IMPACTS OF CLIMATE CHANGE: IMPLICATIONS FOR SOIL MANAGEMENT

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SUMMARY

Soils are highly variable. Their properties result from long-term interactions between geology, topography, climate, vegetation and management. Weather conditions already place constraints on the time available for carrying out field operations and access to land for grazing, and may vary significantly from year to year.

Growers are already noticing the effects of climate change, with some fields particularly susceptible to soil loss by erosion during high intensity storms, for example. Soil management can also contribute to mitigation through storage (sequestration) of reserves of carbon in organic matter in soils. The main effects of climate change on soils will be mediated through the impacts on soil water balance. However, the impacts of climate change will be minor compared to the variability in soil water balance currently experienced due to local soil differences and variability in weather patterns.

On-farm increases in soil moisture coupled with increased high intensity rainfall will mean localised flooding and waterlogging are likely to increase, particularly during winter and spring, when flood duration may prove particularly damaging to crops. Increased run-off and soil erosion due to increased high intensity rainfall is exacerbated on both arable and grassland by soil damage due to traffic when wet, particularly along paths and wheelings, in gateways and through formation of plough pans. In the predicted wetter winters, soil damage during machinery work periods and extended grazing is likely to increase. Dealing with flooding from on-farm sources and water erosion problems can be tackled simultaneously by giving attention to soil structure, identifying problems and remedying compaction as appropriate. Drainage and cultivation of peat soils is a major source of emissions of carbon dioxide equivalents from agriculture. Blocking old drainage systems in peat areas where peat structure and vegetation can be re-established will potentially have very significant benefits for carbon sequestration.

Careful management of rates and timing of fertiliser, crop residue and manure application together with minimisation of compaction will reduce nitrous oxide emissions.

A land manager who understands how their soils work under different conditions now will be better be able to maintain excellent soil condition into the future. Key recommendations for land managers are summarised in the Farming Futures Fact Sheet 20, Focus on Soil Management.

INTRODUCTION

Predicted climate change

The UK Climate Change Impacts Programme (www.ukcip.org.uk) has produced climate change predictions for the UK. In general for the UK, it is predicted that temperatures will be 2-3.5 ˚C warmer on average by 2080, and climate change will also result in:

- warmer wetter winters;
- warmer drier summers;
- more heavy rainfall events;
- more very wet periods in winter and spring;
- more heatwaves;
- less snow and frost.

It is also expected that regional differences in climate will be increased, with larger increases in amounts of rainfall in the north and greater rises in temperature in the south. Ongoing work will provide further detail for the predictions which will be published as UK Climate Projections (UKCP09). More information on climate change and how it will affect agriculture is provided by Farming Futures Fact Sheet 1.

Soil management

Soil is the basis of agricultural systems; good soil management enables soils to simultaneously provide a number of key functions to support crop and animal production and to minimise any negative environmental impacts arising from agriculture.

Key soil functions within sustainable agricultural systems

- Self maintenance of above and below-ground ecosystems

Functions that support economically viable crop yields of good quality

- Supports and anchors plant growth
- Suppresses crop disease
- Provides and buffers physico-chemical environment for plant growth
- Controls water availability for plant growth
- Controls nutrient availability for plant growth

Functions that minimise negative environmental impacts of agriculture

- Provides resilience to environmental change and management
- Buffers water flows to reduce off-site impacts
- Buffers nutrient losses to reduce off-site impacts
- Buffers impacts of pollution and source/sink of greenhouse gases

Each soil is unique and its properties are the outcome of the interaction of the local geology, topography, climate, vegetation and management over thousands of years. Some key soil properties that underpin soil function, such as soil texture, are barely altered by management. However, a number of key soil properties including levels of soil organic matter, soil structure, pH and nutrient supply are directly influenced by soil management.

Soil functions result from the complex interaction of climate and other environmental factors with biological, physical and chemical processes within the soil. Given the predicted changes in climate, it is critical to determine how soil management should adapt to support crop and animal production and to sustain and improve production for the future by maintaining and improving the condition of the soil itself. Soil management can also contribute to mitigation through storage (sequestration) of reserves of carbon as soil organic matter. Changes in soil properties only occur over the medium to long-term, so planning is needed now to reduce risks and costs in the future.

Impacts of current weather patterns on soil management

Weather conditions already place constraints on the time available for carrying out field operations and access to land for grazing. At the local scale, interactions between soil factors (texture, structure, infiltration and drainage capacity), weather (rainfall and evapotranspiration) and topography are critical in determining soil moisture condition. The same factors also interact to influence the risks of water erosion and run-off (Environment Agency's **think soils** manual).

