2011; Singleton et al., 2000). Grazing sheep on vegetation left after sugar beet harvesting or on fodder beet during the autumn and early winter when soils are bare can also increase the risk of soil surface compaction and the use of strip grazing systems for beef cattle and sheep can give rise to significant topsoil compaction (Vallentine, 2000; Jones et al., 2012). Removing stock from vulnerable fields and reducing stocking densities has the potential to reduce the risks of topsoil compaction in livestock systems (Newell Price et al. 2011).

- Forage maize is typically harvested in mid to late autumn using heavy machinery, which can cause compaction, reduce soil water infiltration and increase the risk of surface runoff (Withers and Bailey, 2003). The most common current practice is to retain maize stubbles over winter and cultivate them in early spring before establishment of an arable crop or grassland (SP1315). Surface runoff volumes from compacted maize stubbles can be significantly reduced through the use of a chisel plough or over-sown rye-grass (Defra projects SP0404 and WQ0140).

### 2.3 Effects of working waterlogged land on key ecosystem services

- Working ‘wet’ or waterlogged soils can have knock-on effects for key ecosystem services such as crop production, water quality, flood mitigation and carbon storage. There are important interactions between these services and between the mechanisms that impact on them, since working wet land is likely to result in reduced size and/or connectivity of pores, greater penetration resistance and reduced water infiltration rates with implications for a number of soil functions.

#### 2.3.1 Crop production

- Working ‘wet’ or waterlogged land can result in the development of compacted layers with reduced porosity and greater penetration resistance. Compacted layers in the topsoil increase the likelihood of prolonged waterlogging during wet winters, reducing crop establishment and increasing the risk of a yield penalty due to restricted rooting and limited water uptake in dry summers (Batey, 2009; van den Akker 1999; Whalley et al., 1995).

- Spring crops are generally more susceptible to poor soil structure than autumn-sown crops reflecting smaller root systems which reduce the uptake of nutrients and water (Johnston et al., 2009; SP1605B). Working waterlogged land prior to the emergence of spring crops such as spring barley and sugar beet can therefore have a particularly significant impact on rooting characteristics, water uptake and crop yield (Shepherd et al., 2002).

- The implications for yield are often more significant on light soils due to their inability to restructure through shrink-swell processes and more unstable soil structure compared with heavier soils. Resilience tends to increase with clay and organic matter content (Table 2.1; Appendix 1).
The effects of poor soil structure on crop yield will vary according to crop and soil type, the nature of the soil structural degradation and the weather conditions (particularly spring and summer rainfall) in each year, but for winter wheat yield reductions can be up to 0.7 t/ha for each 0.1 g/cm³ increase in bulk density (Soane and van Ouwerkerk, 1995: Whalley et al., 1995) or each 1 MPa increase in soil strength (Whalley et al. 2006, 2008).

Table 2.1: The risks associated with working ‘wet’ soils on provision of food (crop production) for different farming system and soil type combinations. The symbols *, ** & *** refer to low, moderate and high risk associated with working waterlogged land respectively.

<table>
<thead>
<tr>
<th>Farming system</th>
<th>Heavy</th>
<th>Medium</th>
<th>Silty/Sandy</th>
<th>Peaty</th>
<th>Chalk &amp; Limestone</th>
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<tr>
<td>Winter combinable</td>
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<tr>
<td>Roots combinable (including potatoes, sugar beet and horticultural crops)</td>
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<td>Grassland</td>
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1 reduced likelihood of slaking and capping on limestone and chalk downland soils under grass

Costs of mitigation and yield losses to the farm business

- Cost are estimated from Nix (2013), Soane et al. (1987) and Defra (2012):
- In winter combinable cropping systems where the autumn crop fails, the total cost associated with a switch to spring cropping can be c. £390 per hectare.
- In roots and combinable cropping systems (mainly on medium and light textured soils) the cost of working ‘wet’ soils in autumn is estimated at c. £70 per hectare.

2.3.2 Water quality

- The risk of soil damage and the mobilisation and transport of sediment and associated water pollutants is significantly increased if timing of field operations is not appropriate and soil conditions are not optimal.
- Cultivating compacted tillage soils in suitable conditions (compared with not cultivating compacted soils) typically results in phosphorus and sediment loss reductions in the range of 10-50% (Catt et al., 1998; Chambers et al., 2000; Newell Price et al., 2011), indicating that the soil compaction caused by working ‘wet’ soils can increase erosional losses by up to 2-fold or more.
- Martin (1999) found that late season cultivation of ‘wet’ silt loam soils was the highest risk practice for increased surface runoff and erosion, compared with no tillage or early cultivation in drier field conditions. Chambers et al. (2000) also found that cultivation in wet field conditions, including disrupting tramlines when ‘wet’, was likely to increase surface runoff and erosion.
- For soils under grassland management, compaction caused from travelling on land when ‘wet’ or by high stocking densities in unsuitable conditions can cause increased surface runoff and erosion due to reduced infiltration rates (Table 2.2; Appendix 1). Compacted grassland soils can be a significant source of surface runoff, which can mobilise sediment and associated water pollutants such as phosphorus (Newell Price et al., 2011).
Table 2.2: The risks associated with working ‘wet’ soils on sediment and phosphorus losses (i.e. impacts on water quality) for different farming system and soil type combinations. The symbols *, ** & *** refer to low, moderate and high risk associated with working waterlogged land respectively.

<table>
<thead>
<tr>
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<td>Roots combinable (including potatoes, sugar beet and horticultural crops)</td>
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<td>Grassland</td>
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¹ This relates to lowland peaty soils. Upland landscapes can have very high soil erosion rates and are very susceptible to overgrazing (McHugh et al., 2002).

2.3.3 Flood mitigation

- Soil structural damage caused by working ‘wet’ or waterlogged soils preferentially impacts macropores that are largely responsible for soil drainage. This impacts on both initial and saturated water infiltration rates and hence the vertical transmission of water during periods of intense or prolonged precipitation, which increases the risk of overland flow, flooding and erosion (Dexter, 1988).

- There is an inverse relationship between soil organic matter (SOM) content and surface runoff (e.g. Robinson and Woodrun, 2008; Reynolds et al. 2007). Soils that are low in organic matter are therefore not only more prone to soil compaction (Gregory et al., 2009), but also more likely to contribute towards increased flooding risk.

- Grassland can be a significant source of surface runoff and flooding risk. For example, in the Dart catchment (Devon) surface erosion of grassland soils contributed to 76-85% of channel bed sediment contribution (Collins et al., 2010). Mechanical loosening of ‘high bulk density’, soils can increase saturated water infiltration rates (BD5001) and have the potential to reduce surface runoff volumes and increase soil water storage.

- Holman et al. (2003) investigated the contribution of soil structural degradation to catchment flooding in 2000 and found that cases of severe degradation were mainly confined to late-autumn harvested crops and autumn-sown crops. Severe soil degradation was generally most common on medium and silty soils that experienced occasional or prolonged seasonal waterlogging, but was also common following late autumn harvested crops on freely draining light sand, silty and medium soils (Table 2.3; Appendix 1).

Table 2.3: The risks associated with working ‘wet’ soils on flooding risk (surface runoff) for different farming system and soil type combinations. The symbols *, ** & *** refer to low, moderate and high risk associated with working waterlogged land respectively.

<table>
<thead>
<tr>
<th>Farming system</th>
<th>Heavy</th>
<th>Medium</th>
<th>Silty/ Sandy</th>
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2.3.4 Carbon storage

- Soil erosion by water or wind can lead to significant losses of SOM. Tillage practices that reduce the level of soil disturbance may have a small positive impact on SOM levels in the long term, due to a potential reduction in SOM decomposition rates and losses (Powlson et al., 2014). However, the potential for increased carbon storage will depend on how long the reduced cultivation system can be sustained without the need for inversion tillage. There are also indications that reduced tillage results in a change to the SOM profile with depth, rather than total SOM content (Powlson et al., 2014). Working ‘wet’ or waterlogged land usually involves ploughing, which not only increases soil erosion risk due to induced compaction, but can also increase loss of SOM through mineralisation (Bhogal et al., 2009).

- Restricted rooting depth due to soil compaction can reduce crop yield and impact upon subsoil carbon storage levels (Carter and Gregorich, 2010). Reduced plant growth over many years can lead to a decline in OM returned to the soil which may cause a net loss of soil carbon as the existing carbon stores are mineralised (SP1601).

- Peaty soils are fairly resilient to soil structural degradation (associated with working ‘wet’ sols) due to the high level of organic matter present within the soil. Nevertheless, peaty soils can be compacted by livestock or wheelings and associated reductions in water infiltration rates and increases in surface runoff can result in organic matter loss through erosion (Table 2.4; Appendix 1). The greatest losses of organic matter from peaty soils occur through drainage and oxidation (Foulds and Warburton, 2007).

Table 2.4: The risks associated with working ‘wet’ soils on carbon storage as influenced by soil erosion for different farming system and soil type combinations. The symbols *, ** & *** refer to low, moderate and high risk associated with working waterlogged land respectively.

<table>
<thead>
<tr>
<th>Farming system</th>
<th>Heavy</th>
<th>Medium</th>
<th>Silty/Sandy</th>
<th>Peaty</th>
<th>Chalk &amp; Limestone</th>
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<td>Winter combinable</td>
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<tr>
<td>Roots combinable (including potatoes, sugar beet</td>
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<tr>
<td>Grassland</td>
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</table>

2.3.5 Nutrient cycling

- Reductions of up to 18% in N mineralisation linked to compaction have been reported by Breland and Hansen (1996). They suggested that an increase in physical protection of SOM and microbial biomass within smaller (compacted) pores made them inaccessible to grazing nematodes. By contrast, Gregory et al. (2007) found that compaction had little effect on microbial biomass. The impact of working waterlogged land on nutrient cycling is less certain and varies according to the nutrient (or the form of the nutrient) considered. As a result, no risk table was produced for nutrient cycling.

- Nitrous oxide emissions may increase in compacted soils that are ‘wet’ or waterlogged, particularly if conditions are warm and ‘wet’ and there is a readily accessible carbon source and mineral nitrogen for denitrifying bacteria (Bateman and Baggs, 2005).

- There is also an increased risk of ammonia volatilisation from livestock slurry applied to the surface of compacted soils due to reduced infiltration rates with slurry exposed to the air for longer periods than on well-structured soils (SP1601).

- Phosphorus (P) can only diffuse through soil at a rate of c.0.1 mm per day (Johnston, 2000; Larsen, 1967); so crop P uptake is partly dependent on the ability of root exudates to acidify the soil around root hairs and convert less readily available P to readily available P. Where
poor soil structure limits root proliferation, a smaller volume of soil and a reduced amount of soil P is available for crop uptake, thereby limiting crop growth and reducing the cycling of soil P (Johnston et al., 2001).

2.4 Conclusions

- Waterlogged soils are sensitive to degradation from farming operations through compaction and erosion.
- In medium and heavy soils the main risks occur when the soil is in a plastic state and there is an increased risk of aggregate dispersion (puddling) and spreading of soil by sliding pressure (smear). In England and Wales, approximately 45% of winter sown crops are grown on slowly permeable soils that require field drainage to maximise opportunities for field work in the autumn, winter and spring.
- Sandy and light silty soils are more susceptible to compaction through compression, partly due to their inability to re-structure through shrink-swell processes.
- Soils naturally ‘wet up’ in the autumn as day length shortens and rainfall exceeds evapotranspiration. Late autumn harvesting and establishment of crops is therefore associated with structural degradation due to the likelihood of working soils when ‘wet’ or in a plastic state.
- Working waterlogged soils can lead to compaction, reduced water infiltration and increased surface runoff and erosion which in turn can lead to impacts on a number of ecosystem services. Crop yield can be reduced due to restricted rooting and impacts on the ability of crops to sustain growth and take up water and nutrients, particularly in a wet late winter/spring or dry spring/summer. Reduced macroporosity and the development of platy structure rather than vertical fissures reduces water infiltration rates, and can both increase soil erosion rates and increase flooding risk, thereby impacting on water quality. Accelerated soil erosion can also impact on soil carbon storage. Finally, the soil structural degradation resulting from working waterlogged land can also affect nutrient cycling in terms of the rate of organic matter mineralisation and uptake of soil nutrients.
3. COST-EFFECTIVE MEASURES FOR PREVENTING DAMAGE TO SOILS

3.1 Introduction

This section assesses the costs and effectiveness of implementing measures to prevent soil waterlogging and to alleviate damage caused by accessing or working waterlogged land. The measures include those that focus on:

- Prevention – drainage (field and ditches), moling, cultivation timing, low ground pressure (LGP) tyres, tracked machinery, Controlled Traffic Farming (CTF), auto steer global positioning systems (GPS), and use of in-field track ways/stripes.
- Alleviation – sub-soiling (in arable systems) and top-soiling (in grassland).

The measures include capital investment (amortised over a number of years) such as auto steer GPS and land drainage, and others which will be carried out over a cycle of a number of years, such as moling. The assessment has derived annual costs for implementing the measures which were fully updated and referenced at 2014 levels and expressed in terms of cost per unit, i.e. per hectare or per head of livestock for a ‘typical’ farm.

Costs and returns of measures have been based on the potential to increase output. However, on many farms in many years, implementation or maintenance of measures may not result in any increase in output. For example, output returns from drainage may not be realised in every year. Nevertheless, in wet years, underdrainage system deficiencies can become widely apparent. For example, after 2012-13 there was much drainage re-installation and maintenance activity in the subsequent (drier) seasons. Experience from 2012-13 indicates that installation of drainage in recent years may have been more to do with avoiding yield losses than increasing output.

In the economic assessments below, costs are applied to a 100 ha farm where appropriate and to a larger farm (200ha or more) where economies of scale apply (i.e. the measure could not be economically applied on a 100 ha farm).

Measure effectiveness values were largely derived and adapted (based on expert opinion) from the “Mitigation Methods – User Guide” (Newell Price et al., 2011). Other sources are referenced within each section. Where evidence for effectiveness was lacking and uncertainty was particularly high, no effectiveness tables were provided. The ‘arrow strengths’ used in the effectiveness tables link to effectiveness classes (Table 3.1). For example a single downward arrow represents a 1-30% decrease and two upward arrows represent a 20-80% increase. Where the effectiveness arrows are in brackets the effectiveness is particularly uncertain.

Table 3.1: Option effectiveness classes, ranges and arrow strengths

<table>
<thead>
<tr>
<th>Description</th>
<th>Average (% change)</th>
<th>Range (% change)</th>
<th>Arrow strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>Low</td>
<td>10</td>
<td>1 to 30</td>
<td>↓</td>
</tr>
<tr>
<td>Moderate</td>
<td>40</td>
<td>20 to 80</td>
<td>↓↓</td>
</tr>
<tr>
<td>High</td>
<td>70</td>
<td>50 to 90</td>
<td>↓↓↓</td>
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</tbody>
</table>

Note: Arrow directions may also be upwards where an option increases productivity, erosion, soil organic matter or diffuse water pollution losses.
3.2 Drainage systems (installation and maintenance - field to ditch)

3.2.1 Drainage systems - costs

A functioning drainage system ensures that water is able to move through the soil profile, allowing the soil to be maintained in a 'well drained' condition and extending the window of opportunity for machinery operations and livestock grazing, particularly in autumn and spring. There are around 6 million hectares of drained soils in England and Wales (Withers et al., 2000) and for much of this land, economically sustainable arable cropping would not be possible without an effective drainage system, particularly for farmers on poorly drained soils or on fields with high ground water tables. Actively maintaining field drainage systems usually involves jetting, re-installation and renewed moling.

Drainage installation is a costly operation that typically requires many years for a return on the investment. However, on poorly drained soils artificial drainage enables more flexible field working, provides insurance against very wet years (in which loss of production/profit can be total without a drainage system) and could mean the difference between operating a combinable cropping arable system (e.g. an average gross margin per hectare of £673 for winter wheat; Nix, 2013) and a less profitable extensive livestock grazing system (e.g. an average gross margin per forage hectare of £170 for spring calving suckler cows and £351 for spring lambing flocks; Nix, 2013).

Drainage installation at 40 m spacing costs £1,500-£2,600 per hectare (based on Nix, 2013). On a 100 hectare farm, when amortised over 25 years at an annual interest rate of 5%, the annual charge would amount to between £8,460 and £10,650. Maintenance costs include moling every 4-7 years at a cost of c. £95/ha or c. £20/ha/year and amount to c. £2,000 per annum on a 100 ha farm. Drainage systems increase the number of machinery working days for cultivation, drilling and weed/disease control. In many years this can result in reduced costs (e.g. more effective timing of plant protection products, reducing the number of costly chemical applications) and higher crop yields due to better seedbeds (less likelihood of working the land when wet), reduced duration of waterlogging and better crop rooting systems due to reduced compaction. With winter wheat sold at £150/ha, an average yield increase of 5% would be worth £6,000 on a 100 hectare farm, which depending on the cost of drainage would offset 30-50% of the annual investment and maintenance costs. However, drainage systems can also help avoid catastrophic yield losses in exceptionally wet years (such as 2000-01; 2006-07 and 2012-13); reduce other costs such as sub-soiling to alleviate soil compaction; and as mentioned above can enable the adoption of high output combinable cropping systems on otherwise poorly drained land.

The costs and benefits of installing drainage were reported in Defra Project FFG0923 (Table 3.2). The effect on margin (Table 3.2, column 2) is the annual figure for the lifetime of the 25 year write-off period including the cost of maintenance. Four case study farms were used. Three were located in the Demonstration Test Catchments and a fourth in the Midlands to represent different Defra robust farm types commonly found in these areas:

i. ‘General cropping’ farm in the River Wensum catchment in Norfolk, producing combinable crops along with root crops such as potatoes and sugar beet. The farm is mainly on medium to light soils and in this case, it was assumed that 25% of the soils were sufficiently heavy to require a field drainage system. The farm also keeps a small number of beef cattle on permanent grassland.

ii. ‘Combinable cropping’ farm in the River Avon catchment in Hampshire, with a lowland livestock enterprise producing beef and sheep. The soils were mainly medium and heavy and it was assumed that 50% of the soils were drained.

iii. ‘Dairy’ farm in the River Tamar catchment on the Devon/Cornwall border. The soils were mainly heavy and it was assumed that the whole area was in grass with the whole area drained.

iv. ‘Combinable cropping and beef’ on the Midland plain in Northamptonshire on heavy soils. For this farm, it was assumed that all the soils were drained.
The literature on increased yield from drainage is sparse, but almost all report some benefit (e.g. Armstrong, 1977; Berryman, 1975; MAFF, 1983; Trafford, 1972). Such evidence as there is points to a large range of increases. In this study, the increase in output on arable land was based on a 12.5% increase in crop yield on the proportion of the farm drained; and for grassland, a 25% increase in output (due to increased grass dry matter - DM - yield and, for example, increased liveweight gain in beef cattle) on the proportion of grassland drained (MAFF, 1983). The effect was therefore greater on grassland than on arable land (MAFF, 1981, 1983; Trafford, 1972), as can be seen in Table 3.2 with a £7,000 increase in gross margin on the 100% drained dairy farm and a £22,000 increase in margin with 60% grant aid. On all the other case study farms, the effect of drainage on margin was negative for the ‘average’ year represented (Table 3.2).

Table 3.2: Economic effect of drainage (FFG0923)

<table>
<thead>
<tr>
<th>Case study farm type</th>
<th>Effect of drainage on margin (£)</th>
<th>Area of farm drained (%)</th>
<th>Arable output increase (%)</th>
<th>Grassland output increase (%)</th>
<th>Effect on margin with 60% grant (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>General cropping (25% drained)</td>
<td>-12,500</td>
<td>25</td>
<td>12.5</td>
<td>25</td>
<td>-5,300</td>
</tr>
<tr>
<td>Combinable cropping (50% drained)</td>
<td>-15,000</td>
<td>50</td>
<td>12.5</td>
<td>25</td>
<td>-1,500</td>
</tr>
<tr>
<td>Dairy (100% drained)</td>
<td>7,000</td>
<td>100</td>
<td>12.5</td>
<td>25</td>
<td>22,000</td>
</tr>
<tr>
<td>Combinable cropping + beef (100% drained)</td>
<td>-24,000</td>
<td>100</td>
<td>12.5</td>
<td>25</td>
<td>-3,000</td>
</tr>
</tbody>
</table>

On arable land, there was a net reduction in margin, even with a 60% grant rate (representing the situation when drainage installation activity was at its peak), which indicates that installing drainage schemes does not give a direct economic return for most farm businesses. However, artificial drainage schemes can provide:

i. Insurance against yield loss in very wet years (e.g. in 2012-13).
ii. Greater opportunities to access land and may mean the difference between having all the land within a heavy land combinable cropping enterprise in autumn-sown crops (with drainage) as opposed to having a proportion in spring crops or fallow land (without drainage).

Furthermore, the calculations include maintenance costs which usually occur following failure, e.g. when a drain fails or a headwall becomes blocked. In addition, the drainage systems were costed over a 25 year write-off period after which only maintenance costs remain. In reality, maintenance is often not carried out (i.e. zero cost) for many years and the farm bears no direct or amortised cost for the drainage system.

The costs of maintaining a drainage system (moling and ditching at five year intervals and a maintenance charge of 0.5% of the original capital cost) have never been grant aided and have an important influence on the impact of investments in drainage on farm margins.

The effect on margins on the farming systems described in Table 3.2 include the investment cost of the drainage system and the annual maintenance costs. However, taking just the capital cost of installation over a 25 year investment period, the losses on the arable dominated farms return to profit at a grant aid rate of only 30%. However, the maintenance costs remain significant, which may explain why on many farms the drains are not maintained on a regular basis, leading to some deterioration in drain performance. Without grant aid or a catastrophic yield reduction, there is little incentive to re-install or maintain drainage systems. In many
cases, and depending on the relative prices of inputs and produce, the return on investment 
in terms of increased crop yield) does not justify the cost of drainage maintenance and repair, 
although in some cases the return on investment could be measured by the difference in gross 
margins between grassland and arable production (see above), since on some heavy land 
arable cultivation is not viable year on year without drainage.

3.2.2 Drainage systems - effects

Productivity – the main benefit of drainage systems is to extend the window of opportunity for 
machinery operations and livestock grazing in autumn and spring, particularly on heavy soils 
with a slowly permeable subsoil. Drainage systems may also benefit root and horticultural 
cropping in peaty soils that require ground water table management (e.g. in the Fens). Yield 
increases following drainage can occur due to improved seedbed conditions (reduced 
likelihood of working the soil when it is wetter than the lower plastic limit) and reduced duration 
and intensity of waterlogging (MAFF, 1972, 1983; Table 3.3). Wright and Sands (2009) suggest 
that drainage can lead to yield benefits of up to 20% in spring cereals.

