Soil Case Study

Summary

Key Policy Messages

This case study is focused on the 25YEP goal by 2030, for all of England's soils to be managed sustainably, and the 25YEP/NAP2 action to develop better information on soil health and develop a soil health index. However, the overall 25YEP goal is quite broad, and does not define what is 'sustainably managed', and there are many factors involved in soil management and soil health, of which climate change is only one. Climate change can lead to soil degradation, soil erosion, compaction, and decline in organic matter, although there are other more complex impacts, including some potential benefits. Climate change could therefore be important in soil health (and affect the outcome above) although factors are important (e.g. land management practice). Soil degradation, erosion, compaction and carbon loss (combined) currently has high estimated economic costs, with previous studies estimating annual costs in England and Wales of between £0.9 and £1.4 billion. These could increase under climate change, with indicative estimates suggesting up to a 20% increase in soil erosion (but with high uncertainty).

The current soil management policy and soil health metrics are still being developed, and this makes it difficult to know if further adaptation is needed. An obvious first priority is to ensure that soil health metrics include attributes that can target climate change related impacts (e.g. soil erosion), and ensure that climate information and soil health quality over time are monitored and evaluated. However, for this to be useful, there will be a need to scale this up, and incentivise the farming sector to act on the information it provides, as well as to link back into new agricultural policy as part of an iterative adaptive management. Beyond this, there are opportunities for soil management options with positive adaptation characteristics, although a review of these finds that they have modest economic benefit to cost ratios, and they are less attractive from a financial (private) perspective, due to the time-periods before benefits arise, the fact that many benefits are non-market in nature, and because of opportunity costs and potential trade-offs. There are therefore important barriers to their uptake, i.e. there are likely to be need to be incentives to enable wider uptake, and the delivery of the 25YEP goals.

What is the outcome?

This case study is focused on the soil management theme in the 25 Year Environment Plan (25YEP) (HMG, 2018). The 25YEP set outs the goal/target of 'Improving our approach to soil management: by 2030 we want all of England's soils to be managed sustainably, and we will use natural capital thinking to develop appropriate soil metrics and management approaches'. This is linked to an action to develop better information on soil health, producing a soil health index and testing this.

The 2nd National Adaptation Programme (NAP2) (Defra, 2018) reflects the focus of the 25YEP on soil quality and repeats the goal and actions above. The NAP2 identifies some of the pathways through which climate could affect soils, citing soil degradation such as erosion, compaction and the decline in organic matter, and highlights that addressing these will lead to healthier soils. It also highlights that adaptation to maintain soil health will have a range of co-benefits including carbon emission reductions.

This case study assesses the potential impact of climate change on the 25YEP/NAP2 goal and action on managing soils sustainably and developing appropriate soil metrics. However, it is highlighted that the target in the 25YEP is extremely broad and not well defined. There is no definition of what is 'managed sustainably' and no definition of soil health/ quality (noting these will vary significantly by land-use type). This makes it difficult to assess the impact of climate change on the outcome, except in qualitative terms. Furthermore, the pathways by which climate change affect soil quality are extremely complex (Brown et al., 2016), and need to be seen in the context of the multiple factors that affect soil health, including non-climate related risks, which are currently more dominant. To advance the case study, the analysis has focused down on soil health.

It is noted that at the time of this study, the UK is introducing new agricultural policies following the planned withdrawal from the EU. There is currently great uncertainty around the policy landscape post-Brexit, and a combination of trade and agricultural policy will drive farming practice post-Brexit.

How does climate change affect the outcome, in a 2 vs 4°C pathway?

The importance of effective soil management – and soil quality - derives from the fact that soil performs several important underpinning functions: it supports food production, water storage, biodiversity conservation and carbon storage. The ability of soil to perform its multiple functions is reduced when it is degraded (its quality is reduced) or eroded (its quantity is reduced), as can arise from several factors, which include climate change.

The CCRA2 identified risks to soils from increased seasonal aridity and wetness (Brown et al., 2016). However, climate change can potentially impact on soil quality through a number of pathways (Morison and Matthews, 2016):

- Soil degradation (although this can include multiple processes);
- Soil erosion (from heavy precipitation and extremes);
- Higher rainfall increasing soil compaction;
- Loss of soil organic carbon;
- Multiple climate factors affecting vegetation cover and soil processes, affecting function, water holding capacity, salinization, etc.