In UK conditions the main limitation to soil workability in the past has been excessive soil moisture which reduces the bearing strength of the ground. On much land, the typical period during which soils are at field capacity (maximum soil water storage) is used to indicate the broad limits to ground conditions suitable for tillage and traffic by agricultural machinery more detail of the calculation methods used in the reports of the Soil Survey of England and Wales are given by Smith (1977). However, under drier climatic conditions workability may also be limited by dry conditions creating prohibitively hard soil surfaces at the end of the summer period, especially in clay soils (Rounsevell, 1993). Predictions of machinery work days or grazing periods made in advance from average climate data are useful to guide farm planning (e.g. Cooper *et al*. 1997).

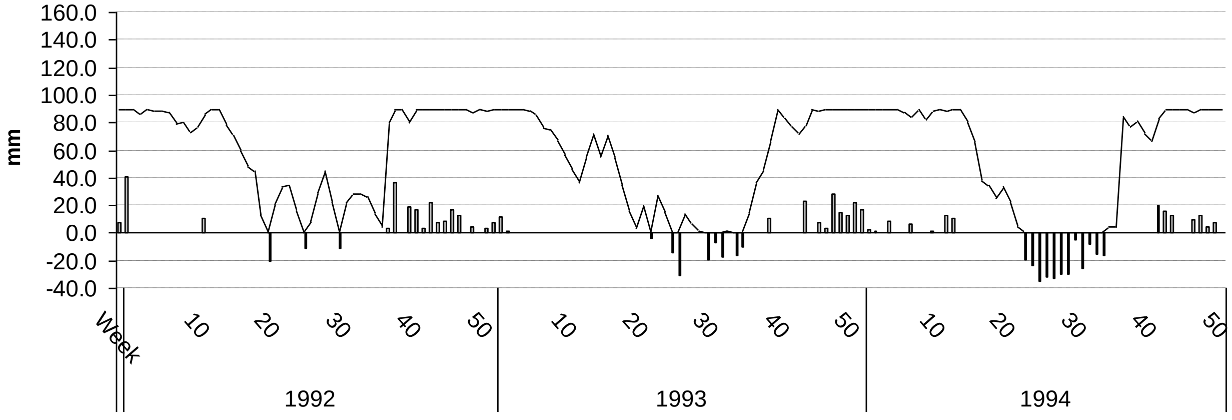
Variability between soil types is much more significant that variation between years (illustrated in Figures 1 and 2). However, for on-site decision making, "there is no better way of estimating the workable state of the soil for any given moment than from field observations" (Rounsevell, 1993).

'Trafficability' is used to describe whether a soil can support and withstand vehicle traffic; workability describes the response of a soil to a particular operation such as seedbed preparation or subsoiling (Rounsevell, 1993). Access to land for cultivation, grazing or fertiliser/pesticide application and the extent of any damage caused is largely determined by soil wetness. Soil structural damage leads to reduction in both soil water storage and infiltration capacity (Hamza and Anderson, 2005). On slowly draining fine textured soils, machinery access and livestock outdoor periods are already limited by soil wetness, particularly during key periods in spring and autumn. Wetter soils during these periods reduce flexibility in operations requiring land access, and can result in soil compaction as a result of trafficking at high soil moisture contents. Three common lowland agricultural practices have been linked to increased damage to soil structure across all soil types (Holman *et al*. 2003). Severe and high soil structural damage was observed in late-harvested crops – maize, sugar beet, main crop potatoes – where heavy machinery had been used on fields likely to be at, or close to, field capacity. Moderate to high structural damage was common on fields where cultivation for autumn sowing of cereals, oilseed rape and field beans had taken place during the wetting up period in autumn. High structural damage was sometimes associated with the overwintering of livestock on grass or fodder crops; however it was just as likely that very limited structural damage would be observed in grassland systems. Risk of structural damage is strongly related to stocking rate, as well as soil moisture content.

For any field operation, the optimum soil moisture condition depends on the characteristics of that operation, e.g. for cultivation, soils must be sufficiently dry to crumble and not too wet to smear (Spoor, 1975). These key limits (often described as plastic limits) can be more easily demonstrated than described. Long term impacts of soil management can also be detected by observation of soils in the field e.g. showing compacted layers (pans) with platy structures just below cultivation depth where cultivation has regularly taken place when soil moisture content was above the plastic limit (see Environment Agency's **think soils** manual).