A functioning under drainage system is a pre-requisite that underpins the viability of production 
on many arable and horticultural farms on medium, heavy or peaty soils. In many cases, 
drainage is therefore a fundamental part of the production system rather than a measure that 
can be viewed in terms of cost-effectiveness.

Table 3.3: The effectiveness of the installation and maintenance of drainage systems on 
productivity for different farming system and soil type combinations (MAFF, 1983; 
Trafford, 1972).

<table>
<thead>
<tr>
<th>Farming system</th>
<th>Heavy</th>
<th>Medium</th>
<th>Silty/Sandy</th>
<th>Peaty</th>
<th>Chalk &amp; Limestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter combinable</td>
<td>↑</td>
<td>↑</td>
<td></td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Roots combinable (including potatoes, sugar beet and horticultural crops)</td>
<td>↑</td>
<td>N/A</td>
<td>↑</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Grassland</td>
<td>↑</td>
<td>↑</td>
<td>N/A</td>
<td>↑</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Organic matter – soil organic matter tends to reduce with improved drainage/aeration, 
particularly in organic mineral and peaty soils (Kirk et al., 2012; Table 3.4). Peat shrinkage and 
subsidence following drainage has led to considerable SOM losses in lowland organic/peaty 
soils, such as the Fens and Lancashire Peat Mosses (Holden et al., 2007). Maintaining 
drainage systems can also reduce erosion–related losses of organic matter through reduced 
compaction and surface runoff, although in some circumstances soil erosion may be a sink for 
carbon due to re-deposition of carbon on lower slopes and storage of carbon through 
replacement by crop residue carbon in erosional slope positions (Dungait et al. (2013). 

Soil erosion – Maintaining field drainage systems reduces the period when soils are at risk 
from compaction and poaching, and reduces the risk of surface runoff and erosion (Newell 
Price et al., 2011; Table 3.4). Soil structure is generally improved and water infiltration rates 
increased, resulting in lower surface runoff volumes. The risks of soil erosion are therefore 
generally reduced as a result of maintaining underdrainage systems.

Diffuse water pollution – Drainage systems can accelerate the delivery of agricultural 
pollutants from land to a watercourse, by acting as a preferential (by-pass) flow route; 
hydrological connectivity and the potential transfer of pollutants to the watercourse is generally 
increased through drainage, particularly in structured clay soils and/or where mole drainage is 
used. On sloping land there is a potential for surface run-off losses to increase where drains 
have deteriorated (see above), potentially resulting in erosion and the loss of sediment and 
associated pollutants to water. On balance, installing and maintaining drainage systems and
the production systems that they support generally increase nitrate leaching, and sediment and P losses, particularly within grassland systems (Newell Price et al., 2011).

Effects of maintaining drainage systems will be similar across applicable soil types (i.e. medium, heavy and peaty soils) although the long term impact on peaty soils will be greater if peaty layers are ultimately lost or incorporated into underlying mineral soil layers. Effects on erosion and diffuse pollution are therefore given irrespective of soil type (Table 3.4).

Table 3.4: The effects of drainage system installation and maintenance in grassland on soil organic matter, soil erosion and diffuse pollutant losses (Kirk et al., 2012; Newell Price et al., 2011).

<table>
<thead>
<tr>
<th>Soil organic matter</th>
<th>Erosion</th>
<th>Nitrate</th>
<th>Sediment</th>
<th>Particulate P</th>
<th>FIOs*</th>
</tr>
</thead>
<tbody>
<tr>
<td>↓</td>
<td>(↓)</td>
<td>(↑)</td>
<td>(↑)</td>
<td>(↑)</td>
<td>(~)</td>
</tr>
</tbody>
</table>

( ) Uncertain.
* Faecal indicator organisms
Change arrows apply to grassland.

Note: Maintenance of an effective drainage system is taken as 'baseline' management for arable land, as without an effective drainage system, economically sustainable arable cropping would not be possible on most medium/heavy soils.

3.3 Moling

Moling – costs

Mole drainage should be a regular (every 5-7 years) activity on many soils in order to ensure fields can be cultivated in a timely fashion and to allow adequate drainage for crop growth. However, moling is a costly activity in time and fuel and is most suitable for land where the clay content of the subsoil is greater than 30% (Nicholson, 1942). However, clay content per se is not the only issue determining the viability of mole drains, as subsoil stability is also an important factor, which may limit the viability of mole drains. Table 3.5 shows the cost of moling for the four farm scenarios described above, carried out at five year intervals (FFG0923).

Table 3.5: Cost of moling £/ha of whole farm (100 ha) at 5 year intervals (FFG0923).

<table>
<thead>
<tr>
<th>Case study farm type</th>
<th>Cost of moling (£/ha of whole farm)</th>
<th>Proportion of farm moled</th>
</tr>
</thead>
<tbody>
<tr>
<td>General cropping (25% drained)</td>
<td>1.20</td>
<td>25%</td>
</tr>
<tr>
<td>Combinable cropping (50% drained)</td>
<td>4.75</td>
<td>50%</td>
</tr>
<tr>
<td>Dairy (100% drained)</td>
<td>19.00</td>
<td>100%</td>
</tr>
<tr>
<td>Combinable cropping + beef (100% drained)</td>
<td>19.00</td>
<td>100%</td>
</tr>
</tbody>
</table>

On slowly permeable soils, moling and drainage maintenance can determine whether or not arable production is viable; and so the main economic benefit is in the difference between gross profit margins achievable within arable and grassland production systems. On impermeable soils, where drain spacing is greater than 20 m, the effectiveness of the drainage system will decline to close to undrained status in the absence of moling.

Moling – effectiveness

The effects of moling on productivity, soil organic matter content, erosion and diffuse pollution are the same as those associated with field drainage system installation and maintenance (section 3.2.2; Tables 3.3 and 3.4).
3.4 Cultivation timing

Cultivation timing - costs

Cultivation timing can have many implications for arable production, including impacts on yield potential and weed/disease pressure. As a general principle, the later that soils are cultivated in the autumn, the greater the likelihood of structural damage (as wetter soils are more prone to compaction) with associated potential impacts on crop establishment and yield. In the scenario tested here, land intended for late sown winter wheat was cultivated instead in spring for a spring barley crop.

To quantify the effect of cultivation timing on outputs it was assumed that in a wet year on heavy soils it was not possible to establish winter wheat in late autumn (because of wet soil conditions) and a proportion of the cereal acreage was replaced by spring barley established by spring cultivations. It was assumed that wheat established in late autumn had a gross margin 15% lower than a crop drilled in late September/early October (Dennett, 1999; Spink et al., 2000) and that spring barley established following spring cultivations (as was the case in this scenario) would produce 75% of the output of a spring barley crop sown following autumn ploughing, based on a likely poorer seedbed and reduced plant population (Conry, 1998). The change from late autumn drilled winter wheat to spring cultivated spring barley would result in a loss of gross margin of c. £213/ha (Table 3.6).

Table 3.6: Economic impact of changing from late winter wheat to spring cultivated spring barley due to a very wet autumn.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Assumed impact on productivity</th>
<th>Gross margin (£/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late-sown winter wheat</td>
<td>Yield lower than earlier drilled wheat</td>
<td>532</td>
</tr>
<tr>
<td>Spring barley – all cultivations in spring</td>
<td>Yield lower than spring barley following autumn cultivation</td>
<td>319</td>
</tr>
<tr>
<td>Change in gross margin (£/ha)</td>
<td></td>
<td>-213</td>
</tr>
</tbody>
</table>

(Data based on Nix 43rd edition)

Cultivation timing – effects

Productivity – Gross margins for spring sown cereal crops are typically lower than autumn sown cereal crops because of lower yields. For example, the difference in gross margin between winter wheat and spring barley is typically c. £125 per ha (Nix, 2013). However, in some situations delaying cultivations may be beneficial in terms of controlling black grass and other herbicide resistant weeds, resulting in a potential increase in productivity over the rotation. No effectiveness table is provided in this instance due to the difficulty of generalising the overall impact of delayed cultivation, better soil structure and changed cropping over a crop rotation. This will vary according to specific site conditions, such as the severity of herbicide resistant weed infestation.

Organic matter – Soil organic matter is mainly affected by adding organic amendments, reducing cultivation or increasing net productivity over many years. For example, applying bulky organic manures, reverting arable land to grassland and growing a cover crop, rather than leaving a field in overwintered stubbles over several crop rotations, can result in soil organic matter increases (Newell Price et al., 2010; Kirk et al., 2012). Cultivation timing is therefore unlikely to have a significant effect on soil organic matter content (Kirk et al., 2012).

Soil erosion – Soil erosion is influenced by the amount of bare soil exposed during late autumn and winter (Evans, 1990) and soil moisture content at the time of cultivation (Martin, 1999). Reducing soil degradation risk in the post-harvest period is best achieved through retaining crop residues or establishing good vegetation cover (>25-30%) over the autumn/winter period (Chambers et al., 2000; Evans, 1990). By cultivating in spring, there will be less risk of soil structural degradation, surface runoff and erosion as retained cereal stubble residues...
protect the soil surface from erosive rainfall. Soil erosion risk is also generally reduced if land is cultivated in dry conditions when soils are in a friable state (Martin, 1999).

**Diffuse water pollution** – Cultivation timing will have some influence on nitrate leaching losses. Early autumn cultivation followed by delayed establishment (e.g. stale seedbeds) is the worst case scenario for nitrate leaching and spring cultivation is the best for reducing nitrate leaching losses (Newell Price et al., 2011). Differences in nitrate leaching losses between late autumn cultivation and early spring cultivation may not be large since soil mineralisation rates are often reduced in late autumn. However, effects will depend on whether a crop is established soon after cultivation and soil temperature (which is key to controlling mineralisation of soil organic nitrogen), with nitrate leaching following late autumn cultivation more likely in the milder south and west, especially where a crop is not established. Cultivating in spring rather than late autumn will generally reduce sediment and associated particulate P losses (Newell Price et al., 2011) since spring cultivation enables retained cereal stubble residues to protect the soil surface from rainfall and runoff in autumn and winter and can mean that working wet soils can be avoided (Table 3.7). This is the case even in a wet spring if cultivation can be delayed until soil conditions allow.

**Table 3.7: The effects of delaying cultivation from autumn to spring on soil organic matter, soil erosion and diffuse pollutant losses (Newell Price et al., 2011).**

<table>
<thead>
<tr>
<th>Soil organic matter</th>
<th>Erosion</th>
<th>Nitrate</th>
<th>Sediment</th>
<th>Particulate P</th>
<th>FIOs</th>
</tr>
</thead>
<tbody>
<tr>
<td>~</td>
<td>↓</td>
<td>↓(✓)</td>
<td>↓</td>
<td>↓</td>
<td>~</td>
</tr>
</tbody>
</table>

(✓) Uncertain.

### 3.5 Low Ground Pressure (LGP) tyres

**3.5.1 LGP tyres – cost**

LGP tyres can be effective in reducing topsoil and subsoil compaction. They are generally wider than conventional tyres and work at lower pressures. Topsoil compaction from tyres is mainly determined by contact pressure, with the level of maximum stress approximately 50 kPa higher than the inflation pressure (Keller, 2005; Schjønning et al., 2006), whereas subsoil compaction is mainly determined by axle/wheel load (Lamandé et al., 2007; Lamandé and Schjønning, 2008; Batey, 2009).

Due to the higher cost of LGP tyres, on most farms considering replacing conventional tyres it can be assumed that LGP tyres would be selected as an upgrade when a new machine is purchased rather than as a replacement of conventional tyres on existing machinery. Silgram et al. (2014) assumed that LGP tyres (e.g. Ultraflex from Michelin, designated ‘VF’) rather than standard radial tyres were purchased for the whole wheeled machine inventory, which for a typical farm would cover two tractors, a trailed sprayer, a combine, two grain trailers and a drill. In this example a 200 ha farm was used, since it is likely to be the lower farm size limit in terms of cost-effectiveness for such an investment. Most farms of 100 ha or less use second hand or older machinery for heavy field work or may even contract out the whole arable operation.

The cost of replacing conventional tyres with LGP tyres was estimated at c. £7,000 (Silgram et al., 2014; Table 3.8). On an amortised basis, the additional cost over five years at 7% was calculated at c. £1,780, which is equivalent to, c. £9/ha on a 200 ha farm (Table 3.8).
Table 3.8: Cost of upgrading to ‘VF’ low ground pressure tyres

<table>
<thead>
<tr>
<th></th>
<th>Conventional (£)</th>
<th>‘VF’ (£)</th>
<th>Upgrade (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Tractors</td>
<td>10,100</td>
<td>12,644</td>
<td>2,544</td>
</tr>
<tr>
<td>Trailed sprayer</td>
<td>3,400</td>
<td>4,096</td>
<td>696</td>
</tr>
<tr>
<td>Combine</td>
<td>10,100</td>
<td>12,644</td>
<td>2,544</td>
</tr>
<tr>
<td>2 Trailers</td>
<td>600</td>
<td>1,200</td>
<td>600</td>
</tr>
<tr>
<td>Drill</td>
<td>1,650</td>
<td>2,226</td>
<td>576</td>
</tr>
<tr>
<td>Total</td>
<td>25,850</td>
<td>32,810</td>
<td>6,960</td>
</tr>
<tr>
<td>Amortised cost</td>
<td></td>
<td></td>
<td>1,780</td>
</tr>
<tr>
<td>Farm area (ha)</td>
<td></td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>Upgrade cost (£/ha)</td>
<td></td>
<td></td>
<td>9</td>
</tr>
</tbody>
</table>

The additional cost of LGP compared with conventional tyres can be offset by increases in crop yields as a result of reduced soil compaction and longer tyre life than conventional tyres. Chamen (2011) suggested that yield increases of 5-10% were possible for winter cereal crops where LGP tyres were used compared with conventional. Also, LGP tyres can be expected to last up to 80% longer due to the higher quality build and reduced rolling resistance compared with conventional tyres (Table 3.9).

Table 3.9: Cost of upgrading to LGP tyres on life (hrs.) basis

| Total cost of VF tyres (£) | £32,810.00 |
| VF tyre life (hours)       | 9,000.00   |
| Cost of VF tyre (£/hr)     | £3.65      |
| Total cost of conventional tyres (£) | £25,850.00 |
| Conventional tyre life (hours) | 5,000.00  |
| Cost of conventional tyre (£/hr) | £5.20    |
| Difference (£/hr) in favour of VF tyres | £1.50    |

The lower rolling resistance of VF tyres also has the potential to reduce fuel consumption by at least 15% (Gordon Brookes, Michelin, pers. comm.) compared with conventional tyres.

3.5.2 Low Ground Pressure tyres – effects

Productivity – Yield reductions due to topsoil compaction generally range from 5 to 25% across a range of crops from winter wheat to forage grass (Graham et al., 1986; Vermeulen and Klooster, 1992; Håkansson, 2005). This is a similar range to that reported by Defra project SP1305 (Hallett et al., 2012) from 24 estimates of crop yield reductions on clay, medium and sandy soils. Mean percentage yield reductions and the number of studies carried out (in brackets) were:

- Clay - 17% (14)
- Medium - 4% (5)
- Sandy - 25% (5)
Compaction effects on productivity can be divided into three aspects (Håkansson and Reeder, 1994):

i) a cultivated/topsoil layer effect lasting c.5 years

ii) an effect from compaction of the 25-40 cm layer; normally alleviated within ten years

iii) an effect due to soil compaction at > 40 cm depth that is persistent and typically amounts to a c.2.5% yield penalty

Arvidsson and Håkansson (1991) modelled the effect of soil compaction on crop yields for standard and optimised slurry spreading systems (Table 3.10) on a sandy loam soil. In each system, the soil was ploughed each autumn and manure was spread and incorporated a few days before drilling of a spring cereal. An 8 m$^3$ slurry tanker, weighing 4 tonnes when empty was used to spread the slurry and the tanker was pulled by a 6 tonne tractor. The two systems differed in terms of the wheel loads, the mean ground pressure, the width of spreading, the soil water content at the time of spreading and the nature of trafficking (planned or not).

**Table 3.10: Characteristics of two slurry spreading systems.**

<table>
<thead>
<tr>
<th>System 1 (standard)</th>
<th>System 2 (optimised)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tractor front axle: 2 tonnes</td>
<td>Tractor front axle: 2 tonnes</td>
</tr>
<tr>
<td>Tractor rear axle: 7 tonnes</td>
<td>Tractor rear axle: 7 tonnes</td>
</tr>
<tr>
<td>Wagon single axle: 9 tonnes</td>
<td>Wagon tandem axle: 9 tonnes</td>
</tr>
<tr>
<td>Mean ground pressure: 140/200 kPa</td>
<td>Mean ground pressure: 80 kPa</td>
</tr>
<tr>
<td>Spreading width: 6 m</td>
<td>Spreading width: 12 m</td>
</tr>
<tr>
<td>Wet soil</td>
<td>Medium dry soil</td>
</tr>
<tr>
<td>Poorly-planned traffic (total driving distance = 4 x spreading distance)</td>
<td>Well-planned traffic (total driving distance = 1.8 x spreading distance)</td>
</tr>
</tbody>
</table>

The effects from compaction in the year of establishment dominate (Table 3.11) and the additional effect on yield losses of higher ground pressure tyres and poorly-planned traffic was estimated as c.9%. The compaction effects in the subsoil mainly depend on the wheel load, which in system 2 was reduced through the use of a tandem axle. The example given may underestimate the effects of compaction within some current systems since the total weight of tractor/trailer slurry spreading systems on some farms may be as high as 50-55 tonnes with axle loads of 13-15 tonnes (Schjønning et al., 2010). Results from an international series of experiments (Scotland, Denmark, Sweden, Finland, Unites States of America and Canada) by Håkansson (2005) indicated that the residual effect of compaction was highest for clay soils. However, this effect is not sufficient to increase the effectiveness class for heavy soils (relative to other soil types) in this study (Table 3.1 and Table 3.14).

Traffic in a growing crop can also cause yield reductions due to direct plant damage in arable as well as grassland crops (Schjønning et al., 2010). The damage from spraying-related traffic may be considerable because it can take place at a late growth stage when there is insufficient time for the plants to recover. Tyres with low inflation pressures and small lugs minimize crop damage.

Campbell et al. (1986) investigated the effects of contrasting trafficking treatments on winter barley yields on a loamy soil (22% clay). A low tyre pressure treatment increased yield by c.3% relative to un-trafficked soil, indicating that consolidation in the un-trafficked soil was below the optimum. The results suggested that on some loamy soils, wide, low-pressure tyres may be more appropriate than using permanent traffic lanes or ‘controlled traffic’ zones.
Table 3.11: Estimated crop yield losses (%) due to soil compaction when slurry spreading prior to drilling of a spring cereal on a sandy loam soil (Adapted from Håkansson, 2005).

<table>
<thead>
<tr>
<th>Type of effect</th>
<th>System 1</th>
<th>System 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Same year plough layer effects</td>
<td>8.9</td>
<td>2.8</td>
</tr>
<tr>
<td>2. Residual plough layer effects</td>
<td>1.5</td>
<td>0.2</td>
</tr>
<tr>
<td>3. Effects in the 25-40 cm layer</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>4. Effects in the &gt;40 cm layer</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Total yield loss (sum of 1-4): %</td>
<td>11.6</td>
<td>3.1</td>
</tr>
</tbody>
</table>

* Effect may vary considerably depending on methods of seedbed preparation and drilling.

Batey (2009) proposed that, to avoid compaction deeper than 40 cm, axle loads should be restricted with a limit of 6 t on a single axle or 8–10 t on a tandem axle. Furthermore, for trafficking in ‘wet’ field conditions, wheel loads should be reduced to a maximum of c.3.5 tonnes. This can be achieved by increasing the number of axles on trailers and/or reducing the weight of machinery. In combination with the use of dual wheels and wider, LGP tyres, reduced wheel loads will protect the subsoil from serious and permanent compaction and automatically provide a benefit to the plough layer soil because the full potential of modern flotation tyres can then be achieved.

**Organic matter** – The use of LGP tyres could potentially result in small increases in crop yield and reduced erosional losses, although it is unlikely to result in higher soil organic matter content (Kirk *et al.*, 2012; Table 3.12).

**Soil erosion and diffuse water pollution** – There is some evidence that the use of LGP tyres can reduce soil erosion that is concentrated down tramlines. Stranks (2006) reported significant reductions in rolling resistance, rut depth and compaction depth as a result of using lower pressure tyres.

The use of LGP tyres on tramlines should reduce surface runoff and associated losses of particulate P. ‘Compacted’ tramlines can act as concentrated flow pathways during periods of increased surface runoff (Silgram *et al.*, 2010). If tramlines are present, for example, as a result of the need to apply agro-chemicals during the autumn period, LGP tyres can help limit soil compaction and maintain water infiltration rates (Newell Price *et al.*, 2011).

Table 3.12: The effects of the use of LGP tyres on organic matter, soil erosion and diffuse pollutant losses.

<table>
<thead>
<tr>
<th>Soil organic matter</th>
<th>Erosion</th>
<th>Nitrate</th>
<th>Sediment</th>
<th>Particulate P</th>
<th>FIOs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(~)</td>
<td>↓</td>
<td>~</td>
<td>↓</td>
<td>↓</td>
<td>~</td>
</tr>
</tbody>
</table>

() Uncertain.

3.6 Tracked Machinery

3.6.1 Tracked machinery - costs

Tracks fitted to machinery can significantly reduce average ground pressure relative to conventional tyres and provide excellent traction thereby reducing wheel slip, although there can be uneven distribution of contact pressure along the length of each track due to the concentration of pressures below the sprockets and rollers (Soane *et al.*, 1981; Horn *et al.*, 2004).

The cost assessment below used a combinable cropping system as the model farm. Track units are only available for the largest combines with the highest working capacity (Class Farm
Machinery, Suffolk; Knight et al., 2009). This type of high capacity machinery is designed for very large acreages and in the example below, the farm area used is 1,200 hectares. This is at the upper end of the Defra classification of very large arable farms for which the threshold is 590 ha, but could also be applicable to a contractor supplying a number of holdings.

In this combinable cropping system, the combine harvester exerts the highest ground pressure; and so tracks were fitted to a combine formerly fitted with conventional tyres. It was also assumed that other machinery within the combinable crop enterprise (e.g. tractors and trailed sprayers) would be fitted with LGP tyres, at lower cost than tracks, to avoid negating the benefits of the tracks. Other machinery included a fleet of tractors and trailers, together with a self-propelled sprayer.