The most direct climate pathway is from soil erosion, which leads to the reduced productivity and reduced soil carbon (and increased GHG emissions), but can also lead to downstream impacts such as on water quality (Defra, 2012: Graves et al., 2015). The other factors involve complex pathways where climate is only one of many factors. Note that there are also some potential positive effects as well, from climate change increasing organic matter and biodiversity due to warmer temperatures and higher primary productivity. It is stressed, however, the scale of negative impacts and any positive effects, will be strongly influenced by land management.

There are estimates of current rates of soil erosion in England (Defra, 2012: Graves et al., 201; POST, 2015), and previous studies have projected that these could increase with climate change, primarily due to changes in rainfall (with estimates of a 20% increase in soil erosion by the end of the century, Cooper et al., 2010). In the medium-term (2050s) there is not much difference in the average and extreme rainfall projected under 2°C versus 4°C pathways, but there is a very large difference due to model uncertainty and variability (Lowe et al., 2018). As these indicate that rainfall projections for England could vary significantly, even in the sign of change, there is considerable uncertainty in the exact changes.

The pathways for other climate change effects on soil, including vegetation cover and soil processes, and the effects on soil health, are not sufficiently well understood to project the detailed effects of climate change.

Nevertheless, climate change clearly has the potential to affect soils, and thus is an important component in soil quality and soil health. In the absence of adaptation, soil health could decline (at least for the component vulnerable to climate change) which could make it be more challenging to achieve the outcome of improved soil health in the 25YEP (though the effect will depend on the exact metric developed). Climate change could also affect the sustainable management of soils, with detrimental effects on the ecosystem services that soil provides.

The case study has also considered the potential for threshold risks for soil quality and also the potential for lock-in. There are a large number of potential thresholds risks associated with soil quality and soil health, but these thresholds are extremely complex, and are likely to be more influenced by other factors. Nonetheless, climate change could be a factor in potential threshold and lock-in risks, notably from soil erosion (especially in the case of unsustainable management). There is a study (GFSP, 2017) which has identified unlikely but plausible major tipping points for areas of England, from the impact of climate change on soil erosion leading to major production losses.

What are the economic costs of climate change, i.e. the effect on the outcome?

Soil erosion can lead to a number of economic costs. This includes the direct impacts on reduced agricultural productivity, but also the offsite cost associated with impacts on environmental water quality and drinking water quality. It also includes the loss of soil carbon and increased greenhouse gas emissions.

Defra (2012) (also published as Graves et al. 2015) estimated the annual costs of soil degradation in England and Wales at between £0.9 and £1.4 billion This reflects total soil degradation. Of this, the annual cost of soil erosion in England and Wales was estimated at £177 million/yr (as the additional input costs to offset losses in productivity). The estimated current cost of compaction was estimated at £472 million per year, about half of which are on-site, and half are offsite. The costs of soil carbon loss were estimated at £566 million/year (based on a carbon price). Soil erosion costs would increase with climate change, under scenarios with higher precipitation and especially higher heavier precipitation. A further study (AECOM, 2015) estimated the potential impacts on soil carbon under climate change for different scenarios, reporting the soil carbon stock could be reduced by up to -12% by 2060, with costs in England of around £30 billion between 2010 and 2060, although there was a large range, which included positive values for some scenarios when positive land use change were included.

There are no robust estimates of the future economic costs of climate change on soil quality or stocks. However, it is possible to provide some indicative estimates by deriving annual totals for the climate change impacts of erosion and compaction. For example, applying the 20% increase identified from the impact of climate change on erosion to the current economic costs of soil erosion indicates potentially large economic costs are possible for England.

What are the potential additional adaptations options to address climate impacts on the outcome?

The current soil management policy and soil metrics are still being developed, and this makes it difficult to know how much climate change adaptation is being factored in. At the simplest level, an obvious first action is to ensure that the soil health metrics being developed include attributes that could be affected by climate change, and then to ensure that climate information and soil health quality over time are monitored and evaluated (with the linkages between the two being explicitly considered). For example, specific factors that relate to climate change related impacts include soil erosion rates and soil carbon content.

However, the current actions set out for soil health in NAP2 (Defra, 2018) are primarily focused on research and monitoring (with soil metrics yet to be derived). For this to be useful, there will be a need to scale this up, and incentivise the farming sector to act on the information this provides. There is also an opportunity to use this information (on monitoring of soil health) at the national scale, to help inform new policy development, as part of an adaptive management (iterative) approach for developing national agriculture policy, and even, for influencing the incentives in agriculture farm payment systems.