Figure 1 - Soil water balance for East Anglia estimated on a weekly basis for 1992-1994. Soil moisture content (mm to 90 cm depth) shown as a continuous line with drainage (+ve) and deficits (-ve) shown as bars. Data estimated for two soil types with different soil moisture contents at field capacity a) sandy loam (90 mm) and b) clay loam (150 mm).

a) Sandy loam



b) Clay loam

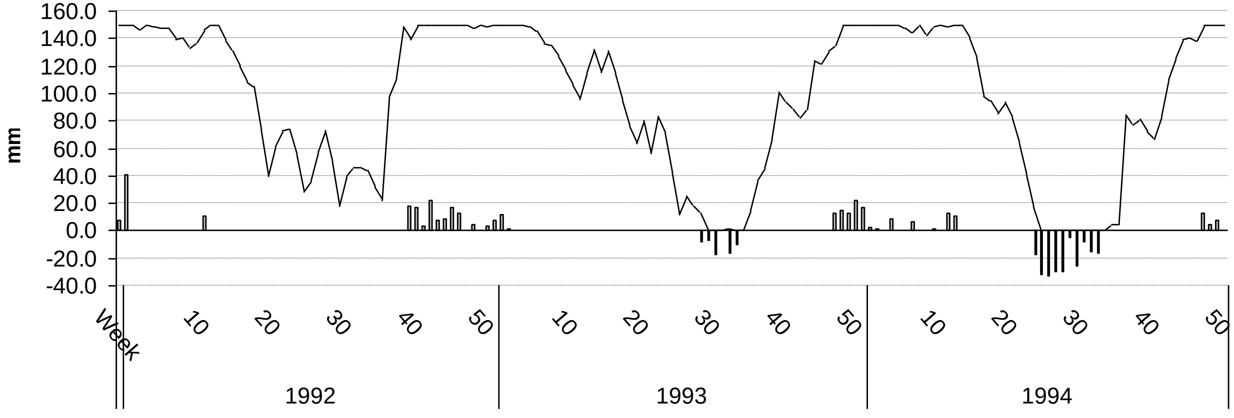
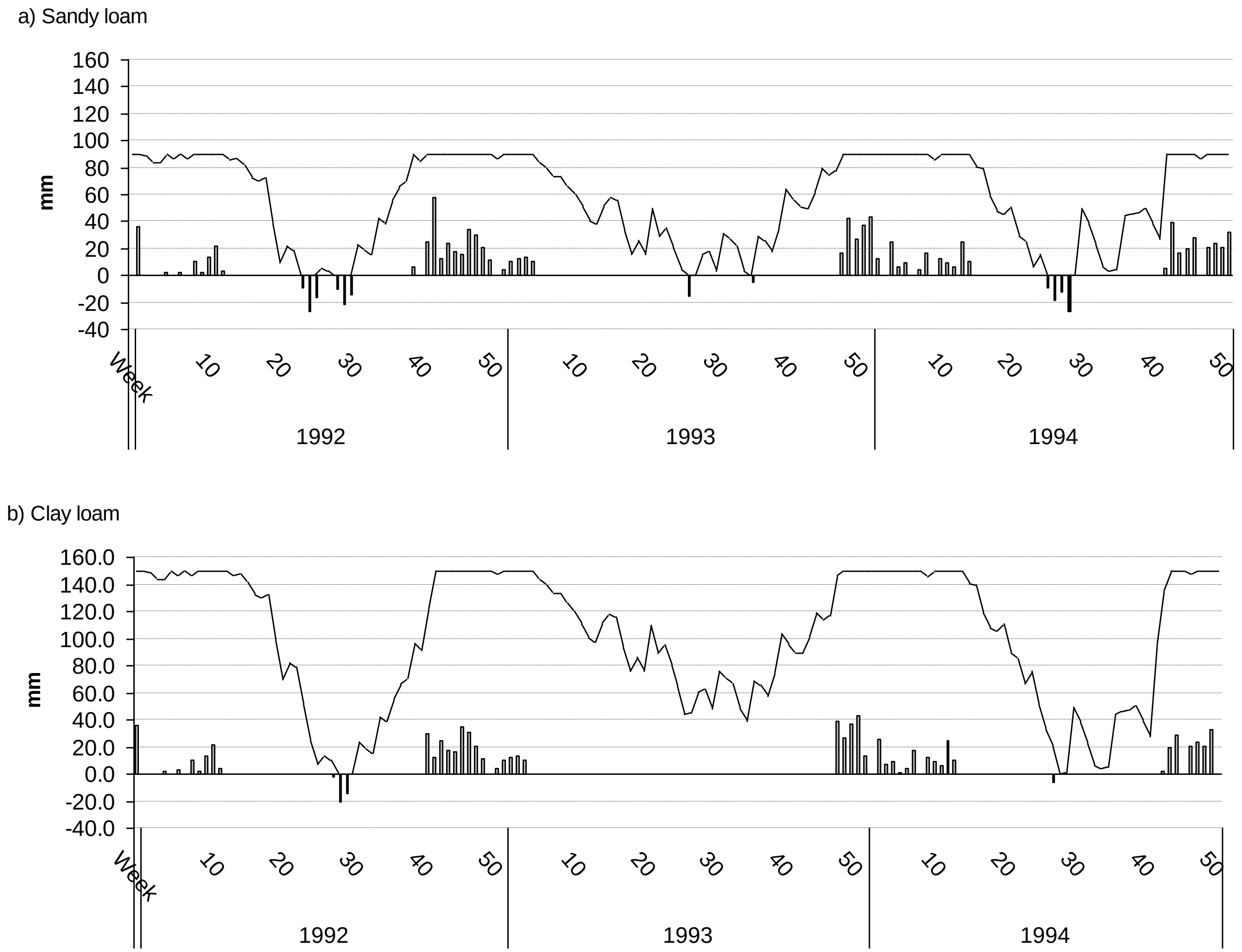