The additional cost of fitting tracks to a new combine was £38,000 (Claas Farm Machinery, Suffolk), representing a substantial upgrade for the highest capacity combines requiring a harvest area of at least 1,200 ha/year to justify the investment (Claas Farm Machinery, Suffolk). The LGP tyre upgrade for the rest of the fleet was assumed to be carried out at the time as replacing the combine at a cost of £8,000 (Michelin; Table 3.13), although in practice, this may occur over a period of years as other machines and tyres need replacing.

On an amortised basis, the total upgrade cost was c. £11,200 per year or £9.40/ha; an insignificant overall cost at this scale, taking into account potential savings in sub-soiling costs and fuel usage.

**Table 3.13: Cost of upgrading to tracked combine & VF tyres**

<table>
<thead>
<tr>
<th>Implement</th>
<th>Upgrade cost (£/vehicle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upgrade to VF tyres</td>
<td></td>
</tr>
<tr>
<td>3 Tractors</td>
<td>3,900</td>
</tr>
<tr>
<td>Self-propelled sprayer</td>
<td>1,600</td>
</tr>
<tr>
<td>3 Trailers</td>
<td>900</td>
</tr>
<tr>
<td>Drill</td>
<td>600</td>
</tr>
<tr>
<td>Upgrade to tracks on replacement combine</td>
<td>38,000</td>
</tr>
<tr>
<td>Total cash cost</td>
<td>46,000</td>
</tr>
<tr>
<td>Amortisation (5 years @ 7%)</td>
<td>244</td>
</tr>
<tr>
<td>Annual amortised cost of upgrade</td>
<td>11,200</td>
</tr>
<tr>
<td>Assumed area - combinable crop farm</td>
<td>1,200</td>
</tr>
<tr>
<td>Upgrade costs £/ha</td>
<td>9</td>
</tr>
</tbody>
</table>

Whilst the capital required to upgrade to a tracked combine is only likely to be justified on a very large farm (i.e. > 590 ha as defined by Defra Robust Farm Types) the potential savings may be attractive on smaller farms as the additional finance costs may be worth the potential reduction in soil structural problems (particularly deeper subsoil compaction) and savings in fuel use. However, the high initial capital cost of combines that can be fitted with tracks may preclude the upgrade (to tracks) on all but very large farms or contractors covering large acreages.

On a 1,200 ha farm, a yield increase of c.1% per hectare per year would pay for the additional cost not including the reduction in sub-soiling costs. A fuel saving of 11% (fuel @ £0.70/litre) or a reduction in sub-soiling costs of c.40% would be required to pay for the increased finance costs.
In terms of the number of farms operating at this scale, the Farm Business Survey indicates that there were around 1,700 ‘large and very large’ farms (> 360 ha) in 2012/2013. However, many farms are now farmed under a contract farming arrangement in which the effective size of the combined farming unit does not appear on any data set. In addition, larger machines are more likely to be used by farm contractors where output efficiency is a key driver for the business.

3.6.2 Tracked machinery - effects

Productivity – Rubber track systems do not universally reduce topsoil compaction, but compared with standard radial tyres can be relied upon to protect subsoils (Keller et al., 2002; Ansorge & Godwin, 2007 & 2008; Chamen, 2011) with potential yield increases of 1-3% across different crops and soils due to reductions in ‘residual’ or persistent compaction (Table 3.14; Hallett et al., 2012; Knight et al., 2009; Schjønning et al., 2010).

Table 3.14: The effectiveness of low ground pressure tyres and tracked machinery on productivity for different farming system and soil type combinations (Hallett et al., 2012; Knight et al., 2009; Schjønning et al., 2010).

<table>
<thead>
<tr>
<th>Farming system</th>
<th>Heavy</th>
<th>Medium</th>
<th>Silty/Sandy</th>
<th>Peaty</th>
<th>Chalk &amp; Limestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter combinable</td>
<td>↑</td>
<td>↑</td>
<td></td>
<td></td>
<td>(↑)</td>
</tr>
<tr>
<td>Roots combinable (including</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>potatoes, sugar beet and</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>horticultural crops)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grassland</td>
<td>(↑)</td>
<td>(↑)</td>
<td>(↑)</td>
<td>(↑)</td>
<td>(↑)</td>
</tr>
</tbody>
</table>

Organic matter – Compared with the use of standard radial tyres, the use of tracked machinery could potentially result in small increases in crop yield and reduced erosional losses. However, it is unlikely that the measure would result in measurable increases in soil organic matter content (Kirk et al., 2012). The effect would be greatest in cultivated (arable and horticulture) systems.

Soil erosion – Erosion risk is reduced when soil structure is improved, due to increased water infiltration rates and lower surface runoff volumes. The use of tracked machinery therefore has the potential to reduce erosion risk, although there is very limited direct evidence to support the use of tracked machinery as an erosion mitigation option (Hallett et al., 2012). The effect would be greatest in arable and horticultural systems prone to erosion.

Diffuse water pollution – The use of tracked machinery can reduce subsoil compaction, thereby reducing the duration and intensity of waterlogging. This should reduce the likelihood of trafficking waterlogged land and reduce the loss of pollutants associated with surface runoff and sediment (Martin, 1999; Newell Price et al., 2011). The effects are likely to be greatest in arable and horticultural systems (Table 3.15). However, nitrate leaching losses are unlikely to be affected (Table 3.15).

Table 3.15: The effects of tracked machinery use on organic matter, soil erosion and diffuse pollutant losses in arable and horticulture systems.

<table>
<thead>
<tr>
<th>Soil organic matter</th>
<th>Erosion</th>
<th>Nitrate</th>
<th>Sediment</th>
<th>Particulate P</th>
<th>FIOs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(~)</td>
<td>↓</td>
<td>~</td>
<td>↓</td>
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</tr>
</tbody>
</table>

( ) Uncertain.
3.7 Controlled Traffic Farming

3.7.1 Controlled Traffic Farming - costs

CTF is not a fixed system; it varies from one farm to another with costs varying widely depending on the starting point (Chamen, 2011). The farm machinery inventory and infrastructure may be difficult to adapt or relatively easy, hence meaningful costs are difficult to provide. However, Knight et al. (2009) claim that “the additional costs of CTF are minimal, provided that the appropriate machinery are purchased within their normal replacement cycles”.

CTF is a way of managing soils and crops, such that all field traffic is supported in permanent lanes with crop growth taking place on non-trafficked, wide beds. CTF uses adapted machinery to confine all traffic to the least possible area of permanent traffic lanes. CTF is an approach rather than a specific product or system. It is based on findings that random trafficking of fields during cultivations and harvesting can result in trafficking 85% of the field area (Chamen, 2011). The associated damage to soil structure has the potential to reduce crop yields.

By avoiding ploughing and adapting the same axle width for all the wheeled traffic engaged in field operations, it can be possible to reduce the field trafficked area to 30% (Vermeulen et al., 2007). Crop yields on un-trafficked land can be 5% to 35% higher than on trafficked land (Chamen, 2011). In addition, by using reduced/minimal cultivation techniques rather than ploughing, fuel use can be lowered by c. 30% (McPhee et al., 1995) and the timeliness of field operations can be improved. Minimal tillage also reduces cultivation time (Defra project SP1605B).

CTF can be difficult to achieve on many farms due to the expense of converting machines or amending purchasing policy, and unsuitable infrastructure such as narrow tracks, bridge crossings and underpasses, lanes and the presence of trees and hedges. CTF can be carried out on any soil type, but is most applicable to intensive arable cultivation systems.

The incidence of herbicide resistant black-grass can be a problem within CTF systems and one option is to carry out an initial ploughing operation before setting up the CTF in order to bury weed seeds. Herbicide choices are limited and need to be linked to careful cultivation timing, but in spite of this, ploughing is typically carried out at around five yearly intervals to aid weed control.

The operating width of farm machinery is an important factor to consider when determining the spacing for permanent tracks in CTF systems. For example, the width of the combine cutter bar may be incompatible with the distance between wheelings established for other field operations (Knight et al., 2009). This could reduce the yield benefit of CTF or compromise the harvesting operation. A track spacing of greater than 6 m is required to achieve significant reductions in trafficked areas. This would require large scale machinery (e.g. a combine with a 12 m cutter bar), thereby increasing the cost of CTF compared with conventional systems. Combine harvester manufacturers are aware of the issue and some plan to introduce cutter bar widths that will be compatible with some CTF inter-wheeling distances (Knight et al., 2009). CTF is usually best suited to large fields with gentle slopes to ensure efficient use of large scale machinery.

In spite of such difficulties, some relatively simple steps can be taken to reduce trafficking at modest cost without the need for CTF. Many tractors and other wheeled machinery have the facility to have their track width altered from the standard 1.8 m to widths appropriate for CTF at relatively low cost (i.e. c.£500/axle).

3.7.2 Controlled Traffic Farming – effects

Productivity – Tullberg et al. (2001) reported a yield increase of 16% in CTF systems for cereal production in Australia. Hallett et al., (2012) reported yield increases of 5-15% across a range of crops, while others have reported increases in yield up to 25% in the non-trafficked zones (Chamen et al., 1994), and overall yield increases in winter cereals from CTF in the
order of 2-8% (Chamen, 2011; Knight et al., 2009). Although there has been little research on CTF in Europe, yield increases due to CTF have been observed in the UK on both heavy (Hanslope, Beds) and light (Ashley, Norfolk) soils.

**Organic matter** – Soil organic matter (SOM) content tends to increase with reduced cultivation/aeration (Defra project SP1106); and so CTF systems might be expected to increase organic matter content over time. However, the requirement for rotational ploughing to reduce weed burden within some combinable cropping systems not only compromises the CTF system, but also reduces the likelihood of increasing SOM content (Table 3.16).

**Soil erosion** – Within CTF systems, there is some potential to create a concentrated flow of surface runoff down compacted tramlines that can enhance soil surface erosion and potential diffuse pollution. However, if the non-trafficked area has higher porosity (Lamers et al., 1986) and elevated water infiltration rates compared to conventionally trafficked soil, surface runoff generated on the tramlines may infiltrate in the un-trafficked ‘bed’ areas, especially if a convex camber is created on the tramlines to shed water into the cropped areas. Erosion rates are only likely to be higher if unconsolidated cropped areas (i.e. lower porosity, reduced soil to seed contact and less water movement through capillary flow) result in lower vegetation cover in the autumn. Overall, erosion risk is therefore likely to be lower within a CTF system. Gasso et al. (2013) reported reductions in surface runoff of 27-42% in a CTF system, compared with conventional trafficking, and likely reductions in associated erosion and nutrient/pesticide losses (Table 3.16).

**Diffuse water pollution** – Improved soil structure and higher water infiltration rates will tend to result in reduced surface runoff and reduced sediment and particulate P losses (Gasso et al., 2013). Higher yields should result in lower residual soil mineral N post-harvest and reduced cultivation will tend to reduce mineralisation resulting in an overall reduction in nitrate leaching losses (Table 3.16; Newell Price et al., 2011).

**Table 3.16: The effects of the use of CTF systems on organic matter, soil erosion and diffuse pollutant losses in cultivated (arable and horticulture) systems (Gasso et al., 2013; Kirk et al., 2012; Newell Price et al., 2011).**

<table>
<thead>
<tr>
<th>Soil organic matter</th>
<th>Erosion</th>
<th>Nitrate</th>
<th>Sediment</th>
<th>Particulate P</th>
<th>FIOs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(↑)</td>
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</tbody>
</table>

( ) Uncertain.

### 3.8 Auto-steer GPS to reduce under and overlaps

#### 3.8.1 Auto-steer costs

Auto-steer uses satellite guidance to allow improved accuracy of fieldwork. This is achieved by installing an electronic steering wheel and satellite receiving equipment and subscribing to a local satellite base station network together with an annual software fee. Costs are c. £12,000 for an electronic steering wheel, c. £1,000 for satellite receiving equipment and c. £600 for a local satellite base station network subscription and software fee. The tractor based equipment and software purchase constitute a capital cost whilst the subscription is an annual fee.

Using a 200 ha farm and assuming a five year life for the investment, the annual amortised cost (based on 5 years @ 7%) would be c. £4,300 plus the annual licence cost of £600. This represents a total cost of £5,000, or c. £25 per hectare (Table 3.17). In practice, larger farms tend to invest in this type of equipment, so the cost per hectare would be lower, but no details are available on the range and number of farms that use auto steer technology.

Typically, work rates during field operations can increase by 10-20% with auto steer technology (Carl Pitelen, Ben Burgess & Co, pers. comm.) with greater increases on farms with larger fields. Field operations typically cost around £30 per hour, so a 10-20% increase in efficiency
would result in a £3 to £6 saving for each hour worked. Furthermore there could be a potential saving in fertiliser and pesticide input costs due to reduced overlaps and underlaps and a potential increase in effectiveness; fertiliser and spray costs are typically £300/ha for winter wheat and £220/ha for spring barley (Nix, 2013).

Knight et al. (2009) calculated fixed and variable cost savings due to guidance systems for drilling and fertiliser spreading in a 12.6 hectare field. Total cost savings were £11/ha for a medium accuracy system (e.g. “SF2/HP” with 10 cm +/- 5 cm accuracy) and £19/ha for a high accuracy Real Time Kinematic (RTK) system (with 4cm +/- 2 cm accuracy), with possible savings of £2,200 per annum and £3,800 per annum on a 200 ha farm for medium and high accuracy systems. These savings do not include any potential crop yield increases due to reduced soil compaction.

Table 3.17: Cost per hectare of autosteer system with GPS.

<table>
<thead>
<tr>
<th>Cost (£)</th>
<th>Annual charge per £1,000 for 5yrs @ 7% interest</th>
<th>Annual cost (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS kit for tractor</td>
<td>11,858</td>
<td>244</td>
</tr>
<tr>
<td>GPS software</td>
<td>5,554</td>
<td>244</td>
</tr>
<tr>
<td>GPS licence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farm area (ha)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>£/ha/yr</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.8.2 Auto-steer effects

Productivity – Auto-steer has the potential to increase yields by 0-5% in combinable cropping systems (Chamen, 2011) as a result of reducing the number of under and overlaps, which has the potential to reduce soil compaction (a reduction in the proportion of a field that is trafficked through greater accuracy and use of route ways), agro-chemical use, and achieve a more even crop (Table 3.18).

Table 3.18: The effectiveness of auto-steer technology on productivity for different farming system and soil type combinations.

<table>
<thead>
<tr>
<th>Farming system</th>
<th>Heavy</th>
<th>Medium</th>
<th>Silty/Sandy</th>
<th>Peaty</th>
<th>Chalk &amp; Limestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter combinable</td>
<td>↑</td>
<td></td>
<td></td>
<td></td>
<td>↑</td>
</tr>
<tr>
<td>Roots combinable (including potatoes, sugar beet and horticultural crops)</td>
<td></td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Grassland</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
</tbody>
</table>

Organic matter – The use of auto-steer technology in combination with LGP tyres could potentially result in a small increase in organic matter content through increased crop yield and reduced erosional losses, although it is unlikely that such potential increases could be measured in the short to medium term (Table 3.19; Kirk et al., 2012).

Soil erosion and diffuse water pollution – auto-steer technology in isolation is unlikely to have a significant effect on soil erosion and diffuse water pollution (Table 3.19). However, in
combination with the use of LGP tyres and/or tracks, reductions in surface runoff and associated sediment and particulate P could be possible.

**Table 3.19: The effects of the use of auto-steer technology on organic matter, soil erosion and diffuse pollutant losses (Kirk et al., 2012).**

<table>
<thead>
<tr>
<th>Soil organic matter</th>
<th>Erosion</th>
<th>Nitrate</th>
<th>Sediment</th>
<th>Particulate P</th>
<th>FIOs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(~)</td>
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</table>

( ) Uncertain.

### 3.9 In-field trackways/tramlines

#### 3.9.1 Track way/tramline costs

Most conventional arable crops are grown in fields using a tramline system. In recent years, tramline spacing has increased from 12 m to more than 36 m on some farms. Increased tramline widths require larger sprayer equipment and fertiliser spreaders capable of accurate applications over wider spacings.

Tramlines are helpful in improving accuracy of field operations from drilling up to harvest, but they do not necessarily reduce random trafficking for a number of reasons. At harvest, trailers used to collect grain from the combine may travel anywhere on the field between the gateway and the combine, and bale-collecting operations have no set pattern. Chamen and Audsley (1993) estimated that, even with tramlines, up to 85% of the field area can be trafficked during a growing season. Tramline systems are less likely to reduce overall field soil compaction than CTF and auto-steer technologies. However, the use of in-field trackways and tramlines is facilitated by and made more efficient with auto-steer technology (see 3.8 above) and is most rigorously applied through CTF (see 3.7 above).

#### 3.9.2 Track way/tramline effects

**Productivity** – The use of tramline/trackways through auto-steer technology can result in yield increases of up to 5% (Chamen, 2011). When incorporated as part of a CTF system, their use can help support net yield increases in the range of 5-15%, depending upon the crop (Hallett et al., 2012).

**Organic matter** – The use of track ways/tramlines in combination with LGP tyres and auto-steer technology could potentially result in a small increase in organic matter content through increased crop yield and reduced erosional losses. However, in isolation, the use of trackways/tramlines is unlikely to have any significant effect on soil organic matter (Table 3.20).

**Soil erosion and diffuse water pollution** – The use of track ways/tramlines in isolation is unlikely to have a significant effect on soil erosion and diffuse water pollution (Table 3.20). However, in combination with the use of LGP tyres and auto-steer technology, reductions in surface runoff and associated sediment and particulate P could be significant (i.e. particulate P and associated sediment losses could be reduced by up to 20% on winter cereal cropped land; Newell-Price et al., 2011).

**Table 3.20: The effects of in-field trackways/tramlines on organic matter, soil erosion and diffuse pollutant losses (Newell Price et al., 2010; 2011).**

<table>
<thead>
<tr>
<th>Soil organic matter</th>
<th>Erosion</th>
<th>Nitrate</th>
<th>Sediment</th>
<th>Particulate P</th>
<th>FIOs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(~)</td>
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</tr>
</tbody>
</table>

( ) Uncertain.
3.10 Mechanical alleviation - Sub-soiling (in arable systems) and top-soiling (in grassland)

3.10.1 Mechanical alleviation costs

Mechanical loosening of soil compaction should only be carried out when there are clear signs of compaction (e.g. poor soil structure leading to reduced soil water infiltration, rooting depth etc.). The analysis below assumes that intervention due to compaction is required one year in four. The costs of sub-soiling arable land or top-soiling grassland on a four yearly rotation are shown below (Table 3.21; from FFG0923).

Costs for sub-soiling arable land are assumed to be £60/ha (equivalent to £15/ha/year on a 1 year in 4 basis) and top-soiling grassland c. £45/ha, equivalent to £11.25/ha/year (on a 1 year in 4 basis; Nix, 2013). For both arable and grassland, it is estimated that output will increase by 5% in year 1 and decline to baseline levels after 4 years. The benefits of sub-soiling on the outputs from the contrasting case-study farms are shown in Table 3.21 (Defra project FFG0923).

Table 3.21: Net benefit of sub-soiling arable land & top-soiling grassland, £/ha of each farm per year, assuming the operations are only carried out at four year intervals.

<table>
<thead>
<tr>
<th>Case study farm type</th>
<th>Annual cost of sub-soiling and top-soiling (£/ha)</th>
<th>Total output from land (£/ha/yr)</th>
<th>Total benefit (£/yr)</th>
<th>Average benefit (£/ha/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>General cropping (200 ha - 25% drained)</td>
<td>15</td>
<td>1,347</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>Combinable cropping (200 ha - 50% drained)</td>
<td>14</td>
<td>1,045</td>
<td>35</td>
<td>10</td>
</tr>
<tr>
<td>Dairy (100 ha - 100% drained)</td>
<td>12</td>
<td>1,408</td>
<td>75</td>
<td>20*</td>
</tr>
<tr>
<td>Combinable cropping + beef (200 ha - 100% drained)</td>
<td>15</td>
<td>1,066</td>
<td>35</td>
<td>10</td>
</tr>
</tbody>
</table>

*Grass output was valued at £200/t dry matter (Nix, 2013). Grazing grassland was valued at 8 t DM/ha on the dairy farm and 6 t/ha on the lower output beef enterprises (Defra project WQ0106).

3.10.2 Mechanical alleviation effects

Productivity – Crop yield increases from sub-soiling arable land are usually short-lived, although there is some evidence that yield increases (when they occur) can persist for longer within reduced tillage systems (Hallett et al., 2012; Murdock and James, 2008; Newell Price et al., 2010). Marks & Soane (1987) found that yield responses to sub-soiling were mainly confined to spring sown crops. At the 25 sites assessed in this category, six provided a yield increase in the range 1% to 10%, but four resulted in a yield decrease in the range 6% to 12%. None of the 17 winter sown crops showed a yield increase, while four resulted in a yield penalty (6-15%). Murdock and James (2008) reported a 5-10% increase in maize following sub-soiling of a compacted silt loam soil, but the method was only effective on land in a no-till (rather than tilled/disced to 10-15 cm depth) system. In general, yield increases from sub-soiling (where they occur) tend to be most consistently detected in spring crops grown on sandy or light silty soils.

Sub-soiling can improve drainage and thereby timeliness of operations by creating fissures or cracks through compacted zones, which is preferable to massive disruption (Spoor et al., 2003). Such improvements in drainage are unlikely to apply every year or on every soil, but in a wet season, could make the difference between establishing a crop or not (Hallett et al., 2012). In general, the benefits of targeted sub-soiling can be partly measured in terms of increased overall yield due to drilling a greater proportion of the cropping area at the optimum time (Table 3.22).
In grassland systems, top-soiling resulted in yield increases of 10-15% (ADAS, 1984) on soils where there were clear signs of compaction prior to intervention. Such yield increases could avoid the need to purchase additional bulky fodder for winter feed. However, in a review of UK and international literature, Bhogal et al. (2011) found that the impact on yield of mechanical loosening in grasslands was inconsistent, with some yields unaffected, some slightly increased and some slightly decreased (Table 3.22). In wet years, compacted land that has been top-soiled is likely to drain better (Curran Cournane et al., 2011), enabling livestock to be grazed for longer in autumn and earlier in spring, thereby reducing the housing period and the need to purchase additional bulky fodder or store and spread additional manure/slurry. The savings for beef cattle have been estimated at c. £1/head/day for bulky forage and another £1/head/day for manure spreading not including any cost of additional manure storage (Newell Price et al., 2011).