Moving to soil management actions, there are already a set of management practices in place and NAP2 sets out an action to incentivise good soil management practices. These will be focused on wider actions to enhance sustainable management, and thus may not prioritise climate resilience, however, there are many measures that have adaptation co-benefits. Such actions have been advanced through a large international and UK literature on climate smart agriculture (FAO, 2013; POST, 2013; POST, 2017). Such practices aim to deliver triple outcomes of increased productivity (income growth), reduced GHG emissions (mitigation) and enhanced climate resilience (adaptation). Most of these measures are forms of sustainable agricultural land management (SALM) practices, which improve soil water infiltration and holding capacity, as well as nutrient supply and soil biodiversity. They are generally considered to be low-regret, rather than no-regret, because they often have opportunity or transaction costs (FAO, 2011: ECONADAPT, 2017).

While improved awareness of these measures will be important, a key issue will be the incentives introduced through farm payments to incentivise them. As highlighted above, UK is introducing new agricultural policies following the planned withdrawal from the EU. A key opportunity will be to integrate (mainstream) climate aspects in such policy development.

What are the benefits and potential costs of adaptation?

There is relatively little economic evidence on the costs and benefits of soil management techniques in England, although there is a large international literature. The literature that exists suggests that the economic benefit to cost ratios for sustainable soil manageable are modest (Kuhlman et al., 2010; UBA, 2012; SRUC, 2013; ECONADAPT, 2017; IFAD 2018), and the private benefit to cost ratio (the rate of return) are often low, because many benefits are non-market in nature, and there are often additional opportunity costs and barriers. In practice, it can be harder to achieve the triple win (of increasing production, reducing emissions and enhancing resilience) and there are often trade-offs involved. Therefore, while sustainable soil management approaches have potential for reducing climate impacts, their uptake requires these barriers to be addressed. These are likely to go beyond information and awareness raising, though there are obvious opportunities to provide additional incentives through revision of the current farm payment schemes.

Step 1. What is the outcome?

Objectives and Outcome

This case study is focused on the soil management theme in the 25 year Environment Plan (25YEP) (HMG, 2018). The 25YEP set outs the goal of 'Improving our approach to soil management: by 2030 we want all of England's soils to be managed sustainably, and we will use natural capital thinking to develop appropriate soil metrics and management approaches'.

The 25YEP also set out the actions to deliver this, which focus on better information on soil health and developing a soil health index. The Plan reports the following actions:

- Working with the industry to update the 2001 guidance on crop establishment and optimal tillage choice.
- Defra will invest at least £200,000 to help develop soil health metrics and test them on farms across the country.
- We will investigate the potential for research and monitoring to give us a clearer picture of how soil health supports our wider environment goals.

The 2nd National Adaptation Programme (NAP2) (Defra, 2018) reflects the focus of the 25YEP on soil quality, and repeats the 25YEP goal (that by 2030 we want all of England's soils to be managed sustainably) and repeats the 25YEP actions on improving soil health and developing a soil health index.

NAP2 states that 'We are developing a soil health index that will make it simpler for farmers and land managers to monitor the quality of their soil, using indicators such as the level of humus and biological activity in the soil. This will allow us to assess whether management practices are having a beneficial impact on soil health and greenhouse gases mitigation, and provides the opportunity to consider how to utilise this data to develop a picture about the 'population' of national soils and trends.' It also sets out that 'We will be working with the industry to update guidance on crop establishment and optimal tillage choice to ensure that farmers choose the best practices for their soils to reduce the rate of loss of soil and carbon. In addition, our new environmental land management system will aim to deliver benefits such as improved soil quality'.

The specific NAP2 actions (as set out in the detailed action log) are shown below:

Table 1 Detailed actions log. Source NAP2 (Defra, 2018). Protecting soils and natural carbon stores

Objective	**Key actions**	**Monitoring and metrics**
1. To improve our approach to soil management: by 2030 we want all of England's soils to be managed sustainably	Incentivise good soil management practices that enhance soil's ability to deliver environmental benefits through future environmental land management schemes to ensure soils are healthy and productive	A soil health index will be utilised at farm level to assess whether management practices are having a beneficial impact on soil health
2. To improve soil health	Support research and monitoring to give us a clearer picture of how soil health supports our wider environment goals	Defra will invest at least £200,000 to help develop soil health metrics and test them

NAP2 does indicate the pathways by which climate could affect soils, through soil degradation such as erosion, compaction and the decline in organic matter. It highlights that addressing these issues through adaptation are expected to have a range of co-benefits including carbon emission reductions. DEFRA's Departmental Plan has also committed to developing a new environmental land management scheme to deliver outcomes from the 25-year environment plan.