Figure 2 - Soil water balance for North West England estimated on a weekly basis for 1992-1994. Soil moisture content (mm to 90 cm depth) shown as a continuous line with drainage (+ve) and deficits (-ve) shown as bars. Data estimated for two soil types with different soil moisture contents at field capacity   a) sandy loam (90 mm) and b) clay loam (150 mm).



Improving knowledge of local interactions between weather patterns and soil condition at a farm scale is critical for effective adaptation to climate change. A land manager who understands how their soils work under different conditions will be better able to maintain excellent soil condition.

As well as a range of books and courses, you can also access information on improving soil management via the web

- Make sure you have a copy of Protecting our Soil Water and Air the new combined Code of Good Agricultural Practice produced by Defra
- Visit the AHRF soil information gateway to access cases studies on best practice soil management and signposting to further soil information
- Visit SOWAP (Soil and Water protection) for advice on sustainable soil management
- Contact the UK Soil Management initiative (SMI) for information on improving soil quality.

KEY IMPACTS OF CLIMATE CHANGE FOR SOIL MANAGEMENT

Impacts on growing season

Predictions suggest that changes in climate will lead to a significant increase in the length of the growing season for all crops. Under a low emissions scenario it has been estimated that there would be an increase of 30-50 days by 2080 and under a high emissions scenario this is further extended to 60-100 days. Increases are greatest in the south and east and lowest in northern Scotland.

Impacts on soil water balance

The main effects of climate change on soils will be mediated by the impacts on moisture regimes. Soil water content through the year is critically dependent on the balance between precipitation and potential evapotranspiration. Hence, although changes in the soil moisture regime will reflect changes in seasonal patterns of precipitation, the picture is complicated by potential increases in evaporation (higher temperature and reduced summer humidity) and in transpiration due to an increase in the length of the growing season. In general, the impacts of climate change on soil water balance in winter are likely to be small as moist soils are already above maximum moisture storage (field capacity). In spring, higher rainfall will be offset by higher temperatures and crop water use, except for spring sown crops. Average summer moisture deficits are highly likely to increase. The return to field capacity date in autumn may be affected by greater summer deficits, but this will be partially offset in some regions by higher rainfall. In all regions storm events causing temporary soil waterlogging, are increasingly likely.

Modelling soil water balance under a changed climate for Scotland Cooper *et al*. (1997) found that the impacts on the timing of soil return to field capacity in autumn and the end of field capacity period in spring were small and not consistently in the same direction because of the interaction of the range of climate and soil factors. The number of workdays per month was reduced particularly during the winter period with a significant loss of winter ploughing days under frost conditions (Cooper *et al*., 1997). However, the modelling also showed that variation between years in number of work days due to weather fluctuations was significantly higher than the change due to a modelled change in average climate. The most significant differences were seen between the two soil types and the four sites modelled with only relatively small differences caused by climate change, within the range of current variability and showing the same broad seasonal pattern (Cooper *et al*., 1997). This suggests that the impacts of climate change on soil water balance will be minor compared to the variability currently experienced due to local soil differences and variability in weather.

Soil temperatures

There is a close relationship between air and soil temperatures. Hence an increase in air temperatures will also be matched by a general increase in soil temperatures. Warmer temperatures will tend to increase the rates of soil processes where they are not limited by other factors such as substrate availability.

ADAPTING SOIL MANAGEMENT TO THE EFFECTS OF CLIMATE CHANGE

Adapting to more extreme events

Run-off and erosion

In all regions, climate change predictions indicate an increased likelihood of severe short duration rainfall events, which will account for an increasing proportion of total erosion, and a disproportionate proportion of off-site damage. Growers are already noticing the effects of climate change, with some fields particularly susceptible to soil loss by erosion during high intensity storms. Situations with increased erosion risk are where soil surfaces are left bare (such as under winter cereals) on easily eroded soils (sandy soils, silts and peats) and on sloping land.