Table 3.22: The effects of sub-soiling (on arable land) and top-soiling (on grassland) on productivity for different farming system and soil type combinations (Hallett et al., 2012; Knight et al., 2009; Schjønning et al., 2010).

<table>
<thead>
<tr>
<th>Farming system</th>
<th>Heavy</th>
<th>Medium</th>
<th>Silty/Sandy</th>
<th>Peaty</th>
<th>Chalk &amp; Limestone</th>
</tr>
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<tbody>
<tr>
<td>Winter combinable</td>
<td>↑</td>
<td>↑</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roots combinable (including potatoes, sugar beet and horticultural crops)</td>
<td></td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>(↑)</td>
</tr>
<tr>
<td>Grassland</td>
<td>(↑)</td>
<td>(↑)</td>
<td>(↑)</td>
<td>(↑)</td>
<td>(↑)</td>
</tr>
</tbody>
</table>

**Organic matter** – there is little evidence to suggest that sub-soiling of arable land or top-soiling of grassland has any effect on soil organic matter content. Yield effects from mechanical loosening are inconsistent in both arable and grassland systems (Hallett et al., 2012; Bhogal et al., 2011) and any small yield increases could be counteracted to some extent by the soil mineralisation effect of mechanical loosening and the oxidation effects of improved drainage (Kirk et al., 2012).

**Soil erosion** – The passage of heavy farm machinery and trampling by livestock (both cattle and sheep) can compact agricultural soils in both arable and grassland systems. Compaction may build-up over a number of years and persist in the long-term, thereby increasing the susceptibility of land to waterlogging and associated surface runoff. Sub-soiling and topsoil loosening can break up compacted layers and allow more rapid rainwater infiltration, thus reducing surface runoff and erosion (Curran Cournane et al., 2011; Newell Price et al., 2011).

**Diffuse water pollution** – When soils are compacted and there is little crop residue or vegetation cover to intercept rainfall, soils can be susceptible to surface runoff and erosion. Sub-soiling or top-soiling (during dry conditions) will enhance water infiltration rates into the soil and reduce surface runoff volumes. Disrupting compacted layers allows more rapid percolation of rainwater into the soil and reduces the risk of pollutants being transported to watercourses in surface runoff. Sub-soiling and top-soiling can typically reduce particulate P and associated sediment losses by 10-50% (Newell Price et al., 2011). Within grassland/livestock systems, FIO losses have the potential to be reduced by a small amount. Effects on nitrate-N leaching losses are likely to be minimal.
Table 3.23: The effects of sub-soiling (on arable land) and top-soiling (on grassland) on organic matter, soil erosion and diffuse pollutant losses (Kirk et al., 2012; Newell Price et al., 2011).

<table>
<thead>
<tr>
<th>Soil organic matter</th>
<th>Erosion</th>
<th>Nitrate</th>
<th>Sediment</th>
<th>Particulate P</th>
<th>FIOs</th>
</tr>
</thead>
<tbody>
<tr>
<td>~</td>
<td>⊘⊘</td>
<td>~</td>
<td>⊘⊘</td>
<td>⊘⊘</td>
<td>(⊘)</td>
</tr>
</tbody>
</table>

(⊘) Uncertain.

3.11 Effectiveness and practicality of measures by climatic regime

The suitability of measures for preventing damage to soils due to working waterlogged land is closely related to cross-compliance soil type (i.e. topsoil texture, organic matter content, soil depth and parent material), but also to soil water regime and climatic regime. Soil water regime is defined by the number of days that soil is waterlogged at 40 cm and 70 cm depth and is linked to soil morphology (colour and degree of mottling). It is largely influenced by subsoil texture (slowly permeable layers usually have clay or heavy clay loam texture), but also by hillslope position and hydrology (spring lines, hydrogeology, groundwater etc.). Poorly and imperfectly drained soils are most susceptible to waterlogging, irrespective of region, management or the state of the drainage system. Waterlogged conditions typically occur most frequently in the wetter west of the country, although paradoxically, the likelihood of working waterlogged land and need for drainage may be greater in parts of the east of the country due to the higher proportion of cultivated land and the growing of combinable crops on moderately well drained to imperfectly drained soils (Davies et al., 1972).

Most soils with a watertable at less than 70 cm depth for four to seven months of the year are liable to compaction by machinery or livestock (Robson and Thomasson, 1977). In these soils, waterlogging within 40 cm is common during late autumn to early spring and can drastically reduce opportunities for cultivation or grazing. Drainage installation and maintenance that can reduce the risks associated with wetter than average years is worthwhile if such land is to be used within productive arable or grassland systems, although maintaining mole drainage systems is key to ensuring overall drainage effectiveness in medium and heavy soils with an impermeable layer at shallow depth, such as Denchworth series (developed on Mesozoic clay shales) and Raqdale series (on Chalky Boulder Clay), both of which are relatively widespread in central and eastern England.

Soil water and climatic regime limit the timing and application of all measures to mitigate soil waterlogging:

- Cultivation timing should be determined by topsoil water content and in wet autumns trafficking and cultivation should be delayed until conditions allow (i.e. until soil water content is below the lower plastic limit and soil is in a friable state); in the wettest years, on imperfectly drained and even moderately well drained soils, this may be the following spring.
- LGP tyres and tracked machinery can limit the degree of topsoil compaction, but should not be used in waterlogged conditions to increase opportunities for accessing land. This will only increase risks of causing persistent subsoil compaction, particularly where wheel loads are 3.5 tonnes or higher. Targeted and appropriate use of LGP tyres and tracked machinery could improve soil structure and drainage, and thereby increase opportunities for accessing land in a wet season, but not on poorly drained soils in the wettest seasons (e.g. autumn 2012).
- CTF approaches can also help increase opportunities to access land through better timing of operations resulting in reduced structural degradation, improved soil structure and better drainage. Energy requirements for tillage can also be reduced in such systems.
- Autosteer GPS and the use of in-field trackways/tramlines are important for CTF type approaches and enhance the use of LGP tyres and tracked machinery. The resulting better
soil structure and improved soil drainage could result in a greater number of machinery working days, which could be important in wetter regions and years.

- Mechanical alleviation through sub-soiling and top-soiling is probably the measure that is most limited by soil water regime and weather. Effective sub-soiling, causing fissuring and cracking, can only be carried out when upper subsoil and lower topsoil moisture contents are in the friable range, which requires a significant soil moisture deficit. Following a prolonged period of wet weather (e.g. a wet August) a few days without rain may allow machinery to travel, but may not dry out the soil sufficiently for sub-soiling to be effective. Sub-soiling carried out in these conditions will have a similar effect to moling, and may be effective in creating a channel to drain water away, but will not cause the fissuring and cracking targeted by sub-soiling. Top-soiling requires some surface moisture with drier conditions below; and so is ideally carried out on a ‘wetting front’ in the autumn. Some years will not be suitable for sub-soiling or top-soiling due to conditions that are too wet (i.e. an early return to field capacity) or too dry for many weeks and then too wet within a few days.

3.12 Conclusions

Measures that can help prevent working waterlogged land mainly relate to improving drainage, better timing of operations, reduced ground pressure and reductions in the trafficked area.

Drainage systems represent a significant capital investment and may be difficult to justify in terms of the return on investment in any single year. However, on slowly permeable soils a functioning drainage system is a pre-requisite for high output arable and grassland systems. Artificial drainage schemes also represent an insurance measure against lack of production on poorly drained soils in exceptionally wet years. In addition, a well-maintained drainage system can be important in the delivery of a number of ecosystem services including crop production, flood mitigation and nutrient cycling.

Delaying cultivation until soil is in a friable state and the use of LGP tyres, tracked machinery, guidance system (e.g. GPS) technology and CTF principles will all help maintain good soil structure and porosity, thereby improving soil drainage, increasing the number of machinery work days and reducing the likelihood of working waterlogged land. Measures that reduce ground pressure and trafficked area can also help increase production, with typical arable and grassland crop yield increases ranging from 1% to 15%. Delaying cultivation can be used on any farm, whereas technologies that reduce ground pressure or trafficked area can entail significant cost to the farm business and require economies of scale.

Alleviating compaction through sub-soiling of arable land and top-soiling of grassland can be effective in improving drainage and in some cases increasing crop yield, but needs to be integrated with visual evaluation of soil structure and should not be carried out unless there are clear signs of compaction.

On slowly permeable soils, field drainage is a necessary part of farm infrastructure to support high output agricultural systems. The other prevention measures represent best practice towards which many larger farms are developing or have developed in order to improve efficiency of production. Alleviation through sub-soiling or top-soiling is widely practiced on a routine basis, but could be better targeted to improve efficiency and effectiveness.

Mitigation measures to help avoid working waterlogged land are likely to be more effective in wetter regions and wetter years. Mitigation measures will also be of benefit if future climate regimes include greater year to year variability and a greater frequency of extreme events such as the prolonged rainfall encountered in 2012-13 (section 8).
4. SOIL PROTECTION BENEFIT AND IMPACT ON PRODUCTIVITY OF CURRENT CONTROLS

4.1 SPR10 ‘Access to Waterlogged Land’ requirements

In the Soil Protection Review 2010 (SPR10) previous restrictions on access to waterlogged land were replaced with a requirement to record access to waterlogged areas and remedial actions undertaken to mitigate soil damage. “Soil is considered to be waterlogged where the whole of the plough layer is saturated or filled with water, by virtue of a high water table or water collected (perched) above a compacted soil” (Defra, 2009).

Farmers must “record any activity on waterlogged soils to carry out mechanical field operations such as harvesting crops or using a motorised vehicle; except where the area of waterlogged soil is within 20 metres of a gateway or other access point and access is required to an area of land that is not waterlogged, or the area is an established track to land that is not waterlogged”.

Farmers must also record:
- The reason for access
- The action to remediate soil damage caused once conditions allow

Actions to remediate soil must be done as soon as possible within 12 months of the first month of accessing waterlogged land.

4.2 Farmers Accessing Waterlogged Land

A telephone survey of 800 farmers, carried out as part of Defra project SP1309 in spring 2012, provided information on the number of farmers who had experienced and accessed waterlogged land since 1 January 2010.

In all, 236 (30%) respondents had experienced waterlogged soils. Of these, 54% had ‘heavy’ soils and 16% had ‘peaty’ soils. Of the 236 that experienced waterlogged soils, 43 (18%) reported having to access the land while it was waterlogged. Therefore, only 5% of all respondents stated that they had accessed waterlogged land (Table 4.1).

Table 4.1: Number of respondents that had experienced waterlogged soil since 2010 by farm type

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Cereals</th>
<th>General Cropping</th>
<th>Horticulture</th>
<th>Dairy</th>
<th>Lowland grazing</th>
<th>LFA grazing*</th>
<th>Pigs &amp; poultry</th>
<th>Mixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of participants</td>
<td>800</td>
<td>155</td>
<td>88</td>
<td>12</td>
<td>83</td>
<td>248</td>
<td>111</td>
<td>16</td>
<td>87</td>
</tr>
<tr>
<td>Experienced waterlogged soil</td>
<td>236 (30%)</td>
<td>37 (24%)</td>
<td>27 (27%)</td>
<td>5 (41%)</td>
<td>34 (41%)</td>
<td>76 (31%)</td>
<td>32 (29%)</td>
<td>5 (31%)</td>
<td>23 (25%)</td>
</tr>
<tr>
<td>Accessed waterlogged soil</td>
<td>43 (5%)</td>
<td>8 (5%)</td>
<td>6 (7%)</td>
<td>0 (-)</td>
<td>7 (8%)</td>
<td>9 (4%)</td>
<td>11 (10%)</td>
<td>0 (-)</td>
<td>2 (2%)</td>
</tr>
</tbody>
</table>

* Less favoured area grazing

The 43 farmers that accessed waterlogged land did so for the following reasons:
- Livestock welfare/feeding (21)
- Drain/ditch management (7)
- Hedge maintenance (5)
- Crop management e.g. spraying (4)
Other reasons - including harvesting to meet contractual requirements and manure spreading (6)

Waterlogged land was therefore trafficked to feed livestock, manage ditches/hedges, spread manure, manage a growing crop or harvest crops. No farmers stated that they had worked waterlogged land to establish a crop. Working (i.e. cultivating) waterlogged land was therefore not acknowledged as an issue among the 800 farmers surveyed.

Of those accessing waterlogged land, 36 respondents (84%) carried out actions to alleviate the damage caused (Table 4.2). There were 7 respondents (16%) who did not carry out any remediation activity. Actions taken were largely directed at specific problem areas (17 respondents; 40%) rather than the whole field (3 respondents; 7%). The majority indicated that the remediation actions they had carried out reduced soil damage ‘considerably’ (23 respondents; 64%) or ‘in part’ (7 respondents; 19%). However, only 6 respondents (17% of those carrying out remediation actions; 14% of those accessing waterlogged land) had assessed the extent of the soil damage before taking any action. This is a clear deficiency in practice, since it is well established that remediation activities carried out without assessing the depth and degree of soil structural damage are usually ineffective and at worst can be detrimental (Frost, 1988; NSRI, 2002; Spoor, 2006).

Table 4.2: Actions to alleviate damage caused by accessing waterlogged soil and the number of respondents who took action. Some respondents chose more than one option.

<table>
<thead>
<tr>
<th>Action</th>
<th>Number (% in brackets)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ploughing/discing/harrowing whole field</td>
<td>3 (7%)</td>
</tr>
<tr>
<td>Ploughing discing/harrowing part of the field</td>
<td>7 (16%)</td>
</tr>
<tr>
<td>Subsoiling part of the field</td>
<td>10 (23%)</td>
</tr>
<tr>
<td>Keeping livestock off affected field</td>
<td>4 (9%)</td>
</tr>
<tr>
<td>Other</td>
<td>19 (44%)</td>
</tr>
<tr>
<td>None undertaken</td>
<td>7 (16%)</td>
</tr>
<tr>
<td>Total alleviating damage caused</td>
<td>36 (84%)</td>
</tr>
<tr>
<td>Total accessing waterlogged land</td>
<td>43 (100%)</td>
</tr>
</tbody>
</table>

4.3 Effect of current controls on soil management

Only 9 farmers were asked how the SPR10 had affected their attitude to accessing waterlogged land (the question was dropped from the survey after the initial pilot survey due to time constraints). Two farmers stated that the waterlogged land guidance was “not practical on their farm” and 5 stated that they were “already doing what the SPR10 suggested”. Nevertheless, another 2 farmers stated that the SPR10 had “encouraged them to make some changes to the way they accessed waterlogged land”. There is therefore some indication that the SPR10 may have affected the way some farmers manage waterlogged land. However, although it was possible to establish that the overall impact of the SPR10 in reducing soil degradation was low with only about 12% of respondents making changes to management practices (not necessarily changing the way they manage waterlogged land) as a result of implementing the SPR10, it is not possible to determine with any confidence the proportion of farmers that have withheld from accessing waterlogged land or changed the way that waterlogged land is managed as a result of SPR10 implementation.

It is possible that if the SPR10 had not been introduced, general awareness of soil issues on some farms would have been lower, possibly resulting in fewer practices that avoid soil degradation such as the use of low ground pressure tyres, not using machinery when the soil is wet or moving feeders at regular intervals. Even so, only 5% of respondents said that the SPR10 had made them more aware of soil issues.
On grassland the SPR10 had a small effect (<10% additional uptake) in increasing the uptake of 'moving feeders' and 'reducing stocking rates when soils are wet'. These measures will have reduced the risk of trampling waterlogged land, compaction, erosion and runoff on those farms where the measures are effectively implemented.

The SPR10 increased awareness of soil issues on a number of farms (about 20% acknowledged this), but only 30% of farmers acknowledged having experienced waterlogged land, while 16% of these acknowledged accessing waterlogged land and 13% carried out actions to remediate the soil damage caused. In the overall survey there was a tendency to select measures that were part of good farming practice, such as maintaining land drainage and removing livestock when soils are wet, both of which can reduce the risk of working or trafficking waterlogged land.

4.4 Impact of current controls on production

In many years and in most rotations there will often be an opportunity to alleviate soil damage within 12 months of accessing waterlogged land. However, this may not always be the case. Soil structural degradation can be alleviated through natural shrink-swell processes in heavier (higher clay content) soils, the introduction of cover/nurse crops within arable/horticultural rotations and through mechanical intervention. The latter involves sub-soiling with tines in a tillage situation or the use of a sward lifter or aerator/slitter in grassland. The use of these machines requires specific soil moisture conditions (Davies et al., 1972). For example, effective sub-soiling requires the soil to be in a friable state (i.e. dry to slightly moist) in the lower topsoil and upper subsoil; and the ideal conditions for sward lifting are a moist soil surface (close to the plastic limit for ease of disc and tine entry) with the lower topsoil in a friable state to maximise shatter and fracturing of the soil. These conditions are most commonly encountered in the early autumn before the onset of drainage. However, in exceptionally wet summers, such as 2012, the ideal conditions may not occur with little to opportunity for mechanical alleviation of soil compaction until the following spring.

The following sections set out the opportunities for alleviating damage caused from accessing waterlogged land within specific farming systems and the impact of the need to alleviate soil damage within 12 months of accessing waterlogged land on soil structural condition. The opportunities to establish crops and the yield of following crops is also discussed.

**Winter combinable:** WW; WB; WOSR

**WW** = Winter Wheat

**WOSR** = Winter Oilseed Rape

**WB** = Winter Barley

Autumn-sown combinable crop rotations mainly occur on medium to heavy soils with natural re-structuring, shrink-swell properties. Yield benefits due to mechanical loosening are less certain on these soils than on spring sown crops grown on light sandy or silty soils (Soane et al., 1987), possibly due to the shrink-swell properties of these soils and the buoyancy effect of pore water (Gregory et al., 2007). Indeed, Soane et al. (1987) found that sub-soiling resulted in a 6-12% yield penalty in four out of 17 winter combinable crops with none of the sites providing a positive response, although the sub-soiling in these cases involved rigorous soil loosening to 450 mm depth with virtually complete loosening of the profile to operating depth. In general, however, the benefits of targeted and less rigorous sub-soiling can be partly measured in terms of increased overall yield due to improved field drainage and drilling a greater proportion of the cropping area at the optimum time (Hallett et al., 2012; Spoor, 2006).

In most years there will be opportunities to alleviate compaction after winter wheat and oilseed rape; but less opportunity after winter barley in this rotation due to early entry of oilseed rape. Nevertheless, sub-soiling operations should be possible in most years, with very wet years such as 2012 an exception to the general rule.
In wet years it may not be possible to alleviate compaction before establishment of the following crop. Indeed the need to alleviate compaction due to accessing waterlogged land within the previous 12 months could reduce the opportunity to establish the following crop without necessarily improving plant growth conditions. It is more important that soils are assessed as it may be that no mechanical intervention is the best option, particularly on more heavily textured or organic (higher organic matter) soils. To this end, it may be preferable to require that soil damage is alleviated at the next available opportunity, according to soil conditions, rather than within 12 months of first accessing waterlogged land.

**Roots combinable**: Pots; WW; SBeet; SB; WB; Veg (carrots/ cauliflower*); SB

- Pots = Potatoes
- WW = Winter Wheat
- SBeet = Sugar Beet (*Cauliflowers can carry beet cyst nematode and would not normally be grown in mixed rotation with sugar beet)
- SB = Spring Barley
- WB = Winter Barley

Roots/combinable crop rotations mainly occur on well-drained ‘sandy and light silty’ soils. These soils normally respond well to mechanical alleviation of soil compaction, particularly when spring crops are grown without irrigation in a dry year (Soane *et al*., 1987). The principal opportunity for alleviating soil compaction in this rotation is in the late summer/early autumn after cereal crop harvest. There is little to no opportunity after late harvested potatoes, sugar beet and vegetable crops, since many soils are ‘wet’ or in a plastic condition in late autumn and any attempt to alleviate compaction can result in further soil structural damage.

Alleviating compaction within 12 months of harvesting root or vegetable crops will be possible in most, but not all years. There may be little opportunity when winter wheat is established after late harvested sugar beet and the following cereals harvest period is wet. In this case, the first opportunity to alleviate damage caused by harvesting sugar beet from waterlogged soils could be up to 18 months after the damage was caused, by which time some heavier textured soils (i.e. not sandy and light silty soils) may have re-structured due to natural shrink-swell processes.

Use of cover and/or nurse crops can improve soil structural condition and is becoming increasingly common in horticultural rotations (Defra SP1309B). However, their use is most likely on owner occupied land and less likely on rented land.

The yield impact associated with a requirement to alleviate compaction within 12 months of causing damage will depend on the soil type and the soil moisture conditions when mechanical alleviation is carried out. Yield improvements are most likely on ‘sandy and light silty’ or ‘medium’ soils when alleviation is carried out in dry conditions (i.e. the soil to be worked is in a friable state) and least likely on heavy or organic soils, particularly if attempts are made to alleviate compaction while the soil is in a plastic state. For spring crops grown on ‘sandy and light silty’ and ‘medium’ soils, compaction alleviation effectively carried out through “fissuring without (excessive) loosening” (Spoor *et al*., 2003) can result in yield increases ranging from 1% to 10% (Marks and Soane, 1987; Defra SP1305A).

**Grassland**: WB; WB; maize; G; G; G; G; G

- WB = Winter Barley
- G = Grass

According to the SP1309 survey, farmers most commonly acknowledge trafficking soils within a grassland rotation (e.g. to feed livestock). Grass generally dries out the soil in late summer and in the above rotation provides an early entry for winter barley. There should be ample opportunity in most years to alleviate compaction within the grassland part of the rotation or in permanent grassland situations. Sward lifting or top-soiling type operations (to 30-35 cm depth)
are best carried out in the autumn and the use of aerators/slitters is best carried out in the autumn or spring, although the risk of impacting grass yield is greater in the spring (Defra project BD5001). Yield increases from sward lifting where soil compaction has been identified can be in the order of 8-12% (Table 4.3).

However, topsoil looseners should not be used unless there are clear signs of soil compaction and the moisture content is suitable (Defra BD5001). In addition, topsoil loosening is not recommended in poorly drained soils if there is no drainage system present. For such soils it is best to leave re-structuring to natural processes such as earthworm activity and shrink-swell during wetting and drying cycles. Grass is generally a good crop for improving soil structural conditions providing stocking rates are not excessive and soils are not trafficked when wet.