Historically, UK soil erosion has been seen as a minor problem compared with the focus it has received in North America and in the tropics and subtropics. Soil erosion is a natural process, and at low levels is sustainable. However, accelerated erosion can have serious on and off-site effects and may occur in a wide range of UK situations (Evans 1971; Spiers and Frost, 1987). Intensive land use practices, removal of hedgerows and particularly a change from grassland to arable farming are widely believed to have led to a significant increase in soil erosion in England and Wales since the 1950s. 36% of the arable area of England and Wales has been estimated to be at moderate to very high risk of erosion (Evans, 1990). Accelerated erosion presents a sustainability issue to farmers through loss of topsoil and nutrients, through blocking of drains and wind scour of seedlings. However, evidence suggests that in the majority of cases, soil erosion is unlikely to result in significant reduction in fertility (Boardman and Favis-Mortlock, 1998). Exceptions are shallow soils (<30 cm) where further decreases in depth are predicted to result in increased droughtiness over the next 50 years (Webb *et al*, 2001).Off-site effects of high rates of soil erosion are likely to become of greater relevance to farmers as a result of cross compliance requirements (Good agricultural and environmental condition, GAEC), and through new water quality directives. Failure to address erosion problems on at-risk land is likely to become increasingly visible to inspectors if major erosion events become more severe and frequent as a result of climate change – for example sediment deposition on public highways.

There are large number of field-scale mitigation options that can be taken against increased erosion risk (e.g. see review of Hamza and Anderson, 2005; SOWAP). These include retaining crop residues, use of cover crops, contour ploughing and vegetated buffer strips which protect the soil surface and promote infiltration of surface run-off. Improvements in grazing management can ensure that compaction is minimised by considering location of feeders carefully and fencing streams. Maintenance of subsurface drains and topsoil structure will also reduce surface run-off and reduce erosion. Tillage erosion (i.e. soil loss due directly to tillage operations) can be substantially reduced by modifying the type of tillage operation (e.g. mouldboard ploughing replaced by cultivation using discs) and ploughing along the contour lines (Van Oost *et al*. 2006). Where necessary, farm or catchment-scale control structures such as sediment traps and vegetated ditches can prevent sediment losses to water courses and reapplication of the sediment to land will mitigate loss of soil material and nutrients. It is unlikely that a single measure will be effective; appropriate integration at farm and catchment scale is needed to minimise run-off and erosion (Verstraeten *et al*. 2002).

A major cause of increased run-off and soil erosion on both arable and grassland is soil damage due to traffic when wet, particularly along paths and wheelings, in gateways and through formation of plough pans. Attention should be paid to soil structure and identifying problems and remedying compaction as appropriate. However, aeration and subsoiling operations are also limited by land access periods, meaning major damage caused during autumn cultivations such as pan formation may be impossible to remedy until the following spring, exposing soils to enhanced run-off and erosion risk over the winter period. Structural damage should therefore be avoided if at all possible.

Storm events are more difficult to control without major changes in soil management. Measures to maximise infiltration and prevent run-off may prove partially effective on arable land, nonetheless heavy rainfall is likely to exceed rates of infiltration leading to surface run-off and increased erosion potential. Best solutions to this problem involve maximising soil surface cover at vulnerable times (following harvest and drilling) particularly through direct drilling (minimum or zero tillage) and crop residue retention or a change in land use from arable to grassland in extreme circumstances. More detail of these options are given by Farming Futures Fact Sheet 18 and by The Catchment Sensitive Farming Initiative funded by Defra and the Environment Agency.

Flooding

Increases in extreme weather events present an increased likelihood of damaging flood events on UK farmland. On farm increases in soil moisture coupled with increased high intensity rainfall will mean localised flooding and waterlogging are likely to increase, particularly during winter and spring, when flood duration may prove particularly damaging to crops. Similar changes at a catchment scale are also likely to result in more extensive flooding by rivers, severely affecting farmland in low-lying areas.

Poor soil condition can contribute to increased flooding on farm, as well as downstream. Damage to soil structure which decreases infiltration of precipitation will increase surface ponding, run-off and peak stream discharges. Winter flooding as a result of unusually wet conditions in the winter of the year 2000 led to a study of several catchments in England and Wales to assess the impacts of soil structural degradation on the resultant floods (Holman et al., 2003). Estimates of the impact of damage associated with cultivation of wet soils (primarily winter cereals) suggested that degradation of topsoil structure resulted in increases in run-off by as much as 10-20 mm per unit area compared with soils in good structural condition. If wetter winters become a reality, the likelihood of cultivation damage during machinery work periods, and of extreme rainfall events is likely to increase.