**Table 4.3: Effect of top-soiling treatments on grass yields - tonnes dry matter (DM)/ha (ADAS, 1984, 1987).**

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

Column values with different letters are significantly different (P<0.05)

Waterlogged soils are also commonly trafficked during forage maize harvest. Maize tends to be harvested in the September to November period, so field operations are often carried out after the onset of field drainage and soils are susceptible to compaction. There are opportunities to reduce impacts of accessing waterlogged maize fields through over-sowing a grass or cover crop or chisel ploughing post-harvest. Both methods have been shown to be effective in reducing surface run-off and erosion (Defra projects SP0404 and WQ0140).

**4.5 Conclusions**

The current controls have helped raise awareness of the issues associated with accessing waterlogged land. The SPR10 encouraged some farmers to make changes to the way they accessed waterlogged land. However, the overall impact of the SPR10 in reducing soil degradation was low with only about 12% of respondents making changes to management practices as a result of implementing the SPR10.

The proportion of farmers stating that they have accessed waterlogged land was low, although the survey was carried out in spring 2012 before the wet summer/autumn of 2012 and the wet winters of 2012/13 and 2013/14. Working (i.e. cultivating) waterlogged land was not acknowledged as an issue among the 800 farmers surveyed.

There were clear deficiencies in practice when remediating compacted soil as few farmers assessed the extent of the soil damage before taking any action. This is an area for improvement that could be made through the development of guidance materials and soil management workshops and farm walks.

Mechanical alleviation generally improves drainage and can increase crop yields, particularly on spring crops grown on sandy and light silty soils, but only when there are clear signs of compaction, the machinery is set up correctly and soil conditions are suitable. In general, it is best to delay mechanical operations to alleviate compaction until soils are in a friable state rather than require that actions are carried out within 12 months of first accessing waterlogged land (in some extreme cases mechanical intervention may be needed while soils are still 'wet' to create a channel or pathway for water to drain away). Furthermore, a certain amount of natural re-structuring can take place in some soils with >18% clay and therefore no remediation is needed. Allowing a degree of flexibility would help farmers take appropriate and timely action.
5. IMPACTS OF PROLONGED WATERLOGGING

- This section summarises the impacts of prolonged waterlogging in terms of soil quality, soil processes and productivity; the effect on farm practices and associated remediation options. A more in depth assessment is provided in Appendix 2.

5.1 Impacts of prolonged surface waterlogging on soil quality and soil physico-chemical and biological processes

- Waterlogging occurs when the pores within the soil matrix are completely saturated with water and generally results in anoxic (anaerobic) soil conditions. Prolonged surface waterlogging can have a serious impact on soil physical and chemical properties and on biological processes. This can profoundly affect the quality of soil as a medium for plant growth, although draining and drying a flooded soil will reverse most of these changes (Ponnamperuma, 1984).

- In this report, prolonged waterlogging is defined as occurring when the whole of the ‘A’ horizon or plough layer is saturated or filled with water for more than 24 hours.

5.1.1 The chemistry of waterlogged soils

- When a soil is flooded or waterlogged, the micro-organisms which decompose soil organic material quickly use up any free oxygen causing the soil to become anaerobic. When soil is first flooded a number of gases are given off including nitrogen (N) and nitrous oxide ($\text{N}_2\text{O}$) as a consequence of the reduction of nitrate to nitrite. After the first few days of flooding the main gases emitted are carbon dioxide and methane.

- The pH of a waterlogged soil usually rises mainly due to the denitrification of nitrate to gaseous N, which neutralises acidic H+ ions by forming water molecules as part of the biochemical reaction. In the agricultural lowlands of England and Wales most soils when waterlogged for prolonged periods have a pH of 6.7 to 7.2 (Alloway, 1990), compared with an optimum pH of 6.5 and 6.0 for mineral soils under arable cropping and continuous grass, respectively (Defra, 2010).

5.1.2 Transformations and cycling of major nutrients

Nitrogen

- Mineralisation. In flooded soils, the mineralisation of organic N to inorganic N stops at the ammonium ($\text{NH}_4^+$) stage because of the lack of oxygen to carry the reaction through to nitrate. As a result, ammonium builds up in flooded soils, although the quantity accumulated depends on the organic matter content and temperature (Ponnamperuma, 1984; Unger et al., 2009).

- Nitrification/denitrification. The reduction of soil nitrate to nitrite and gaseous nitrogen in waterlogged soils also release $\text{N}_2\text{O}$. Factors affecting $\text{N}_2\text{O}$ emissions from soils include moisture, temperature, organic matter content and soil structure. Water filled pore space (WFPS) is a measure of the degree to which the gaps (pores) between soil particles are filled with water (as opposed to air). Notably, UK studies have indicated that the largest $\text{N}_2\text{O}$ emissions frequently occur under more anaerobic conditions i.e. at a WFPS >60% (Dobbie et al. 1999; Dobbie & Smith, 2001; Dobbie & Smith, 2003). Numerous studies in the literature have shown that $\text{N}_2\text{O}$ production increases with temperature and with a rise in soil moisture (Smith et al., 2012; Dobbie & Smith, 2003; Dobbie et al., 1999). Clearly, soils waterlogged in summer (i.e. in warm and wet conditions) will be at greater risk of increased $\text{N}_2\text{O}$ emissions than soils waterlogged in winter.

- Immobilisation. Nitrogen can be immobilised in soils by both chemical and biological processes, which make it temporarily unavailable for plant uptake. The high concentration of ammonium in flooded soils will favour both processes (Ponnamperuma, 1984). Once the
soils have dried out, the N immobilised by microbial activity will be released over time as the microbes themselves die off and are decomposed.

- **Biological N fixation.** Flooding increases the capacity of soil micro-organisms to biologically fix N, which occurs via the reduction of N\(_2\) to NH\(_4\) (Ponnamperuma, 1984). Nonetheless, N fixation by many terrestrial legumes is greatly reduced during flooding (e.g. Sánchez et al., 2011), which has been attributed mainly to a reduction in oxygen supply to the nodules (e.g. Loureiro et al., 1998).

- **Nitrate leaching.** Nitrogen in the form of nitrate (NO\(_3\)) is easily lost from soils due to its high solubility and mobility. Nitrate losses are more rapid on light soils (where water can readily percolate through the soil matrix) or on heavier clays (where losses occur via bypass flow through cracks in the soil and under-drainage systems).

- **Crop N supply.** As a consequence of the changes to soil chemistry highlighted above, soils are likely to be depleted in N after waterlogging; the supply of N to the next crop will be affected and N fertiliser applications may need to be slightly higher than in most years due to low Soil Nitrogen Supply.

**Other nutrients**

- Phosphorus (P) is strongly bound to soil particles and soil erosion processes may result in large amounts being lost to surface waters and ditches which can have deleterious impacts on aquatic ecosystems by degrading habitat condition and directly impairing biota (e.g. Collins et al., 2012). In waterlogged soils, phosphates are released into soil solution from the reduction of iron oxides. However in England and Wales, crops are unlikely to be growing and actively taking up P under waterlogged conditions, so some of the mobilised phosphate may be lost through leaching.

- Other soluble nutrients such as sulphur (S), which are susceptible to leaching losses in the same way as nitrate, are also likely to be depleted in flooded or waterlogged soil, in some circumstances necessitating additional fertiliser inputs for following crops.

### 5.1.3 Changes to contaminant and agrochemical behaviour

- In general, heavy metals (e.g. zinc, copper, lead, cadmium and mercury) are retained in soils either bound to clay minerals, adsorbed to solid surfaces or complexed with organic matter. However, the changes to the redox status and pH of soils that occur during waterlogging may affect the availability, mobility and toxicity of some heavy metals. For example, reducing conditions may cause the dissolution of Mn and Fe oxides such that any co-precipitated metals are released into soil solution, where they may be more available for plant uptake. Furthermore, the availability of molybdenum may increase with an increase in pH.

- Exceptionally wet weather increases the risk of pesticide movement from soil to water, with leaching being the main mechanism of movement of soluble products. However, where soil erosion occurs, the less mobile pesticides bound to soil particles will also be lost.

### 5.1.4 Impacts on soil biology

**Soil microbial community**

- Organisms inhabiting waterlogged soils must be able to survive with little or no oxygen. When a dry soil becomes waterlogged the soil microbial community will change from being predominantly aerobic to predominantly anaerobic. Anaerobic microbes are less active and less diverse than aerobes, so that organic matter degradation and assimilation is slower (Ponnamperuma, 1984). In general the temperature of flooded soils will be lower than that of well drained soils; which will also impact on microbial activity, nutrient release and plant growth.
Macro-invertebrates

- If waterlogging is temporary, then enough air bubbles are likely to be trapped in soil pores to allow macro-invertebrates to survive for some time. However, prolonged waterlogging reduces the oxygen content of the soil and can have serious effects on soil macro fauna, especially earthworms, which are driven to the surface where they die from exposure to ultraviolet light or are predated. In a review of invertebrate populations in flooded grasslands, Plum (2005) found that flooding immediately reduced the diversity, abundance, and biomass of all groups of soil macrofauna.

5.1.5 Changes to soil physical quality and structure

Soil structure

- To enable roots to travel unhindered to depth and to allow optimum crop growth, the physical soil structure must be in good condition i.e. existing as discrete aggregates (or peds) separated by a continuous system of pores and fissures which are wide enough for roots to enter or 'loose' enough for roots to form their own channels. An open soil structure also facilitates the flow of oxygen, which must be present at depth for respiration by roots and to allow microbial activity. DeCampos et al. (2009) reported a strong positive correlation between changes in the redox potential and aggregate stability; aggregate stability decreased with redox potential, which also decreases under the reducing (anaerobic) conditions found in waterlogged soils. The aggregate stabilities of cultivated soils were more sensitive to reducing conditions than uncultivated soils, with a decrease in aggregate stability of up to 21% reported for cultivated soils.

Capping, sealing, slumping and slaking

- Capping and sealing reduce the soil’s ability to absorb water, leading to surface waterlogging and increasing the risk of runoff and erosion. Slumping occurs when soil collapses downwards or sideways, with slumped soils also prone to erosion and surface runoff. If the soil structure in surface soil layers is degraded by flooding then not only is water unable to move in these layers, but it is prevented from moving into the subsoil (where soil structural condition may be good).

Soil erosion and sediment transport

- Heavy rain and flooding will entrain and transport soil and sediment; soil loss from sloping or bare fields can be visible and extensive. Soil erosion also leads to losses of organic matter and nutrients (especially P), which may pollute receiving watercourses.

- In flooding situations, large amounts of entrained soil-sediment materials may also be re-deposited onto the soil surface. This issue is generally most pronounced along rivers or other areas where water flow is suddenly restricted. When sandy materials are deposited on top of finer textured soils (clay loams and clays), the abrupt change in soil texture can result in a substantial reduction in subsoil water infiltration, which can only be corrected by deep tillage to mix the two layers.

5.1.6 Resistance and resilience to waterlogging

Impact of soil type

- Because clay soils contain a higher proportion of smaller pores (<0.5µm diameter) that are frequently filled with water, it take less additional water for them to become waterlogged from field capacity compared to sandier soils. Pores in clay soils are also unstable and can collapse when emptied of water, so drainage is not always followed by the entry of air. Clay soil pores are less well connected than those in sandier soils and thus drain more slowly because hydraulic conductance (i.e. the ease of water movement between pores under gravity) is low (Jackson, 2004). However, in clayey soils, low hydraulic conductance can sometimes be offset by a tendency to crack thereby opening up fissures through which
water may move more rapidly. Channels formed by earthworms and roots, also increase the drainage rate.

**Improving resistance to waterlogging**

- The severity and duration of waterlogging will vary considerably based on the weather conditions (rainfall, evapotranspiration) as well as the soil type, existing structural status and land use/cropping. The best methods for erosion control on arable land are to implement appropriate cropping rotations and adopt soil management techniques that preserve good soil structure and porosity, and provide protection for the soil surface in the form of vegetation cover or crop residue (Chambers et al., 2000; Defra, 2009). The Code of Good Agricultural Practice (Defra, 2009) also encourages the creation of rough seedbeds in order to reduce the risk of soil capping, which can lead to reduced seedling emergence, encourage surface waterlogged conditions, and on sloping land, increase runoff and erosion risk. Equally it is suggested that where possible drilling autumn-sown cereal crops early will help to establish a suitable level of ‘cover’ to reduce the risk of bare soil being exposed and of conditions suitable for capping to occur.

5.2 Changes in crop physiology, growth and productivity as a result of waterlogging.

5.2.1 **Crop physiology and growth**

**Change to crop physiology**

- Under waterlogged conditions, impacts on crops are predominantly a consequence of oxygen \((O_2)\) deprivation (Sairam et al., 2008), because \(O_2\) diffuses approximately 10,000 times slower through water than through air (Killham, 2006). If waterlogging continues for 48 to 96 hours or longer, oxygen levels will drop to a level that can cause problems for plants (HGCA, 2014b). The overall effect of \(O_2\) depletion on plant growth (Cannell et al., 1980; Zhou & Lin, 1995; Gutierrez Boem et al., 1996) is related to the:
  - Duration of waterlogging
  - Soil temperature at the time of waterlogging
  - Particular stage of crop development at which it occurs

- Under short-term waterlogging, submerged roots experience hypoxia, where the \(O_2\) available to root cells is reduced, and aerobic respiration to produce energy is limited by \(O_2\) availability. In contrast, longer term waterlogging can result in anoxia, (i.e. a complete absence of oxygen supply to the plant roots) and so anaerobic fermentation is the only source of energy for plants.

- Waterlogged plants can suffer from an internal water deficit as stomatal resistance and water uptake is limited as a result of decreased root permeability (Kramer and Broyer, 1995). This can result in reduced photosynthesis as the stomata do not open as often (Huang et al., 1993), which will consequently affect both above- and below-ground plant growth. Waterlogging can also decrease the nutrient uptake of plants as the active transport of nutrients such as N, K and Ca requires a supply of oxygen (Boem et al., 1996; Malik et al., 2002).

- Despite the negative effects of waterlogging on respiration and photosynthesis, plants can respond physiologically to reduce the impact on growth. There is evidence that ethylene production is induced in oxygen deprived plant roots (Huang et al., 1997), which is thought to facilitate the development of adventitious roots and protect the growing root from injury (Shiono et al., 2008). Adventitious roots can act as a functional replacement for existing roots that fail to supply the plants with water and nutrients under waterlogged conditions (Kozlowski, 1984). In some plants, including many crop species (Saqib et al., 2005) ethylene can also stimulate the development of aerenchyma, which are formed by the breakdown of the cells in the centre of the root cortex to produce a hollow tube that can
transfer air from aboveground to the oxygen starved roots below the water surface (Shiono et al., 2008).

**Crop establishment and growth**

- The impact of waterlogging on plant growth depends on the stage of crop development when the waterlogging occurs, with the greatest impact before plants have started to tiller (Watson, 1976). Winter wheat is most sensitive to waterlogging post germination, but before emergence (Cannell et al., 2006).

- If waterlogging occurs at the time of planting, it can be detrimental to plant establishment (Trafford, 1974) because oxygen flow to the seed is restricted, limiting germination (Blake et al., 2004), nutrient uptake (Malik et al., 2002) and photosynthesis efficiency (Parent et al., 2008). Waterlogging can result in poor rooting in winter cereal and oilseed rape (OSR) crops leading to overwinter plant loss (HGCA, 2006a; HGCA, 2008; HGCA, 2012a).

- Both short-term and prolonged waterlogging can severely impact root growth and survival. In particular, studies have found severe impacts of waterlogging on lateral root production (Malik et al., 2002; Bragg et al., 1984). Nodal roots may be produced in response to waterlogging (e.g. Dickin et al., 2009) and canopy growth can be reduced, e.g. Bragg et al. (1984) reported that the maximum number of winter wheat shoots was 25% less in waterlogged soils compared to drained soils.

- Malik et al (2002) found that with increasing waterlogging duration, reductions in N concentrations in leaves, stems and seminal roots became apparent. Bragg et al. (1984) also reported that winter wheat plants grown in undrained field plots showed signs of nutrient deficiency and that N, P and K uptake was lower than on drained plots.

5.2.2 **Disease, pest and weed issues**

**Diseases.**

- Waterlogging in winter can increase the incidence and severity of take-all (*Gaeumannomyces graminis* L.) in winter wheat (Cannell et al, 1980; Ellis et al., 1984). However, if drilling is delayed as a result of waterlogging, levels of take-all can be reduced, especially if the wet ground conditions continue through winter (Shepherd et al., 2001). The risk of Clubroot (*Plasmodiophora brassicae*) is increased in OSR following flooding as it is spread by water movement.

**Pests**

- Vernavá et al. (2006) found that short term flooding had no effect on slug (*Deroceras reticulatum*) eggs, although the eggs can be washed away by flooding. Shepherd et al. (2001) reported that slugs could be a problem in wet conditions especially on crops drilled after OSR due to the reduced opportunity to apply pellets.

- Barley yellow dwarf virus (BYDV) is transferred to plants through vectors such as aphids. Late drilling of cereals due to wet weather conditions can reduce the migration of aphids onto crops and therefore reduce the impact of BYDV (Shepherd et al. 2001).

**Weeds**

- Wet conditions can limit the opportunities to apply herbicides resulting in missed treatment deadlines and consequently an increased risk of weed problems such as blackgrass in cereals. Broad-leaved weed growth is not usually facilitated under wet conditions, except for *Stellaria media* (chickweed) which can develop large cushions of stems and leaves, and can outcompete crops (Shepherd et al., 2001).
5.2.3 The impact of waterlogging on crop productivity

Cereals
- The area of cereals affected by flooding and waterlogged conditions is likely to be higher than for other arable crops, as they are widely grown on all soil types apart from peat (Shepherd et al., 2001). Winter barley tends to be grown on lighter soils where the effect of wet weather is normally less severe. There is strong evidence from a range of studies that waterlogging can reduce cereal crop yields by 7-24% (e.g. Armstrong, 1977; Bragg et al. 1984; Cavazza & Rossi Pisa, 1988; Dennis et al. 1981; Dickin & Wright, 2008; Dickin et al., 2009; Ellis et al., 1984).

Oilseed rape
- Waterlogging has been shown to reduce yield of OSR crops grown on a sandy loam soil by 14% (Cannell et al, 1980), with similar results reported in other studies (Cannell and Belford, 1980; Jackson and Drew, 1984). Gutierrez Boem et al. (1996) found that winter waterlogging had a larger effect upon both plant growth and yield than spring waterlogging. They suggested that winter waterlogging decreased the number of seeds per plant, whereas spring waterlogging decreased the size of seeds per plant. Consequently, winter waterlogging had a greater impact on seed yield than spring waterlogging, with seed yield almost halved by winter waterlogging but reduced by approximately a third by spring waterlogging.

Grassland
- Prolonged waterlogging can impact on grassland productivity by causing large reductions in the root and shoot biomass of grassland species, reducing photosynthesis (McFarlane et al., 2003) and decreasing the number of healthy, viable grassland species within the pasture. In addition, waterlogged soils can become weak and more sensitive to damage from grazing livestock (e.g. more prone to ‘poaching’).
- The total yield of grassland can be improved by drainage of waterlogged soils with typical dry matter yield increases of 7-10% (Berryman, 1975; Parker, 1983). However, one of the main benefits of draining waterlogged grassland is an increase in the number of grazing days on the drained soils with a reduced poaching risk in the autumn (Berryman, 1975).

Legumes
- Waterlogging can affect growth and development of field pea crops (Belford et al., 1980). Jackson (2006) found that after one to four days of waterlogging symptoms included extensive desiccation and chlorosis of the foliage and lower rates of transpiration, stem extension, and growth of shoots and fruits. Field beans (Vicia faba L. minor) are also affected by waterlogging, with Pociecha et al. (2008) reporting that beans subjected to waterlogged conditions for 7 days displayed reduced growth and damaged the photosynthetic apparatus in field beans. Overall in 2000, the yields of field peas and beans were reduced on a per hectare basis, as a consequence of wet weather and waterlogging (Shepherd et al., 2001).

Root crops
- Glycoalkaloid’s are naturally occurring toxins within the Solanaceae family (Papathanasiou et al., 1989) and waterlogging can affect concentrations in potato crops. If a potato crop is waterlogged for more than a few hours, the centre of the potato turns black as result of O₂ starvation; if the crop remains O₂ starved for more than 24 hours it will begin to rot. In the wet autumn of 2000 up to 10% more of the potato crop was still in the ground at any one time compared with 1999 and up to 50% of the over-wintered crop was lost to winter frost (Shepherd et al. 2001).
- In 2000, soil conditions made it difficult for harvesters to lift and clean sugar beet with lifting costs increasing by an estimated average of c.£50/ha (Shepherd et al., 2001). Thus, although it was reported that up to 50,000 tonnes of sugar beet were lost due to flooding
in some areas, and small areas of un-lifted beet were commonplace, the largest impact of the wet weather was the increased cost of harvesting rather than a reduction in yield. The delay in harvesting can also put the crops at risk of frost damage, which may result in rejection by the factory.

5.3 Duration of impacts

- An assessment was made of how long soils remain waterlogged under current climatic conditions, based on the Field Capacity Days (FCD) analysis carried out in section 6 (Temporal and spatial extent of waterlogging) for the ‘baseline’ climate scenario (i.e. the mean average climate for 1961-2000).

5.3.1 Farming system

- Under the baseline climate scenario, a proportion of all farm types were estimated to experience shorter duration (1-30 days) waterlogging, with 17-24% of Cereals, General cropping and Horticulture holdings affected (Table 5.1). However, for some farm types, a larger proportion of farms were estimated to be affected by much longer term waterlogging, with 48% of Less Favoured Area (LFA) grazing livestock and 38% of dairy holdings estimated to experience >180 days of waterlogging each year (predominantly located in the north-west and south-west of England and in Wales, corresponding to the main dairy and sheep farming regions of the country).

- These data indicate that the majority of farms within all farm types should be prepared to deal with episodes of prolonged waterlogging and should consider appropriate measures to mitigate the effects of such events. However, according to current climate predictions, longer-term waterlogging is more likely to be a problem for livestock farmers.

Table 5.1: Likely duration of waterlogging by robust farm type (% total number of holdings*) under the baseline climate scenario.

<table>
<thead>
<tr>
<th>Farm type</th>
<th>Days of waterlogging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-30</td>
</tr>
<tr>
<td>Cereals</td>
<td>17</td>
</tr>
<tr>
<td>Dairy</td>
<td>5</td>
</tr>
<tr>
<td>General cropping</td>
<td>19</td>
</tr>
<tr>
<td>Horticulture</td>
<td>24</td>
</tr>
<tr>
<td>LFA grazing livestock</td>
<td>3</td>
</tr>
<tr>
<td>Lowland grazing livestock</td>
<td>9</td>
</tr>
<tr>
<td>Mixed</td>
<td>12</td>
</tr>
<tr>
<td>Specialist pigs</td>
<td>16</td>
</tr>
<tr>
<td>Specialist poultry</td>
<td>15</td>
</tr>
<tr>
<td>Unclassified</td>
<td>13</td>
</tr>
</tbody>
</table>
*Note: percentages refer to the number of holdings, not to the area they contain (i.e. a small holding gets equal weighting to a large holding).
5.3.2 **Soil type**

- Under the baseline climate scenario, all soil types were estimated to undergo some degree of short duration (<30 days) waterlogging. Shallow soils over chalk/limestone and sandy/light soils were unlikely to be waterlogged for longer than 30 days. However, c.20-40% of heavy, medium, peaty and other soils were estimated to experience >180 days of waterlogging annually (Table 5.2).

**Table 5.2: Likely duration of waterlogging by cross-compliance soil type (% total number of holdings*) under the baseline climate scenario.**

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Days of waterlogging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-30</td>
</tr>
<tr>
<td>Chalk and limestone</td>
<td>3</td>
</tr>
<tr>
<td>Heavy</td>
<td>8</td>
</tr>
<tr>
<td>Medium</td>
<td>11</td>
</tr>
<tr>
<td>Peaty**</td>
<td>30</td>
</tr>
<tr>
<td>Sandy and light silt</td>
<td>18</td>
</tr>
<tr>
<td>Other</td>
<td>11</td>
</tr>
</tbody>
</table>

* Note: percentages refer to the number of holdings, not to the area they contain (i.e. a small holding gets equal weighting to a large holding).

** Raw peats were not included in the analysis.

5.3.3 **Drainage system**

- Section 7 of this report uses a modelling approach to investigate the impact of degraded drain function on the duration and intensity of waterlogging. Clay soils comprise c.45% of the arable land in England & Wales (Cannell *et al*., 1978); their drainage status is therefore of considerable importance to the growth of winter cereals over large areas of the rural landscape. Under-drainage were discussed further in section 3.2. Where drainage systems have been allowed to deteriorate, there will be a tendency for an earlier return to field capacity, potentially resulting in more difficult soil management conditions and increased difficulties in applying autumn pesticides and early spring fertilisers. Harris *et al.* (2000) concluded that effective drainage of clay soils reduced the risk of flood run-off due to increases in water storage and consequent reductions in surface run-off.

5.3.4 **Type of waterlogging**

- Surface water flooding occurs where stream, river or other drainage channels cannot cope with the amount of water that is flowing into them during periods of higher than normal rainfall, and the water breaks or overspills the banks.

- In contrast, groundwater flooding occurs as a result of water rising up from the underlying rocks, or from increased spring flow or new springs. This tends to occur after long periods of sustained high rainfall. Groundwater flooding may occur with a delay following periods of high rainfall rather than immediately during storms. Groundwater flooding takes longer to dissipate than surface water flooding, leading to floods which can last for weeks or months.

5.4 **Effects of waterlogging on farm practices**

5.4.1 **Autumn waterlogging**

- Heavy rainfall during the autumn drilling window can affect the crop area planted, as opportunities to travel on the land are limited. Prolonged waterlogging can also affect how crops are established and drilled once soils have dried out sufficiently for machinery to
travel, e.g. ploughing rather than minimum tillage cultivations, particularly on heavy soils. Autumn waterlogging can lead to a move from winter cropping to spring cropping and, where crops are autumn drilled, poor crop establishment, sometimes resulting in crops of questionable viability that may require re-drilling.

- Autumn waterlogging also has consequences for livestock farms. For example, cattle may need housing earlier than normal due to poor grazing and poached land (Shepherd et al., 2001).

5.4.2 Winter waterlogging

- Winter waterlogging impacts on farmers’ ability to carry out pesticide and fertiliser operations because it becomes increasingly difficult for farmers to access land when soils become too wet, resulting in increased weed and disease pressure and potential yield reductions.
- Prolonged waterlogging can prevent the drilling of winter cereals (and OSR) which are replaced by spring varieties that can be planted later in the season. A switch from winter cropping to spring cropping has implications for the farm economy with spring crops typically yielding 20-30% less than their autumn drilled counterparts (Defra, 2013).

5.4.3 Spring waterlogging

- Waterlogging can impact on timing of spring drilling, fungicide applications to cereals, late spring weed control and the late application of fertilisers, all of which can have consequences for crop yields.
- Spring waterlogging can also impact on the time livestock spend at pasture, leading to extended housing periods which put pressure on the demand for supplementary forage to feed stock.

5.4.4 Summer waterlogging

- Summer waterlogging during grain fill can affect yield. Evidence from ADAS Crop Reports showed that prolonged summer waterlogging led to a reduction in the specific weight of wheat in 2011 (i.e. 66 kg/hl in 2012 compared to 73.2 kg/hl in 2011).
- Summer waterlogging can also impact on the time livestock spend at pasture, leading to extended housing periods which put pressure on demand for supplementary forage to feed stock.

5.4.5 Impact of prolonged waterlogging on yield

- Cold conditions and waterlogging can decrease plant growth and affect crop yields. For example, in the 2012-13 season, the yields of winter wheat and winter OSR were 0.3 t/ha and 0.5 t/ha respectively lower than the UK five year average, partly due to poor establishment conditions caused by waterlogged soils and cold temperatures (Defra June Census, 2013).
5.5 Remediation options

5.5.1 Drying out soil

- Drying out the soil is a crucial first step to prevent further soil damage; subsequent field operations should not be carried out until the soil surface has dried sufficiently to bear livestock or machinery. Heavy rainfall may have caused drainage ditches to become silted up or blocked with debris. Clearing ditches as soon as possible and removing debris from drain outfalls will help dry out the soil more rapidly.

- Where the soil has been compacted as a result of waterlogging, consideration should be given to mole ploughing just below or in the compacted layer with the mole being taken right into the ditch to allow drainage as rapidly as possible. Once the soil has dried out sufficiently and where it is possible, the field should then be drilled to allow a growing crop to help the soil dry out further.

5.5.2 Soil structural issues

- In grassland, capping or compaction of waterlogged soils down to 10 cm can be alleviated to some extent by using a soil aerator with spikes to break the cap. If clear signs of compaction extend to between 20 and 35 cm depth, a sward lifter would be required on grassland, and arable fields may need to be ploughed or sub-soiled.

- In the longer term, applying additional organic matter in the form of bulky organic materials such as farmyard manure or compost will improve soil structure and resilience (Gregory et al., 2009; Pote et al., 2003). For example, Bhogal et al. (2009) measured positive relationships between total soil C inputs and available water capacity.

- Sub-soiling can be used to tackle drainage and runoff problems caused by compaction, such as water pooling on the soil surface, thus allowing the soil to dry and warm up more rapidly in the spring. The depth of sub-soiling should vary according to the depth of compaction with tines ideally set 3-5 cm below the lower surface of the compacted layer.

5.5.3 Damage to crops

- After an episode of prolonged waterlogging or flooding of a month or more, an application of fertiliser N or a foliar N spray (depending on crop stage and intended market) can be applied to surviving crops to assist recovery (Jackson, 2004).

- It may be necessary to review the variety and even the crop grown in individual circumstances given the delays in cultivations that can be caused by waterlogging. Leaving land fallow with plant growth from natural re-generation or broadcast ‘tail corn’ or green manure can help to improve soil structure and aeration.

5.5.4 Loss of soil fertility

- Soluble nutrients such as N and S can be leached away leaving soils deficient in these nutrients. Also, where soil has been eroded, P, K and Mg can also be removed. Soil analysis for pH and these major nutrients will be important to assess the impacts on soil fertility and to determine the best remedial action.

5.5.5 Drainage management

- At the catchment scale, one approach to reducing the rate of water input to flood-prone agricultural land is to retain as much water as possible upstream by preserving and improving what remains of upstream flood plains. More locally, an important method by which to prevent or minimise the recurrence of waterlogging is to install a suitable drainage system or to properly maintain existing systems. Well-maintained ditches allow under-drainage systems to flow, drain the cultivated layer and lower the water table within the root zone. A functioning drainage system also increases the number of machinery work
and grazing days, reducing the likelihood of trafficking or trampling waterlogged land, thereby reducing the risk of soil structural degradation, damage to tracks and soil erosion on sloping land.

5.5.6 Plant breeding and novel crops

- Breeding and selecting cultivars tolerant of waterlogging is yet to achieve commercial success. Nevertheless, there have been reports of greater than normal tolerance in a number of major crop species (e.g. trifoilium, winter wheat, spring wheat) that could perhaps be employed in plant breeding programmes to introduce tolerant traits (Jackson, 2004).
- Planting of waterlogging tolerant trees could be considered as a method for utilizing land that is regularly flooded. Stands of alder or willow absorb large volumes of water and could be cut for biomass energy or fed to ruminants.

5.6 Conclusions

- The lack of oxygen in the soil, as a result of prolonged surface waterlogging, has significant effects on soil chemical and biological processes, and on the physical structure of the soil. This can profoundly affect the quality of soil as a plant growth medium, although draining and drying a flooded soil can reverse these changes to some extent.
- In general, clay soils are more susceptible to waterlogging than sandier soils, although the extent and duration of waterlogging depends on a range of factors including climate, topography, soil water regime, cropping and land management. The main practices to limit the impacts of waterlogging on any soil type are to maintain and improve soil structure, and facilitate drainage by:
  1. Maximising soil surface protection in the form of vegetation, crop residue or mulch.
  2. Maximising surface roughness to reduce capping risks.
  3. Avoiding compaction pressures such as trafficking and poaching through smarter timing of field operations.
  4. Alleviating soil compaction where present.
  5. Increasing soil organic matter content by the addition of bulky organic materials such as farmyard manures and compost.
  6. Maintaining or improving field drainage.
- Impacts on crops grown under prolonged waterlogged conditions are predominantly a consequence of oxygen deprivation. However, the overall effect on plant growth is related to the duration of waterlogging, soil temperature, and stage of crop development at which waterlogging occurs. There is strong evidence from a range of studies that prolonged waterlogging reduces yields of cereal crops, OSR, grass, legumes and roots. The overall economic impact of prolonged waterlogging is likely to be greatest for cereals because they are widely grown on most soil types, although the consequences for potato farmers who experience complete losses of this high value crop could be very significant.
- All farm types should be prepared to deal with short-term waterlogging, although longer-term waterlogging is more likely to be a problem for livestock farmers. The greatest flood risk is normally from heavy clay soils that have been traditionally under-drained and used to grow arable crops.
- The timing of waterlogging is key to the impacts on farm practices. Autumn waterlogging can affect drilling/establishment while winter waterlogging (in isolation) has minimal impacts. Spring waterlogging can delay spring drilling, chemical and fertiliser applications, whilst summer waterlogging can lead to reduced grain fill. The spring to summer period is key to determining the degree to which crops can ‘recover’ from earlier setbacks and ultimate effects on crop yield.
• Adaptations to prolonged waterlogging include changing the rotation in favour of spring crops, changing cultivation method to suit the soil conditions, installing farm tracks to combat livestock poaching, installing drainage systems or taking a more proactive approach to the management of existing drainage systems.

• Issues which may need to be addressed by farmers and growers following periods of prolonged waterlogging include drying out the soil; addressing any soil structural issues caused by waterlogging (e.g. compaction, capping and/or slumping); correcting loss of soil fertility; and dealing with crop damage/loss and animal health issues.
6. SPATIAL AND TEMPORAL EXTENT OF WATERLOGGING

6.1 Introduction

The main objectives for this section were to:

- Assess the spatial variation in the extent and duration of soil waterlogging under both baseline and potential future climatic conditions.
- Determine whether the conditions in the winter of 2012-2013 were statistically unusual, and what the likely return period of these events would be.

The main steps to achieve this were as follows:

i. Using the Met Office Rainfall and Evaporation Calculation System (MORECS) model, generate the median number of days at field capacity under current climatic conditions.
ii. Generate a relationship between predicted median days of field capacity and rainfall quantity and timing.
iii. Using UK Climate Projections (UKCP) scenarios, generate predictions of future rainfall patterns and assess the impact of this on field capacity days.
iv. Using soil characteristics data, relate days at field capacity to days of waterlogging under current and future climate scenarios.
vi. Use data on farm locations to calculate the impacts on different robust farm types.
v. Use the number of waterlogged days to determine the return period of the waterlogging event during 2012-2013

6.2 Methodology

6.2.1 Calculation of median days at field capacity

The procedure for the prediction of field capacity days was built upon existing work by Chapman et al. (2011) and Anthony (2012). To calculate the median days at field capacity the Meteorological Office Rainfall and Evaporation Calculation System (MORECS) version 2.3 was used. This was designed to provide estimates of weekly and monthly soil moisture deficits averaged over a 40 km x 40 km grid using daily synoptic weather data as inputs.

The median days at field capacity was calculated for 120 40 x 40 km² grid squares covering England and Wales, matching the spatial resolution of the MORECS model outputs.

For each year and for each grid square the daily soil moisture deficit (SMD) was extracted from MORECS for a grass crop. (1st January 1961-31st December 2013). While using grass as the reference crop has shortcomings, because some crops have bare soil for part of the year, it does provide a consistent methodology for the whole country. This same approach was used in Defra project SP1104 (Keay et al., 2014).

The start and end date of field capacity, and the number of field capacity days (FCDs) in individual years were then calculated as follows:

- The end of field capacity was defined as the start date of a drying sequence of 10 days or more with a soil moisture deficit of 5mm or more. Short periods with an SMD of less than 5mm were not considered i.e. such periods are defined as zero SMD and the start date of the end of field capacity was not changed. This is necessary because MORECS does not account for super-saturation of soils or any standing water. Even in mid-winter some evapo-transpiration will occur and therefore, if there is no precipitation, a finite, if small, SMD will result within MORECS. The 5mm threshold is consistent with the work of Francis (1981), whilst both Smith (1976) and Francis (1981) use a 10 day period in their definitions.
- The return to field capacity (i.e. the start of the field capacity period) is the day following the last day of the longest period of non-zero SMD and the number of FCDs is the length in days of the year minus the length of the longest period of non-zero SMD.
The periods of interest are those when soils are at field capacity during what is known as the “winter period” in drainage terms. This extends from the time when field capacity is reached in the autumn to the time when soils dry out in the spring. Thus for the autumn/winter of 1961-1962 the days following return to field capacity in the autumn of 1962 are added to the number of days before the end of field capacity in 1963, to give the total number of FCDs for the winter period for 1961/62. This was repeated for all of the years in order to determine the days of field capacity for each year, the median of these values was then taken for each 40km MORECS square. Across the large number of MORECS squares and years studied there were a small number of situations where in individual years the above rule set produced outlier results. This was where the SMD was highly variable and so it did not define a constant field capacity period, despite there being a large number of days at field capacity. The use of the median rather than the mean accounted for these outliers and so did not skew the final results.

6.2.2 Relating field capacity days to rainfall

In order to examine future climate conditions it was necessary to relate median days at field capacity with rainfall. This allows us to adjust the FCDs for future climate scenarios for which the changes in rainfall have already been modelled.

The approach used was that described by Anthony (2012) and Keay et al. (2014) where a relationship was derived between median days at field capacity and average summer and winter rainfall. The relationship was derived using a curve fitting approach and had an $r^2$ of 0.94 with a root mean squared error of 15 days, which is in line with the error found in the work of Anthony (2012).

The relationship used was as follows

$$ FCD = 461 + \left( -96815 \times \frac{1}{\text{Summer Rainfall}} \right) + \left( -15177 \times \frac{1}{\text{Winter Rainfall}} \right) $$

6.2.3 Future climate scenarios

The UKCP climate projections provides estimates of future rainfall patterns under a range of scenarios. Data for low (UKCP b1), medium (UKCP a1b) and high (UKCP a1fi) emissions scenarios for each of 2020, 2050 and 2080 on a 25 km$^2$ grid were extracted and the rainfall averaged (including the production of summer and winter rainfalls). This generated separate scaling factors for summer and winter rainfall which then could be applied to the baseline MORECS rainfall figures in order to predict future rainfall by 25 km$^2$ square, taking account of seasonality. By using these rainfall figures in the relationship derived in section 2.2 a median number of FCDs was generated for each MORECs square for each of the 9 future climate scenarios.

6.2.4 Relating days at field capacity to actual waterlogging

The days at field capacity is an indicator of the risk of waterlogging based on climate, it does not take into account local soil types.

The definition of waterlogging is that the soil profile is wet within 40cm. A further method was needed to relate the FCDs to actual waterlogging, taking into account the spatial variety in soil characteristics.

The work of Hollis (1989) contains a rule set that relates soil type to wetness class (Figure 6.1). There are six wetness classes defined, each of which has a typical number of days where the soil profile is wet within 40cm, based on field measurements

The rule set takes the form of a set of decision trees depending on a number of soil characteristics, including the hydraulic rock class, the depth to semi-permeable layer, the depth to gleying, integrated air capacity and peat status. The final step of each decision tree is a set of thresholds of FCDs and wetness class. Each wetness class defines a range of days of waterlogging. By defining the relationship between the top and bottom of each of these ranges and each threshold of field capacity days and linearly interpolating between each threshold it
was possible to link each possible value of FCDs to a different number of days of waterlogging for each of 10 different soil groupings used in the Hollis (1989) work. Raw peats or soils that did not require drainage were not considered in this analysis. An example of part of the decision tree is shown below.

**Figure 6.1.** A reproduced extract of the rule set for determining soil wetness class from soil properties and field capacity days. Based on diagram of Brignall and Rounsevell (1994)

The dominant soil type for each 1 km² in England and Wales (taken from NSRI NATMAP 1000 data) was passed through the decision tree analysis described above, and using the number of FCDs in each 1 km² square under the 10 scenarios (baseline and 9 future climate) it was possible to derive a predicted days of waterlogging for each 1km². It should be noted that although the soils data was at a 1 km² scale, the days at field capacity was at a spatial resolution of 25 km². The methodology for predicted waterlogging combines previously validated methodologies of work into wetness and waterlogging (Hollis, 1989) and prediction of FCDs (Keay et al., 2014, Anthony, 2012). It was investigated whether the baseline predictions could be validated against farmers survey results (e.g. Farmers Voice). Unfortunately any survey questions on waterlogging asked only if the farmer had ever experienced it, rather than any estimation of duration or severity, and so a comparison was not made.

In recognition of some of the uncertainty in the above approach the final predicted days of waterlogging were put into 30 day categories (e.g. 1-30, 31-60 etc.). There was also a category of 0 days, which relates to the Hollis wetness class I where the soil is never waterlogged, i.e. wet within 40 cm of the surface. The category NS refers to soils which are never susceptible to waterlogging; and so are not assigned a Hollis wetness class. These categories were then mapped (Figures 6.2 to 6.10) to show the spatial extent of waterlogging.
6.2.5 *Impacts by farm type*

It was also necessary to consider how changes in waterlogging may impact on different farm types. The 2010 agricultural census data, which provided farm location and robust farm typology, was used to assess this. For each of the approximately 100,000 commercial farms in the dataset, the wetness class at its location was extracted for each of the 10 scenarios. The distributions of each farm type in each waterlogging class were then calculated and summarised.

6.2.6 *Determination of the return period of the 2012-2013 event*

The calculated number of days at field capacity were used in a further analysis to determine the return period, the estimate of the likelihood of this number of days occurring. In this case rather than the duration of a continuous period above field capacity the actual number of days at field capacity were used. This was to account for the outlier data points discussed previously, where the continuous period of field capacity determined by the rule set did not adequately reflect the actual number of days at field capacity.

For each year studied (1960-2013) the number of days at field capacity was totalled for the periods September to December and January to April. The number for the winter of 2012-2013 was then ranked relative to the previous years. To calculate the return period an initial attempt was made to fit a statistical distribution to the data, such that return periods outside the range of the data could be estimated. A statistical distribution which consistently fit the data was not found. Instead the return period was calculated empirically for each MORECs square, based on the probability of the rank of the 2012-2013 value being exceeded.

As this was done empirically, it is not possible to infer return periods outside of the range of the data. This means that for a situation where the return period is calculated as 52 years (i.e. it was the highest number of days at field capacity in the time series) it is not possible to estimate how much higher than 52 years the true return period may be.

6.3 *Results and Discussion*

6.3.1 *Spatial and temporal extent of waterlogging under changed climate scenarios*

The spatial extent of waterlogging across England and Wales is presented for each of the 9 climate scenarios and baseline conditions (Figures 6.2 to 6.10). The pattern is a reflection of rainfall and soil types, and is spatially complex. However, although the overall degree of waterlogging changes over time in the climate scenarios, the overall pattern of where waterlogging is most and least severe does not change significantly.

The percentage of farms in each robust farm type in each waterlogging class under the baseline climatic scenario is presented in Table 6.1. The farms included in this analysis are only those considered commercial by Defra (those with significant agricultural activities). For all farm types, approximately half the farms fall experience 30 days or less of waterlogging. Defining a threshold above which a farmer is significantly impacted is difficult, as the exact timing of the waterlogging compared to when they need to work the land is important. Waterlogging of under 30 days is defined by Hollis (1989) as wetness class 2 (the lowest class with any waterlogging). Grazing farms situated in LFA s had the longest duration of waterlogging, because they are more likely to be located at higher elevations, and hence in higher rainfall areas than other farm types.

Tables 6.2 to 6.4 show the changes in waterlogging under each of the climate scenarios. Cells highlighted in green indicate an increase compared with the baseline, whereas red indicates a decrease. Where cells are highlighted as having changed, but no change of numerical value is shown this indicates a change of <1.
Table 6.1: Percentage of farms by waterlogging class for each farm type; baseline climate conditions. NS denotes farms on soils not susceptible to waterlogging that were not assigned a Hollis wetness class. The zero days category relates to Hollis wetness class 1, where the soil is never wet within 40cm.

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Table 6.2: Percentage of farms by waterlogging class for each farm type; low emissions scenario. Green cells indicate an increase since the baseline, red cells a decrease. NS denotes farms on soils not susceptible to waterlogging that were not assigned a Hollis wetness class. The zero days category relates to Hollis wetness class 1, where the soil is never wet within 40 cm.