Dealing with flooding from on-farm sources is closely associated with water erosion problems discussed above; both result from excessive surface run-off. However on susceptible soils, there may still be areas within fields which are subject to frequent flooding of sufficient duration to be damaging to crops and grass. In these areas it may be most judicial to take this land out of production and offset losses with environmental stewardship payments (for conservation management). A renewed emphasis on flood control by Defra and the Environment Agency is likely to include agricultural management as a tool in flood prevention, in recognition of the increasingly important role agricultural land management in mitigating downstream urban flooding. Farmers have been involved in flood mitigation schemes e.g. by *inter alia* introducing temporary storage ponds, removing flood embankments. More detail of these options are given by Farming Futures Fact Sheet 18. Increases in risks of extensive flooding from rivers and streams will require consideration in catchment management and should involve the Environment Agency and local authorities.

Key recommendations

- Reduce the length of time bare soil is exposed, especially sandy and loamy soils by ensuring groundcover with productive grass or crops
- Use appropriate cover crops such as mustard and rye where possible, unless this would compromise establishment of subsequent crops. Leave “weedy” stubbles overwinter. Consider using nurse crops such as barley to protect against wind erosion.

- Plan field and cropping layout to reduce risks of erosion and retain sediment. For example, avoid gateways at the bottom of fields, plough and align tramlines across slopes where possible.
- Leave buffer strips and hedges as protective barriers if appropriate. Woodland buffer strips may also help to protect watercourses.
- Consider using GPS to help reduce the need for designated tramlines.
- Promote infiltration of water and reduce slumping and capping in susceptible soils by increasing soil organic matter. Ensure the land is not overcultivated and return organic materials regularly.
- Avoid cultivating wet soil and make regular additions of organic matter to soil in crop residues and manures to increase structural stability.
- On soils with very poor structural stability consider moving towards ley-arable rotations.
- Improve grazing management to minimise soil compaction and poaching. Locate supplementary feeders carefully and move regularly. Consider fencing along streams to prevent grazing animals eroding soil directly into the water.
- Develop a run-off management plan considering soil type, topography and hydrology e.g. by integrating soil storage ponds in some areas and improving drainage capacity in others.
- Capture rainfall and run-off to reduce your water costs.

Adapting to warmer drier summers

Drought

The greatest impact of summer soil moisture deficits as a result of warmer, hotter summers are likely to be felt in the south and east of England. However, there is an increased likelihood of drought in all areas, particularly on sandy soils and under grassland. Light textured soils hold less available moisture which may be insufficient to meet optimum crop requirements under drier climates. Drought is ultimately caused by insufficient water, an issue which is beyond the remit of this study. However there are well established soil management practices which can maximise water storage in the soil and minimise requirements for increasingly limited abstracted water for irrigation. However, finer textured soils can also be susceptible to drought, particularly where the effective rooting depth of crops is limited by cultivation pans, and where surface compaction or capping cause increased run-off and reduce rainfall infiltration into the soil (a phenomenon which is also common in sandy soils). Plant access to soil water can be optimised in every soil by ensuring that root growth is not restricted by cultivation pans or other subsoil constraints. Maintaining soil surface cover by retaining crop residues will reduce capping by raindrop and irrigation water. Increasing organic matter levels, particularly in sandy soils, through addition of crop and animal residues and through rotation will increase water holding capacity and reduce soil susceptibility to capping. Cracking of some clay soils will lead to increased soil moisture deficits and may also increase the risks of groundwater contamination in those areas during rewetting in autumn. These issues are also covered by Farming Futures Fact Sheet 18.

Wind erosion

Wind erosion is generally recognised as a localised problem, particularly in areas of susceptible soils (sands, silts and peats) and in susceptible land use sectors (e.g. sugar beet or outdoor pigs). Unlike water erosion, in the UK wind erosion is a problem primarily associated with dry soils, particularly during harvest. Climate change predictions suggest summer moisture deficits are likely to increase, particularly in drier regions such as East Anglia which are already at risk. A recent study of rates of peat erosion by wind in the North Pennines (Foulds and Warburton 2007) suggested that more frequent peat dessication due to climate change could result in greater incidence of wind erosion.

Key recommendations

- Improve plant access to soil water by ensuring that root growth is not restricted by cultivation pans or other subsoil constraints
- Check compaction levels before sowing and remediate using a sub-soiler set just below the compacted layer
- Improved access to water for crops on sandy and clay soils by using regular additions of organic matter (leys, crop residues manures, compost …) to optimise the retention of plant available water in the soil to rooting depth
- Identify soils at particular risk of drought and plan cropping accordingly – sandy soils with no groundwater available in summer are particularly susceptible.
- Reduce wind erosion by planting shelter belts and consider use of min-tillage techniques to maintain organic matter levels at the surface.
- Where wind erosion is a risk, aim for as coarse a seedbed as is practical for the crop to help stabilise the soil. Consider nurse crops such as barley with sugar beet to help protect vulnerable soils from wind erosion.