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Table 6.3: Percentage of farms by waterlogging class for each farm type; medium emissions scenario. Green cells indicate an increase since the baseline, red cells a decrease. NS denotes farms on soils not susceptible to waterlogging that were not assigned a Hollis wetness class. The zero days category relates to Hollis wetness class 1, where the soil is never wet within 40 cm.

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Table 6.4: Percentage of farms by waterlogging class for each farm type; high emissions scenario. Green cells indicate an increase since the baseline, red cells a decrease. NS denotes farms on soils not susceptible to waterlogging that were not assigned a Hollis wetness class. See Table 6.3 for the definition of the zero days category.

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Figure 6.2: Predicted median days of waterlogging; baseline conditions
Figure 6.3: Predicted median days of waterlogging; low emissions scenario, 2020
Figure 6.4: Predicted median days of waterlogging; low emissions scenario, 2050
Figure 6.5: Predicted median days of waterlogging; low emissions scenario, 2080
Figure 6.6: Predicted median days of waterlogging; medium emissions scenario, 2020
Figure 6.7: Predicted median days of waterlogging; medium emissions scenario, 2050
Figure 6.8: Predicted median days of waterlogging; medium emissions scenario, 2080
Figure 6.9: Predicted median days of waterlogging; high emissions scenario, 2020
Figure 6.10: Predicted median days of waterlogging; high emissions scenario, 2080
Under the 2050 and 2080 scenarios the number of farms in the higher median days of waterlogging classes has generally fallen relative to the baseline (Tables 6.3 and 6.4). The future UKCP climate scenarios include both an increase in rainfall and a change in seasonality, with an increase in winter rainfall and a decrease in summer rainfall. Applying the previously derived relationship, this leads to a reduction in the length of the field capacity period. This finding supports that of previous studies such as Defra SP1104 (Keay et al., 2014), which showed the number of field capacity days falling in the period 2020-2080 under 3 future climate scenarios.

The exception found in this work is under the 2020 scenarios, where the increase in winter rainfall in some areas outweighs the decrease in summer rainfall, leading to the number of farms in one of the higher waterlogging categories (i.e. 271-300 waterlogging days) increasing.

6.3.2 Return period analysis for the of the 2012-2013 waterlogging event and the impact of field drainage

Field capacity conditions in September to December 2012 were unusual, with considerable areas of the country experiencing an event with a return period of greater than 1 in 10 years and some areas experiencing conditions with a return period of greater than 1 in 50 years (Figures 6.11-6.12). However, as previously stated it is not possible to determine how much greater than 1 in 50 the true return period was due to the limitations of the dataset. By contrast, spring 2013 was not unusual, with return periods generally less than 2 years. When the two ‘seasons’ were combined, the return periods for September 2012 to April 2013 were greatest in north east and western England (Figure 6.13), although clearly September to December 2012 represented the more extreme conditions.

Figure 6.14 looks specifically at the return to field capacity date for 2012 compared to the median value for 1961-2011. The previous analysis shows that the duration of field capacity in winter 2012 was unusual, and analysis of the start date shows that this occurred unusually early across the majority of the country. It is particularly notable that, following a very dry period over winter 2011-2012, some areas reached field capacity when rainfall arrived in spring 2012 and clearly stayed there for the rest of the period. Other areas in eastern England, where median return to field capacity normally occurs in December, reached field capacity in August. This had significant implications for access to land to complete field operations and exacerbated the impact of the wet autumn considerably.
September - December 2012

Return Period (yrs)
- <2
- 2 - 5
- 5 - 10
- 10 - 25
- 25 - 52
- 52+

Figure 6.11: Return period of days at field capacity (winter 2012)

January - April 2013

Return Period (yrs)
- <2
- 2 - 5
- 5 - 10
- 10 - 25
- 25 - 52
- 52+

Figure 6.12: Return period of days at field capacity (spring 2013)
Figure 6.13: Return period of days at field capacity (total winter 2012/spring 2013)
Figure 6.14: Comparison of return to field capacity date for 2012 with median values; output from MORECS model
6.4 Conclusions

These predictions indicated that the duration of waterlogging is likely to reduce under all the climate change scenarios evaluated. This is a consequence of less rainfall occurring in summer and early autumn which leads to a late return to field capacity and hence shortening the period when the soil is above field capacity and at greatest risk of becoming waterlogged. This is similar to the findings from Defra project SP1104, which found a trend towards drier soils in early autumn under future climate scenarios.

The overall spatial extent of soils at risk of prolonged waterlogging is also more likely to reduce under all climate change scenarios. Under current climatic conditions, the areas of lowest risk (< 30 days duration) are mainly in the east of the country, with extensive areas at risk of waterlogging for > 120 days in central and western areas. The low risk areas expand from east to west as time progresses with the largest change observed under the highest emission scenarios. However this progression is not linear in all areas. Under the 2020 scenarios, the increase in winter rainfall in some areas outweighs the decrease in summer, leading to some of the high waterlogging categories (for example 270+ days) increasing in the short-term.

During September to December 2012, soils were at field capacity over significant areas of the country for a duration that had a return period greater than 1 in 50 years. This period of waterlogging also started unusually early with many areas returning to field capacity in the summer rather than late autumn/early winter, which is normally the case. This limited access to the land for both harvest and post-harvest cultivations.
7. IMPACT OF DEGRADED DRAIN FUNCTION

7.1 Introduction

The main objectives of this section were to:

- Consider the impact of excess water above drainage capacity on a day at field capacity
- Consider what the impact of drain degradation is likely to be on this excess water

This modelling work uses the methodology of the previous section to define whether a soil was at field capacity on any particular day during the period. Where the soil was at field capacity, the field drainage design criteria were compared with daily rainfall data to assess the severity of waterlogging.

7.2 Methodology

7.2.1 Determination of severity of waterlogging by use of drainage design criteria

In addition to the duration of waterlogging calculated in the previous section, another factor which may impact on agriculture is the severity of the wetness on a day on which the soil is at field capacity, i.e. the waterlogged period may not have been unusual in length, but may have been unusual in intensity. This was examined by considering the individual daily rainfall for each MORECS square during the period of waterlogging, and comparing these with the design capacities of the field drainage systems likely to be in place. If on a day of field capacity the rainfall exceeds the drain capacity then more severe and intense waterlogging (and/or greater runoff) is likely to occur. The methodology for determining whether the soil was at field capacity was the same as the previous section.

Each MORECs square was assigned to an agro-climatic zone. MAFF (1983) gives the recommended design standards for field drainage in each of these zones. These were the recommended standards used when installing field drainage, and so the daily capacities listed should reflect the drains installed. For each day of field capacity over the 52 year period it was calculated whether the daily rainfall exceeded any of the design thresholds (which were “mole drains for arable”, “mole drains for grass”, “tile drains for arable” and “tile drains for grass”). To represent possible current conditions where the mole drains have not been renewed, a degraded mole scenario was also considered. In this case, the discharge capacity used was 50% of a system where mole drains had recently been installed.

A second approach was also used which considered the cumulative total rainfall compared to the drain design capacity. In this approach the excess water held above field capacity was calculated for each day. For each day where the soil was at field capacity, the daily drain design capacity was subtracted from the quantity of rainfall. If a quantity of rainfall remained (i.e. more rain fell than could be drained) then the day was considered to have excess water. The excess water from the previous day was then carried over and added onto the following day’s rainfall, so the water available to be drained on the following day was the water not drained on the previous day plus the following day’s rainfall.
The calculation was as follows:

If soil at field capacity:

\[ \text{Excess}_{\text{today}} = (\text{Excess}_{\text{yesterday}} + \text{Rainfall}) - \text{Drain Capacity} \]

If soil not at field capacity:

\[ \text{Excess}_{\text{today}} = 0 \]

If the soil dropped below field capacity then it was considered that all the excess water would be drained.

A set of hypothetical data is presented in Table 7.1 to demonstrate the process.

**Table 7.1: Illustration of the process to calculate days with excess water, for a hypothetical site with a daily drain capacity of 10 mm.**

<table>
<thead>
<tr>
<th>Day</th>
<th>At field capacity?</th>
<th>Excess water from previous day (mm)</th>
<th>Rainfall (mm)</th>
<th>Water drained (mm)</th>
<th>Excess water current day (mm)</th>
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<tbody>
<tr>
<td>1</td>
<td>Y</td>
<td>0</td>
<td>10</td>
<td>10</td>
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<td>7</td>
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</table>

### 7.3 Results and Discussion

The median and mean number of days when the soil was at field capacity and rainfall exceeded drain design threshold was calculated across the time period for England and Wales, with each design threshold applied to each MORECS square. The value for 2012/2013 was also calculated and compared to these averages (Table 7.2).

Table 7.2 shows that, on a national basis, there were more days than average during 2012-2013 when the rainfall during the field capacity period exceeded the capacity of the drainage. The impact was widespread, with the majority of MORECs squares having a higher than average value in the period 2012-2013. This may explain why the waterlogging in this period and the volume of runoff was perceived as so severe. Although the length of the waterlogged period may not have been exceptional, the quantity of rainfall which fell during this period when the soils were already waterlogged was high.

This approach only takes into account days where the rainfall exceeds drain capacity, and does not take into account the effects of a sequence of days where rainfall was near to drain capacity, and so may underestimate the issue. To address this a second approach was used, where the excess water held above field capacity was calculated for each day and compared with the drainage design criteria for the locality. Any water over and above that which could be drained was carried over to the next day and added to the rainfall. The number of days in which there were excess water was totalled for each MORECS square, for each hydrological year. Using the 51 complete years for which data was available, the return period of the number of days with excess water in the period 2012-13 was calculated, and mapped for each drain type (Figure 7.1, Table 7.3).
Table 7.2: Days at field capacity on which daily rainfall exceeded a range of drain design thresholds

<table>
<thead>
<tr>
<th>Drainage:</th>
<th>Moled</th>
<th>Degraded moles</th>
<th>Tile drained without moles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days at field capacity where rainfall exceeded design capacity</td>
<td>Grass</td>
<td>Arable</td>
<td>Grass</td>
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<tr>
<td>National mean (1961-2011)</td>
<td>1</td>
<td>1</td>
<td>8</td>
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<tr>
<td>National mean (2012-2013)</td>
<td>2</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>National median (1961-2011)</td>
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<td>0</td>
<td>7</td>
</tr>
<tr>
<td>National median (2012-2013)</td>
<td>1</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Percentage of MORECS squares where 2012-2013 value is greater than its 1961-2011 mean</td>
<td>63</td>
<td>54</td>
<td>89</td>
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<tr>
<td>Percentage of MORECS squares where 2012-2013 value is greater than its 1961-2011 median</td>
<td>58</td>
<td>51</td>
<td>86</td>
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</table>

Table 7.3: Days at which there was excess water above field capacity for a range of drain design thresholds

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<thead>
<tr>
<th>Drainage:</th>
<th>Moled</th>
<th>Degraded moles</th>
<th>Tile drained without moles</th>
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<td>Days with excess water</td>
<td>Grass</td>
<td>Arable</td>
<td>Grass</td>
</tr>
<tr>
<td>National mean (1961-2011)</td>
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<td>15</td>
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<tr>
<td>Percentage of MORECS squares where 2012-2013 value is greater than its 1961-2011 mean</td>
<td>54</td>
<td>29</td>
<td>100</td>
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<tr>
<td>Percentage of MORECS squares where 2012-2013 value is greater than its 1961-2011 median</td>
<td>94</td>
<td>51</td>
<td>86</td>
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</tbody>
</table>

A return period of 2 years represents the median condition for the duration of days when soil is above field capacity. The median represents the number of days with excess water that is likely to occur in at least half of the years.

The return periods in Figure 7.1 show that, for the majority of the country, the return period of the number of days where excess water could not be drained was significantly greater than the median, with large areas having a return period greater than 25 years. The spatial pattern reveals that the Midlands and South West experienced the most unusual number of days with excess water above field capacity. This second approach took into account the total rainfall amount that fell during a period of field capacity, rather than just the duration. It indicated that, although the duration of field capacity was unusual in some areas, what was more unusual was the quantity of rainfall that fell in this period, and the temporal pattern of rainfall, such that there was an unusually high number of days with water in excess of the drain and field capacity. This led to the waterlogging being perceived as especially severe, even if the actual number of days where the soil was waterlogged, as defined in this project, was not always significantly greater than usual.

The drainage simulations indicate that degraded drains can increase the occurrence of waterlogging. A recent survey (Defra project FFG0923) reported widespread lack of drainage.
system maintenance (see section 3). If the areas surveyed under FFG0923 are typical of the wider landscape, limited drainage maintenance may well have exacerbated the impact of the unusual climatic conditions.

7.4 Conclusions

This analysis has shown that for large areas of the country the field capacity period in 2012/2013 was unusually long and started unusually early, limiting access to the land.

This impact of the waterlogging in September to December 2012 was further exacerbated by the fact that daily rainfall totals were such that rainfall falling on one day failed to drain from the soil in time to allow the soil to return to field capacity before the next rainfall event, leading to excess water being stored in the soil or producing drainage or surface runoff for long periods. The modelling demonstrated that the impact of this would be greater in areas where drainage has not been well maintained. The areas which experienced the most unusual conditions were mainly in the Midlands and the South West.

Conditions in the winter of 2012/2013 were often perceived to be particularly severe by the farming community. Although the number of days of waterlogging was not highly unusual, the excess quantity of water which fell onto the soil during the waterlogged period was unusual and this is likely to have contributed to the severity of field conditions in terms of waterlogging, and the volumes of drainage and surface runoff.
Figure 7.1: The return period of days with excess water above field capacity for autumn 2012 to spring 2013, by drain type.
8. ADAPTATION METHODS

8.1 Introduction

In this section, we investigate the changes to cropping, soil/land management and farming systems that may be required under future climate change scenarios to minimise soil disturbance or trafficking activities during vulnerable periods, and the potential impacts on the farming business. In section 6, an analysis of field capacity days was used to estimate the likely timing and duration of waterlogging for future standard periods (2020s, 2050s and 2080s) under low, medium and high emission scenarios. The predictions indicated that the duration of waterlogging is likely to reduce under all the climate change scenarios evaluated. This is a consequence of less rainfall occurring in summer and early autumn (on average), which would lead to a late return to field capacity and hence shortening the period when soils are at or above field capacity and at greatest risk of becoming waterlogged.

In this section, the adaptations that can be made to farming systems to increase resilience against prolonged waterlogging conditions are discussed in relation to the economic trade-offs and cost/benefits of changes to farm infrastructure (e.g. improving drainage) or changes to cropping system (e.g. change from autumn to spring sowing).

8.2 Changes to waterlogging risk

The changes from baseline to the 2020 low emissions scenario in the percentage of farms in each farm type and waterlogging class were relatively small, and generally less than 5% across all waterlogging classes and farm types (section 6). Changes by date (i.e. 2050 and 2080) and by scenario (i.e. medium and high emissions) were of a similar magnitude to the 2020 low emissions scenario.

Since the changes reflect differences in the percentage of farms in a given waterlogging class, a 2% change may represent a significant area of land, for example, for every million hectares of cereal farms, a 2% change in the area of land in a waterlogging class could correspond to c. 20,000 hectares. In the lower (shorter duration) waterlogging classes, an increase in the length of the waterlogged period (where this is predicted) may or may not result in impacts on production, such as reduced populations of viable plants in the field. However, in the higher classes where the duration of waterlogging is longer, plant populations and opportunities for carrying out field operations are likely to be affected.

These data suggest that irrespective of date or emissions scenario, it is unlikely that there will be significantly increased duration of waterlogging in the future for any farm type i. Indeed, the results indicate that despite the likelihood of increased winter rainfall in future the duration of waterlogging is expected to reduce. This is explained by drier summers and early autumns causing a later return to field capacity (section 6), and is supported by previous work that has found that the number of field capacity days will fall under future climate conditions (Keay et al., 2014). However, it is possible that the severity of waterlogging within the period when it occurs may be greater than currently experienced due to the larger rainfall totals causing drainage systems to be overwhelmed.

If, in an average year, field capacity is delayed in the autumn, there is unlikely to be a significant impact on field operations, unless soils are ‘baked’ hard resulting in high soil bearing strength and penetration resistance and a delay to cultivations. However, an increase in the frequency of extreme events under future climate change scenarios could increase the duration of waterlogging in wetter years, which would impact on field activities.
8.3 Impact on mitigation and adaptation methods

In the future, if the severity of waterlogging within the period when it occurs is greater than currently experienced due to larger daily rainfall totals and if there is an increased incidence of extreme weather events (despite overall drier conditions in some areas of the UK), periods of short-term waterlogging may increase resulting in a greater need for mitigation and adaptation measures. For example, it may become more important to ensure high water infiltration rates to minimise surface runoff as a result of increased incidence of high intensity or prolonged rainfall. Where soils are wetter due to more intensive rainfall, there will be a need for water to drain away effectively without causing erosion and localised flooding. By contrast, if the growing season becomes drier, it will also be important to increase infiltration to retain moisture in soils in order to support crop growth.

Adaptation of farming practices

Changes to farm practice that would increase resilience to prolonged or more intense periods of waterlogging and improve efficiency of production include:

- More efficient machinery to establish crops rapidly in a narrower cultivation window.
- Replacing degraded field drainage systems and maintaining existing systems including regular mucking to maintain connectivity between the soil surface and drains.
- Use of lower ground pressure tyres, controlled traffic farming and satellite guidance systems to reduce soil compaction and minimise soil disturbance.
- Timely and appropriate use of sub-soilers and top-soilers to alleviate compaction caused by farm operations in ‘wet’ conditions.
- Applying bulky organic manures to improve soil resistance and resilience.
- Establishing crops earlier in fields prone to prolonged waterlogging.
- Adopting spring cropping rather than winter cropping in higher risk fields. On farms with land suitable for spring crops, fields with lighter soils may be used for this purpose, allowing those at risk of waterlogging to be drilled with autumn sown crops earlier.
- Establishing grass on a rotational basis in order to provide an early entry for autumn cereals.

Typical farm practices and farm infrastructure defined in Defra project WQ0106 were used as a baseline to consider the changes that may occur within arable and grassland systems under future climate change scenarios, associated economic benefits and barriers to uptake.

8.3.1 More efficient machinery to establish crops more rapidly in a narrower cultivation window

With an increase in the average size of farms and a drive for greater efficiency, there is a trend towards higher work rates to cultivate soils and drill crops more quickly. To achieve this, machinery with greater capacity in terms of area cultivated and drilled per day would be needed. Greater capacity can be achieved through reduced cultivation techniques, but also often involves heavier field machinery for sub-soiling and other field operations. Indeed, there has been a general increase in the size of agricultural machinery and greater use of contractors for all field operations in the past few decades (Håkansson and Reeder, 1994; Batey, 2009). In the 1980’s, wheel loads of 50 kN were considered to be high, but by 2001 the use of 90-120 kN wheel loads was common place (Van den Akker and Schjønning, 2004), although to deliver sufficient draft, mass per unit of horse power has remained similar.

The use of heavy machinery with low ground pressure (LGP) tyres can allow fieldwork to be carried out in conditions that would not have been possible 30 years ago. Nevertheless, the increase in the size of machinery may give rise to soil compaction issues if tyre inflation pressures are higher than necessary and machinery is used when medium and heavy soils are in a plastic state or light sandy and silty soils are ‘wet’ (see section 2). This needs to be
GPS-guidance systems – benefits and costs

The uptake of field guidance systems (GPS) can also provide a significant increase in output, due to reductions in the number of overlaps and underlaps, thereby allowing farmers to cover more ground in a given work day. Conventional tillage practice can result in trafficking across 86% of a field (Kviz et al., 2014a). The usage of guidance systems can reduce within-field machinery traffic, save energy and improve soil conditions (Sharpe et al., 2005; Kroulik et al., 2011; Kviz et al., 2014a). Indeed, Kviz et al. (2014a) found statistically significant differences between the total area treated by machinery without any guidance system and machinery using precise guidance systems. Savings of up to 6% in fuel, seed, fertilizer and pesticide can be achieved within a single field operation (Kviz et al., 2014b).

However, upgrading machinery inventories over a normal replacement cycle can be a financial challenge. On a 200 ha farm, achieving greater accuracy using field guidance systems can cost around £15-20/ha for one upgraded tractor, or £20-25/ha for two units (Carl Pitelen, Ben Burgess & Co, pers. comm.) and to pay for this would require an increase in field work productivity of 5-10% (Nix, 2013; section 3) or a reduction in fuel use. Anecdotal evidence suggests a 10-20% increase in field work rate may be possible (J. Goodchild, Old Hall, Bartlow, Cambs, pers. comm.). Reducing overlaps and greater field work precision can save on seed, fertiliser and sprays, with equivalent saving to that from field work rate (Knight et al., 2009; Kviz et al., 2014b). Shannon et al. (2012) calculated that a return on investment in GPS-guidance systems could be realized through fuel savings alone. Knight et al. (2009) calculated that guidance system costs decrease exponentially with increasing farm size with benefits of a high precision Real Time Kinematic (RTK) system (typically c. £22 per hectare) exceeding costs on a farm with 500 hectares or more (Figure 8.1).

The use of controlled traffic principles and guidance systems can help achieve 5-15% yield increases with fewer overlaps and reductions in fuel use of up to 25% (Gasso et al., 2013). The use of CTF principles and satellite guidance (combined with low ground pressure tyres; see 8.3.3 below) can also negate the need to relieve soil compaction. In these cases, guidance systems and CTF principles can help avoid the need for additional sub-soiling and the loss of fieldwork days.

Reduced tillage systems – benefits and costs

Increasing capacity may involve the use of reduced tillage systems, which operate at shallower depths than conventional inversion tillage. Moitzi et al. (2014) found that area-specific fuel consumption increased linearly with working depth for both a mouldboard plough and a short disc harrow, but disproportionately for a sub-soiler. Reduced tillage operations therefore move less soil than inversion tillage, resulting in savings in time and fuel; and so should have a positive economic impact where weed and disease burden remains the same (Safa et al. 2010). Reduced tillage systems can also reduce trafficked area by 25%; Kroulik et al. (2011) reported that changing from conventional inversion tillage to a reduced tillage system reduced wheeled area from 86% to 64%, thereby reducing fuel use and the area of compacted soil. Moitzi et al. (2013) reported that replacement of a plough with a disc/tine cultivator reduced work time and fuel consumption for soil tillage, as well as energy consumption per unit volume of soil moved, to c. 50%. The highest savings (more than 85%) were achieved through direct drilling without tillage.