Adapting to warmer and wetter winters

It is difficult to predict the effects of climate change on soil wetness problems in Autumn. The latest climate change predictions suggest increases in summer deficits and reduced autumn rainfall in southern regions, which may lead to greater flexibility and opportunities on soils where autumn wetness has been a problem. In northern areas slightly increased rainfall is likely to offset summer moisture deficits. However, such changes are likely to be relatively minor, particularly when compared with differences between soil types which may occur in neighbouring fields.

Climate change predictions suggest an increase in winter rainfall together with an increased likelihood of unusually wet winters and springs. Increased winter rainfall will lead to greater soil waterlogging and or higher run-off, particularly on sloping land and slowly permeable soils, and where infiltration is reduced by compaction and pan formation through poor management. Spring wetness is also likely to be an increased problem, particularly in northern England and Wales. While autumn sown crops and grass will begin growing earlier in the year, this is unlikely to be sufficient to offset winter and spring rainfall increases in the north, and this increased transpiration will not offset rainfall when land is fallow over winter in preparation for spring sowing. The available work period for spring sown crops is likely to be significantly reduced on average, with an increase in very wet years when no period of safe access occurs (Cooper *et al*. 1997).

Greater rainfall in winter is likely to result in greater vertical flow through soils, resulting in the leaching of soluble nutrients, notably nitrate. While infiltration should be maximised to prevent run-off and erosion, this management strategy increases the likelihood of nutrient leaching. This is particularly problematic on coarse textured soils and, as is increasingly recognised, on tile drained land where subsurface drainage facilitates a rapid pathway for nutrients in soils with a low natural leaching potential. Limiting excess nitrogen applications, whether as fertiliser or manure, is a fundamental management strategy in preventing excessive leaching losses.

Soil wetness can only be actively managed through land drainage. In most instances susceptible land will already have been drained. However, maintenance of tile, mole and surface drains is important to maintain efficient systems. In some instances land access or poaching by livestock may cause soil structural damage, which can lead to enhanced waterlogging, rooting restriction, flooding and erosion problems and build up of pests. This damage will exacerbate problems caused by other climate change impacts and should be ameliorated by sub-soiling. In extreme circumstances a change in land use may be judged necessary, such as from spring sown cereals or potatoes to autumn sowing or grassland. These problem areas are likely to be those which already suffer from reduced flexibility and seasonal problems, and require particular consideration in the context of the likely effects of future climate.

Key recommendations

- Improve field drainage where appropriate e.g. by subsoiling to maintain and improve drainage connectivity, taking into consideration seasonality and the risks of increased nitrate pollution.
- Minimise cultivation damage by visually checking the condition of the soil before and during operations. The greatest risk of structural damage occurs when cultivation is carried out too soon on a drying soil. Cultivation when a soil is too dry may be a waste of diesel.
- Reduce compaction and impact from wheelings by ensuring that machinery and trailer tyre pressures are set to operator guidelines. Consider using low ground pressure tyres and consider tracked units for late season harvesting equipment.
- Avoid travelling on tramlines in wet conditions as the compaction caused provides a route for much of the run-off from fields.
- Soil structure is prone to damage by most forms of cultivation; plan soil cultivation techniques used throughout the rotation carefully. Where appropriate consider min-till or no till (e.g. where known wet winter soil conditions mean a high risk of damage).
- Manage extended grazing periods carefully to minimise the risks of compaction and poaching; locate supplementary feeders carefully and move regularly.
- Make use of extended growing seasons by including cover crops to improve soil structure and reduce nitrate leaching. Use of leguminous cover crops may reduce requirements for nitrogen fertiliser in the following crop. Use of cover crops should be evaluated to ensure establishment of subsequent crops is not compromised.
- Capture run-off from field and tracks in swales or sediment ponds.

HOW SOIL MANAGEMENT CAN HELP MITIGATE CLIMATE CHANGE

Increasing soil organic matter

Soil organic matter is one of the major pools of carbon in the biosphere and a significant manageable store of carbon for agricultural systems; this can be seen in the Farming Futures diagram of the Carbon Cycle of a Farm . The size of the pool of carbon in any soil is the result of an equilibrium between inputs of organic materials and the decomposition of carbon to obtain energy by the interacting communities that make up the soil food web

(Dawson and Smith, 2007). Inputs of organic materials are usually dominated by plant residues, but may also include animal excreta and returns of organic materials following industrial processing. Where decomposition is slowed, particularly due to waterlogging, then organic matter can accumulate very significantly leading to the formation of peat soils. Soil organic matter can therefore act as both a sink and source of carbon depending on the current balancing point in the local equilibrium.