The Soil Management Initiative (SMI) booklet ‘A Guide to Managing Crop Establishment’ provides background information and a range of case studies. For example, at Loddington Farm in Leicestershire, where work was carried out into non-inversion tillage, fuel use for non-inversion tillage was half that of conventional (inversion) tillage; 49 litres/ha compared with 93 litres/ha. Trade information on reduced fuel usage suggests significant savings are possible (Michelin 2014). The use of reduced tillage can provide a c. 50 min/ha advantage over ploughing. Establishment costs can be reduced by around 30%, although if herbicide costs increase there may be no overall saving (A. Leake, Allerton Project, pers. comm.).
Zero-till drilling of winter wheat can reduce fuel consumption by 60% in some cases (G. Buckingham, Hill Farm, Fransden, Suffolk, pers. comm.). Furthermore, zero-till crop establishment provides greater opportunities for establishing crops due to the short time required for drilling compared with inversion tillage and secondary cultivations for seedbed preparation. Fuel costs, time and wear on machinery are significantly reduced under zero tillage and weed control can be improved in some circumstances, such as when ploughing has buried herbicide-resistant seeds in the previous season (Shah et al., 2012). In a direct-drilling system, weed seeds remain on the soil surface and a greater proportion germinates over a short time period, making weed control by cultural or chemical methods more effective than under a plough-based system, which may distribute weed seeds at a greater depth range resulting in an extended germination period (A.J. Reynolds, Thurlby Grange, Bourne, Lincolnshire & G. Buckingham, Hill Farm, Fransden, Suffolk, pers. comm.). However, where herbicide resistance is encountered, rotational ploughing and/or spring cropping is often required as a weed control measure (Shah et al., 2012; K. Ashby, Ashby Farms, Kenardington, Kent, pers. comm.). This increases the time required for seedbed preparation and increases costs. Yields in reduced tillage systems can be comparable with conventional tillage when carried out in suitable conditions (Davies and Finney, 2002).

Fuel use records indicate that adopting modern technologies and systems, such as the use of LGP tyres, GPS guidance and reduced cultivation can effect a reduction in field operation and fuel use from over 115 litres per ha to as low as 32 litres per hectare (Trevor Atkinson, Sentry Farms, pers. comm.). Indeed, the use of LGP rather than conventional higher ground pressure tyres alone can result in a marginal increase in farm profits (Vermeulen and Klooster, 1992). There is therefore some potential to improve field work efficiency and reduce cultivation and drilling costs on many farms, while also increasing crop establishment capacity.

The use of minimum tillage equipment reduces the required number of machinery passes for crop establishment, resulting in savings of around £40/ha compared with a plough-based system (Nix, 2013). Reduced tillage can be used in most years although exceptions occur.
when ploughing is necessary to remove compaction or to bury weed seeds or in ‘wet’ years when the soil become too ‘wet’ for min-till operations (section 2). Reduced time requirements for fieldwork can result in improved timeliness, which in turn may offer greater flexibility for weed control; a critical issue for winter cropping in some areas. Whilst the costs of direct drills and other reduced tillage equipment is significant, savings on machinery for secondary cultivation can balance out any such increases.

**Barriers to uptake**

The additional cost of GPS and tractor guidance may be something some farmers are not willing to consider and economies of scale apply (Figure 9.1). Controlled traffic farming can require significant changes to machinery and configuration of machines (see section 3) and for all the trouble and expense, any benefits can be lost if operatives for any reason run on what should be non-trafficked parts of the field (e.g. when harvesting under pressure in difficult weather conditions).

On smaller farms, it is difficult to justify more than one cultivation system on cost and on a more general note, the recent expansion of herbicide resistant black-grass has tended to encourage farmers to plough rather than min-till. The adoption of new techniques requires knowledge exchange and confidence in the new system, which can require patience over a number of seasons if increased costs have to be absorbed before benefits are realised.

### 8.3.2 Replacing degraded field drainage systems and maintaining existing systems including regular moling to maintain connectivity between the soil surface and drains

**Benefits**

The cost effectiveness of field drainage systems is discussed in section 3 (Cost-effective measures for preventing damage to soils) and the effects of degraded field drainage systems are investigated in section 7 (Impact of degraded drain function). Clearly, replacing degraded field drainage systems involves significant capital cost. However, in addition to the capital outlay, the drainage system requires infrastructure maintenance, including mole draining and ditching at significant cost and time. However, on some slowly permeable soils maintenance of a drainage system can mean the difference between operating a high output arable production system and an extensive grazing livestock system (MAFF, 1983). The repair and maintenance of drains may determine whether or not it is possible to grow an autumn sown crop in some extreme wet years.

Since the withdrawal of grants for field drainage, investment in land drainage and maintenance has significantly declined (Defra project FFG0923). For many years, field conditions were not sufficiently adverse to persuade farmers to invest in drainage or maintenance, but the autumn and winter of 2012-13 and winter of 2013-14 were exceptionally wet and many farmers were unable to establish autumn/winter sown crops or suffered significant yield losses due to waterlogging and flooding. Re-drilling with spring crops also increased costs. Grassland systems were also impacted due to lack of grazing and cutting opportunities in many areas resulting in the need to purchase additional forage and thereby increasing costs (Defra project SP1309).

Within a grassland system, Tyson et al. (1992) found that drainage had a relatively small effect on both herbage production and liveweight gain. The main benefit of drainage was in spring when herbage dry-matter was 11% greater on undrained plots. Earlier work on field drainage in grassland systems reported overall increases in output of around 25% (MAFF 1972, 1983). In extremely wet years, underdrainage systems are likely to provide benefits in terms of an increase in the number of days that land can be accessed by machinery or grazing animals.

**Barriers to uptake**

On some farms, it is difficult to completely re-instate degraded field drainage systems due to ditches being fenced or overgrown. In other cases, jetting of drains is not sufficient to remove sediment and broken and dislodged pipes are too numerous to deal with, such that re-
Installation of the system is needed resulting in a significant increase in costs, which may not be justified economically (Nix, 2013).

8.3.3 Use of lower ground pressure tyres, controlled traffic farming and auto-steer systems to reduce soil compaction and minimise soil disturbance

Benefits
In the past decade, new tractor tyre designs with constant low pressure irrespective of field or road use have provided the potential for increased traction; reduced tyre wear and rolling resistance (lower fuel consumption); and reduced soil compaction (Schlee et al., 2003; Chehaibi et al., 2012). Low ground pressure (LGP) tyres of the ‘VF’ (very high flexion) type can run on the road at field inflation rates and hence do not require adjustments to be made for travelling from the farm to the field by road or farm track. However, the initial cost of the tyres is significantly more than conventional tyres, although it is becoming increasingly common for some machine manufacturers to fit ‘VF’ tyres as standard (S Robertson, Chafer, pers. comm.).

Whilst ‘VF’ tyres cost more to buy, evidence from both Michelin (Schlee et al., 2003; Michelin 2014) and tyre dealers indicates that their lifetime is significantly longer than conventional tyres on the same land, although there may be exceptions for some soil types; for example flinty soils where tyre losses from cuts are common. The additional benefits of ‘VF’ tyres can include lower fuel use due to lower rolling resistance and a lower risk of compaction, thereby resulting in potential yield increases (e.g. Håkansson, 2005) and reduced sub-soiling requirements, saving fuel, time and cost. The use of LGP tyres can result in a fuel saving of £4/ha over 100 hectares (Philip Wright, Independent consultant, pers. com.). Yield increases in winter cereals of 5-10% are possible due to reduced compaction in the topsoil and subsoil (Chamen, 2011), which would more than pay for the cost of purchase. Avoiding the need for sub-soiling would save around £65/ha and in particularly wet seasons, the lack of compaction could improve timeliness of other field operations.

Costs and barriers to uptake
On many farms field operations are not changed or adapted because they are routine practices. Divergence from the routine involves risks to both the business (monetary risks) and the farmer’s reputation. Many of the techniques discussed above have costs associated with them (see sections 3.5.1, 3.7.1 and 3.8.1) and even though they are generally cost effective, the initial investment cost and the uncertainty of benefits represent significant barriers to uptake and implementation for many farmers. The new ‘VF’ tyres are significantly more expensive than conventional radials and most farmers are not prepared to bear the investment cost unless they understand and have confidence in the potential to save on operational costs.

8.3.4 Timely and appropriate use of sub-soilers and top-soilers to alleviate compaction when it is caused by farm operations in ‘wet’ conditions

Benefits
The benefits of effective sub-soiling are widely reported (Batey, 2009; Spoor et al., 2009), but a more systematic approach to the use and operation of sub-soilers (and top-soilers) may be needed to improve cost effectiveness. In wet autumns, harvesting and autumn crop establishment are often carried out in less than ideal conditions resulting in extensive soil compaction. Targeted sub-soiling can be effective in alleviating compaction, with working depth adjusted to the depth of compaction. However, on many farms sub-soiling is carried out on a routine basis (Hallett et al., 2012) and some farmers/contractors take the view that soil structural damage can be removed or alleviated through cultivation using large powerful tractors, even in sub-optimal field conditions (e.g. when soil moisture content is above the lower plastic limit). However, such operations are more likely to consolidate or exacerbate existing structural degradation (Batey, 2009).

An objective approach to soil management is required where the need for sub-soiling is correctly assessed along with soil conditions to ensure that the operation is carried out effectively. On both arable and grassland farms, it is important to carry out soil examination by

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digging a number of soil pits in fields showing signs of subsoil or topsoil compaction, to assess
the need for sub-soiling. Unnecessary sub-soiling can result in excessive loosening and
weakening of soils (Spoor et al., 2003). If soil conditions are not suitable, the operation can be
ineffective or lead to increased soil compaction.

On grassland farms, unless weather conditions are either extremely wet or extremely dry,
grass growth can be unaffected even where moderate soil compaction is present. However,
soil compaction and waterlogged soils pose problems for sward use, including grazing and
machinery access and susceptibility to poaching by animals (Frame et al., 1995). During wet
spells or heavy rainfall, reduced water infiltration rates can also result in surface runoff and
localised flooding. Soil compaction can also reduce rooting depth, leading to yield penalties
during dry conditions (Hopkins, 2000). Poor soil conditions can discourage productive species
and encourage unproductive grasses. Top-soiling on grassland farms can therefore be an
effective method for increasing the number of machinery working and grazing days and in
some cases increasing grass dry matter yields (ADAS, 1984). However, the method is
unsuitable on slowly permeable soils without an effective drainage system (ADAS, 1984).

Costs and barriers to uptake
Standard costs for sub-soiling are c. £60/ha (Nix, 2013), although this would vary according to
local conditions such as slope and field size/shape. Costs for top-soiling of grassland are not
available in Nix, but the NAAC (NAAC 2014) suggests a guide price of c. £65/ha. For surface
compaction in grassland soils, sward slitting costs would be around £25/ha.

Clearly, there are barriers to carrying out correct and timely soil examination and management,
largely due to lack of awareness and in some years due to lack of time and the appropriate
soil conditions. Without soil visual evaluation, the lack of obvious signs of compaction at the
soil surface can also be a barrier to uptake.

8.3.5 Applying bulky organic manures to improve soil resistance and resilience

Benefits
Many arable farms have operated without a livestock enterprise for many years, resulting in
long periods without organic manure use in some cases. When soils are cultivated, aggregates
are exposed to the air and anaerobic microbes are brought to the surface resulting in oxidation
of organic matter. There is some evidence that on farms that have been cultivated for many
years without addition of bulky organic manures, soils may be losing SOM/carbon (Bellamy
et al., 2005; Webb et al., 2001). With reduced levels of soil organic matter, crop available water
supply is reduced and soil structure and soil resilience to perturbation is likely to suffer (Gregory
et al., 2009). Protecting and enhancing SOM levels will have beneficial effects for water
infiltration, overall soil quality/fertility and erosion control (Chambers et al., 2003).

On many arable fields, combines with straw choppers ensure that straw is returned to the soil.
However, the availability of bulky organic manures can be a problem for many arable farms
without a livestock enterprise. Other available bulky organic manures include sewage sludge
(biosolids), green compost, paper crumble and digestate fibre, although supplies of these
organic materials are limited. Around 5 million tonnes of sewage sludge, 2.4 million tonnes of
compost and 1.4 million tonnes of digestate are recycled to agricultural land in the UK each
year. This compares with around 92 million tonnes of livestock manures applied to land (Water
UK, 2010; WRAP, 2013). Addition of bulky organic manures can help increase porosity,
available water capacity and extractable nutrients and increase water infiltration rates. For
example, Chambers et al. (2003) found that application of biosolids over four to ten years,
amounting to the addition of between 6 and 24 tonnes of organic matter per ha, resulted in a
trend towards higher water infiltration rates at four out of seven sites, increases in topsoil
available water capacity (on the lightest textured soil), increased soil porosity and strength,
and increased availability of some major and micro plant nutrients. The resilience of the soil to
compaction is therefore increased, drainage improved and the risk of waterlogging reduced.

When soil organic matter declines, water holding capacity declines and structure tends to
become coarser with larger aggregates requiring more work to produce a suitable seedbed,
reduced resilience and an increased susceptibility to compaction (Gregory et al., 2007, 2009). As these effects continue, the infiltration rate of rainfall can decline, making crops more susceptible to dry spells, and increasing the severity of waterlogging and runoff and generally reducing the number of available work days suitable for field work.

Many farm businesses can therefore benefit from the addition of bulky organic manures even when there is a charge for spreading. The majority of water companies in the east of the country now charge for sewage sludge. However, the cost is often below the value of the major nutrients alone, resulting in a net benefit to the farm. For example, at current fertiliser prices (N = 74 p/kg; P = 59 p/kg) the nitrogen and phosphate value of spring applied sludge cake is approximately £10/t.

Barriers to uptake
The main barrier to applying bulky organic manures is availability of supply. Approximately 100 million tonnes of organic material are applied to agricultural land each year in the UK (Water UK, 2010; WRAP, 2013) and there are around 11.4 million hectares of agricultural land.

8.3.6 Establishing crops earlier in fields prone to prolonged waterlogging

Benefits
Ensuring that cereal crops in fields prone to waterlogging are drilled early when conditions are more conducive to maintaining better soil structure and good crop establishment can encourage root systems to develop and dry out the soil and result in improved yields and better conditions for establishing the following crop. The benefits can be compounded with better drained soils resulting in more opportunities to access the land and better yields in exceptionally dry or wet years. Section 3 reported that wheat established in late autumn generally has a gross margin 15% lower than a crop drilled in the same conditions in late September/early October (Dennett, 1999; Spink et al., 2000).

Costs and barriers to uptake
A move to earlier crop establishment has been evident in recent years (e.g. ADAS, 2008). However, when autumn sown crops are established early there is no opportunity to practice stale seedbed techniques, resulting in increased survival of weed species. Early establishment also provides a ‘green bridge’ for pests and diseases to move straight into the newly emerging crop. Some fields may need to be sub-soiled prior to establishing the next crop, which can take some time if weather conditions are not favourable. It is a perennial task for farmers to balance soil management, seedbed preparation and ensuring optimum timing to achieve a well-established vigorous new crop before winter. Even if there is the intention to bring forward drilling dates, this may require additional staff and machinery that is not available.

In particular, the increased risk of black-grass infestation may increasingly delay establishment due to the need to create stale seedbeds through early autumn cultivation sequences or the use of broad spectrum herbicides (Orson and Harris, 1998; Defra project SP1315).

The penalties associated with winter cereal establishment in late summer can be increased weed growth and pest and disease carry over, resulting in increased crop protection product costs and a potential reduction in yield and quality where weed burden and pest and/or disease pressure is high. Examples may be additional crop protection costs of £50 to £100/ha and yield penalties from very little to 4 t/ha (i.e. c. £400/ha for winter wheat at £100/t).
8.3.7 Adopting spring cropping rather than winter cropping in higher risk fields

**Benefits**

Spring crops are most suited to light soils with autumn sown crops typically drilled on medium/heavy soils, which are more prone to waterlogging. When an autumn crop is drilled in poor (wet) conditions and waterlogging persists in subsequent weeks, yield can be affected, margins can suffer significantly and the following crop may also be affected due to soil structural degradation from cultivating/drilling in poor conditions (e.g. Cavazza & Rossi Pisa, 1988; Dickin & Wright, 2008). Moving to spring cropping may reduce income in some years due to the difference in gross margin between winter and spring cereals; spring crops typically yield 20-30% less than their autumn drilled counterparts (Defra, 2013). However, over the course of a rotation (or rotations), the overall difference in gross margin could be negligible due to reduced weed control costs and year-to-year differences in the weed/disease burden associated with earlier and later drilled crops. Including spring cereals within the rotation may be a more sustainable approach, particularly in high risk areas for black-grass and other herbicide-resistant weeds.

With the increasing incidence of multiple herbicide resistance grass weeds, an increasing number of farmers are being forced to look to spring crops to avoid catastrophic losses of winter cereals year on year. The loss of output in the winter cereal area due to a switch to spring cropping may be less than the increasing costs of attempting to control resistant grass weeds and the associated potential yield reduction in the winter wheat crop (Orson and Harris, 1998; Table 9.1).

**Barriers to uptake**

The main barrier to uptake is a lack of realisation or awareness that spring cropping may provide better returns in the long run for some farmers. Potential gross margins are higher for winter cereals than spring cereals, mainly due to higher output in autumn sown cereals (Nix, 2013). However, where total variable costs increase in winter cereals due to weed and disease pressure, gross margins can be eroded to the extent that spring cropping may be more profitable. This is particularly the case in a wet autumn when cultivation and drilling is likely to result in a poor seedbed and reduced plant numbers over winter. The other barrier to uptake is a lack of willingness or confidence to change practices.

8.3.8 Establishing grass on a rotational basis in order to provide an early entry for autumn cereals

**Benefits**

The use of rotational grass leys can improve soil structure, increase soil organic matter, reduce the risk of waterlogging and provide crop residues that contain useful levels of nutrients, particularly mineralised N (Johnston et al., 1994; Hatch et al., 2002). The following arable crop (e.g. potatoes and spring cereals) can benefit when established after a grass break in terms of cultivation, nutrients and reduced pressure from weeds (Easson, 2002). In these situations, the benefits can make up for reduced levels of production during the grass break. At current fertiliser prices (74 p/kg N), on medium to heavy soils in a moderate rainfall area, the value of the N released following a 1-2 year high output ley can amount to £60-£120/ha and following a 3-5 year grazed ley, £150-£200/ha (Hatch et al., 2002; Defra, 2010). Furthermore, where the control of herbicide resistant black-grass has become a significant problem, the income foregone with a grass break can be less than the increasing annual costs of dealing with difficult weeds.

Where there is no opportunity to utilise the grass, the overall impact on the farm business will relate to the length of the grass ley and the loss of crop output. The annual cost of grass establishment for a two year grass ley will be less than the annual cost of combinable crop establishment, but the output from the grass ley will vary according to circumstances (Nix, 2013). Many farmers would be able to re-coup income by offering grazing and thereby reducing losses to the difference in margin between a poor arable crop (under significant weed pressure) and let grass (£86-173/ha; Nix, 2013). The margin for one year's grass would be a loss of £98-
155/ha (i.e. the establishment cost; Nix, 2013) if there are no livestock to graze the grass; up to a gross margin of c. £200/ha for grass keep; and up to c. £400/ha for a lowland spring lamb enterprise. This compares with a possible loss from a grass weed infested arable crop with increasing spend on weed control and a significant reduction in yield (Table 8.1).

**Barriers to uptake**

Grass leys are a common part of mixed and livestock farms. Rotational grass or grass leys cover around 1.2 million hectares, approximately 5% of the UK land area (Defra, 2013). The main barrier to uptake for arable farmers in the east of the country is the lower numbers of livestock to utilise grass leys (compared with Wales and the west of England) and the fact that many cereals and general cropping farmers are not experienced in grassland agronomy. Nevertheless, an increasing number of arable farmers are establishing grass leys to grow hay or haylage to sell into the horse industry (Nix, 2013).

**Table 8.1: Estimated gross margins for winter wheat and ley grassland scenarios**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Price (£/t)</th>
<th>Yield (t/ha)</th>
<th>Output (£)</th>
<th>Variable costs (£/ha)</th>
<th>Gross margin (£/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter wheat (feed) - average yield</td>
<td>£140</td>
<td>8.4</td>
<td>£1,169</td>
<td>£496</td>
<td>£673</td>
</tr>
<tr>
<td>Spring oats - average yield</td>
<td>£130</td>
<td>5.5</td>
<td>£715</td>
<td>£263</td>
<td>£452</td>
</tr>
<tr>
<td>Winter wheat with increased weed control costs and half the average yield</td>
<td>£140</td>
<td>4.2</td>
<td>£588</td>
<td>£646</td>
<td>-£58</td>
</tr>
<tr>
<td>Grass keep (land let for grazing)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>£86-£173</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Output (£/ewe)</th>
<th>Variable costs (£/ewe)</th>
<th>Gross margin (£/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finishing store lambs</td>
<td>£24</td>
<td>£19</td>
<td>£140</td>
</tr>
<tr>
<td>Lowland spring lambs</td>
<td>£93</td>
<td>£52</td>
<td>£417</td>
</tr>
</tbody>
</table>

**8.4 Conclusions**

Changes to the duration of waterlogging under future UKCP climate change scenarios are predicted to be relatively minor, and generally less than 5%. Indeed, both decreases and increases in the duration of waterlogging may be observed under average conditions with a reduced duration of waterlogging in most areas, mainly due to a later return to field capacity following generally hotter and drier summers. However, it is possible that the severity of waterlogging within the period when it occurs may be greater than currently experienced due to larger daily rainfall totals. Furthermore, there may also be an increased incidence of extreme events, including high intensity or prolonged rainfall in some years.

Farming adaptations that improve soil drainage, maintain or enhance organic matter levels and produce better structured soils will help to mitigate against such events and will generally benefit the farm business overall. These adaptations include:

- Replacing and maintaining field drainage systems on slowly permeable soils
- Applying bulky organic manures to improve soil resistance and resilience
- Visual assessment of soils combined with timely use of sub-soilers and top-soilers, where appropriate
- The use of low ground pressure tyres and satellite guidance systems in suitable field conditions
The use of more efficient machinery to establish crops more rapidly, particularly on larger farms

The first three methods (where they are applicable) should be cost effective on all farms after a number of years (i.e. a decade or more). The other methods involve economies of scale and are mainly applicable to farms with at least around 200 ha of agricultural land with costs reducing (and therefore relative benefits increasing) with increasing farm size.
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WQ0128 - Extending the evidence base on the ecological impact of fine sediment and developing a framework for targeting mitigation of agricultural sediment losses.

WQ0140 - Competitive Maize Cultivation with Reduced Environmental Impact.