Within agricultural landscapes it is important to conserve uncultivated areas (woodlands, permanent grasslands). Cultivation has significant impact on the capacity of soils to oxidise methane and uncultivated soils are significant soil carbon sinks in the agricultural landscape (Goulding *et al*. 1996). In recent decades changes in land use and management in the UK have lead to a significant decline in organic matter levels in lowland agricultural soils (Webb *et al*. 2001; Bellamy *et al*. 2005). Consequently most soils under arable cultivation in the UK, under appropriate management have the potential to accumulate (sequester) more carbon. However, the capacity of soils to sequester significant additional carbon while under intensive agricultural management is limited. Reducing the intensity and frequency of disturbance and moving towards a ley-arable rotation on sandy soils will tend to increase soil organic matter and the regular addition of crop residues and manures should enable arable soils to maintain organic matter levels. Regular additions of organic materials have been shown to increase water holding capacity for light soils, improve drainage for heavy soils and increase soil structural stability, increasing resistance to damage during cultivation. Maintaining and increasing soil organic matter levels together with improvements in soil structure are also likely to support increased efficiency by reducing costs and implement wear during cultivation.

It is estimated that 12% of the British rural land area is classified as peatland and contains 43% of the total remaining British organic carbon stock (Falloon *et al*., 2006). Peat soils have been under threat for decades due to harvesting for horticultural use and as a result of drainage for use in crop production. The Country Land and Business Association, CALM calculator (Carbon Accounting for Land Managers) estimates losses of 42 tonnes of CO_2 equivalent for each hectare of drained peat (> 1m depth) with an additional 2 tonnes CO_2 equivalent associated with each tillage operation. This is at the very high end of estimates from the literature (e.g. losses of 27 tonnes of CO_2 equivalent were measured in cultivated peat soils in Finland; Maljanen *et al* 2004). However, further drying out of peat soils in the uplands as a result of a warmer, drier summer climate is likely to increase losses and contribute significantly to the total amounts of carbon dioxide released from soils in the UK. Blocking old drainage systems in peat areas and seeking to increase water tables in peat areas where peat structure and vegetation can be re-established will potentially have very significant benefits for carbon sequestration (Moore, 2002).

Key recommendations

- Reducing the intensity and frequency of soil disturbance will help to protect soil carbon sinks. Consider changing cultivation techniques to min-till or no till where appropriate, or moving towards ley arable rotations on sandy soils.
- Reduce cultivation and/or drainage of peaty soils, as emissions are increased markedly compared with similar operations on mineral soils.
- Carbon sequestration in soils under most agricultural management is limited; farmers can potentially improve and maintain organic matter in soils by regular addition of crop residues and manures or other organic materials such as compost.
- Conserve and maintain uncultivated areas (woodlands, permanent grasslands, buffer strips) within arable areas to preserve them as soil carbon sinks and to protect their capacity to oxidise methane.
- Restore degraded peatland habitats for example blanket bog, fens and raised bogs, to reduce carbon losses and restart sequestration.

Reducing nitrous oxide emissions

Nitrous oxide (a potent greenhouse gas) is released in the soil during the microbial processes of nitrification and denitrification; this can be seen in the Farming Futures diagram of the Nitrogen Cycle of a Farm. Adding nitrogen to soils, whether in fertiliser or as a result of mineralisation of organic matter, increases the likelihood of nitrous oxide release (Johnson *et al*. 2007). However, the risks of nitrous oxide release are greatest in wet, warm and clay or compacted soils, where levels of decomposable organic matter are high. Around 10-15% of the emissions of CO_2 equivalent for drained peat soils are in the form of nitrous oxide (Maljanen *et al* 2004).

Improving nitrogen use efficiency will reduce potential nitrous oxide emissions. More detail of how this can be achieved is given by Farming Futures Fact Sheet 21. Careful management of rates and timing of fertiliser, crop residue and manure application together with minimisation of compaction will reduce nitrous oxide emissions.

Key recommendations

- Applying fertiliser and manure to crops and grassland at optimal times and rates using recognised nutrient management planning and fertiliser recommendations will help to reduce nitrous oxide emissions.
- Reducing soil compaction will help improve porosity and reduce nitrous oxide losses from soil.

CONCLUSIONS

Although some of the impacts of climate change will happen only in the medium or longer term, it's important to think ahead for the future, especially as improvements in soil properties driven by management often take years to be realised. The soil management practices that are required to achieve Good Agricultural and Environmental Condition will only partially achieve the aim of developing effective soil management in a changing and increasingly variable climate. Farmers will experience different impacts of climate change depending on geographic location, slope, farming system and their soil types – consequently it is important for each farm to develop its own flexible and targeted soil management plan.

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