It is highlighted that the outcome in the 25YEP / NAP2 above is extremely broad and it is not well defined, i.e. there is no definition of what 'managed sustainably' means, or even what criteria it could involve. There is also no definition of soil health/ quality, and it is noted these will vary by land use type. This makes is difficult to assess the impact of climate change on the outcome, except in qualitative terms.

It is also highlighted that the pathways by which climate change affects soil quality are extremely complex, and need to be seen in the context of the multiple factors that affect soil health and soil management, including more dominant non-climate related risks. Principal non-climatic factors include agricultural and forestry practices, as well as a range of land use decision-making. It is also highlighted that the regulatory framework regulating soil management is very complex, and to deliver the outcome requires cross-Government linkages, and clearly a major role for the private sector.

To advance the case study, the analysis has focused down on soil health, and developed an indicative theory of change would involve:

- Activities of soil health research, with these being developed into a metric (that can be measured).
- Outputs, to develop legislation or create the enabling environment, to encourage sustainable management to improve performance against this metric.
- Outcome: Soil management in England is sustainable and carbon stock losses are minimised (confirmed by progress against the soil health metric)
- Impact: England soils are managed sustainably, contributing to the wealth of the people, the environment, and the economy.

Finally, at the time of this study, the UK is introducing new agricultural policies following the planned withdrawal from the EU. One objective is to reduce the environmental impacts of agriculture (POST, 2017). There is currently great uncertainty around the policy landscape post-Brexit. A combination of both trade and agricultural policy will drive farming practice post-Brexit. This includes the new Agriculture Bill[1] going through Parliament.

Step 2. How does climate change affect the outcome, in a 2 vs 4°C pathway?

The importance of effective soil management – and soil quality - derives from the fact that soil performs several important functions: it supports food production, water storage, biodiversity conservation and carbon storage. The ability of soil to perform its multiple functions is reduced when it is degraded (its quality is reduced) or eroded (its quantity is reduced).

The CCRA2 Evidence Report (Brown et al, 2016) identified 'Risks to soils from increased seasonal aridity and wetness (3.3)' and highlighted that further action was needed for this risk. It reported that future climate projections suggest that climate, in combination with the other pressures, could lead to a major increase in risk due to the effects from higher temperatures, more intense rainfall and increased aridity, depending on location and soil type.

Climate change is expected to potentially impact on soil quality in England in a number of different ways (Morison and Matthews, 2016). These include:

- The effects of more frequent or higher intensity extreme weather events leading to soil erosion. This involves the physical removal of soil - caused by water and wind. Erosion will lead to sediment run-off to drainage channels and reduced soil fertility, and thus on agricultural productivity.
- Higher rainfall increasing the risk of soil compaction and of more leaching of nitrates. These effects depend on crop growth, nutrient uptake patterns and fertiliser applications;

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[1] https://services.parliament.uk/bills/2017-19/agriculture.html

- Changes in temperature and rainfall affecting the type of vegetation feeding the soil, and negative effects of soil processes, which influence soil properties such as structure, organic matter content, water-holding capacity, pH and fertility. Loss of organic matter impairs most soil functions and water holding capacity, and leaves soils vulnerable to erosion and compaction;
- Changes in temperature and rainfall leading to changes in soil organic carbon content. In warmer environments where water is not a limiting factor, there will be higher crop productivity and therefore more carbon inputs, but also higher soil respiration rates. The net effect is not known (AECOM, 2015);
- Salinisation results when irrigation water or coastal flooding and inundation evaporates leaving salts which can build up in soil to levels that reduce fertility or are toxic for plants.

It is highlighted that many of these involve extremely complex pathways, where climate is only one of many factors. There are different aspects here, although the literature varies in exact definitions:

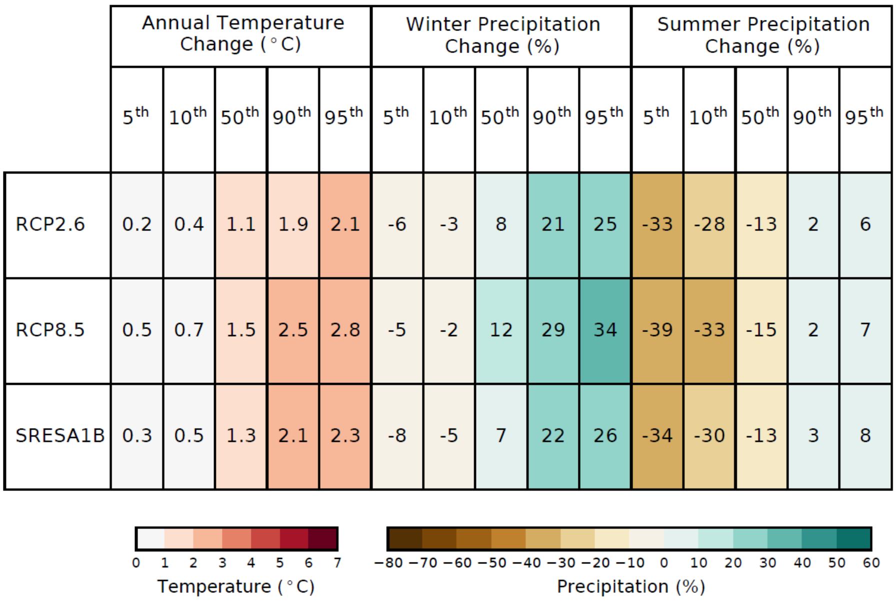
- Soil degradation relates to declining soil quality, i.e. the deterioration in physical, chemical and biological attributes of the soil, either from erosion (below) or other processes (e.g. compaction, surface sealing and crusting, waterlogging, aridification, chemical degradation, acidification, salinization, pollution, etc.
- Soil erosion is the physical process that causes land and soil degradation, i.e. the erosion by water and/or wind and reduction in soil productivity due to physical loss of topsoil, reduction in rooting depth, removal of plant nutrients, and loss of water.
- Land degradation captures the broader reduction or loss, i.e. in biological or economic productivity of land more generally, from soil erosion, deterioration of the physical, biological or economic properties of the soil; and long-term loss of natural vegetation.

There is a climate component to all of these: whether from the contribution of wind and water to soil erosion, from the effects of climate on soil quality, and from the effects of climate on vegetation cover and possible land degradation. This is a particular issue for water erosion. However, socio-economic factors are also important (e.g. land-use pressures, changes in farming practice such as from residue loss, loss of wider natural vegetation cover and watershed effects, etc.) and it is important to consider the attribution of these various factors.

The most direct climate pathway, however, is from soil erosion. Soil erosion is a physical measure (the loss in tonnes/hectare). Soil erosion is typically a major issue when there are steep slopes and high run-off from precipitation, or where there is high wind-blown loss of dry soil. It can, however, act directly and indirectly. It is also influenced by management practice (e.g. erosion control). In practice, soil erosion patterns even within a specific watershed can be very heterogeneous, locally specific and difficult to assess.

In England, there are some data that report on soil erosion. Defra (2012) found that an estimated 1 million ha are at risk of erosion in England and Wales, mainly associated with arable farming on silts and sands. Erosion in England and Wales was calculated to be approximately 2.9 Mt yr-1, which is similar to the 2.2 Mt yr-1 estimate given by the Environment Agency (EA).

There are also some studies that look at how soil erosion rates might increase under climate change. Cooper et al. (2010) reports that rates of erosion from rainfall are projected to increase by 0.1 tonnes per hectare per year to an average of 0.55 tonnes per hectare per year by the 2080s – approximately an increase of 20%. Erosion from wind, on the other hand, is projected to be negligible, based on current projections of changes in wind speed. Soil erosion is often assessed using some form of Universal Soil Loss Equation, where average annual erosion is estimated from the climate factors (rainfall, wind), soil factors, topography (slope) and land utilization factors (cropping management and erosion control practices. For climate change, the key factor that will change is precipitation. This provides some indications of how soil erosion might change under future 2°C and 4°C scenarios. However, a look at the UKCP18 scenarios (Lowe et al., 2018), shows that there is very little difference in the mid-century climate (2041-2060) between 2 and 4°C pathways for rainfall (as captured by RCP2.6 and RCP8.5), but a huge difference across the probabilistic projections, e.g. between the 10th and 90th probability level. As an example, taking the 50th value, there is only 2 to 4% difference in rainfall between 2 and 4°C, but between the 10th and 90th differs even in sign.



	Annual Temperature Change (°C)					Winter Precipitation Change (%)					Summer Precipitation Change (%)				
	5th	10th	50th	90th	95th	5th	10th	50th	90th	95th	5th	10th	50th	90th	95th
RCP2.6	0.2	0.4	1.1	1.9	2.1	-6	-3	8	21	25	-33	-28	-13	2	6
RCP8.5	0.5	0.7	1.5	2.5	2.8	-5	-2	12	29	34	-39	-33	-15	2	7
SRESA1B	0.3	0.5	1.3	2.1	2.3	-8	-5	7	22	26	-34	-30	-13	3	8

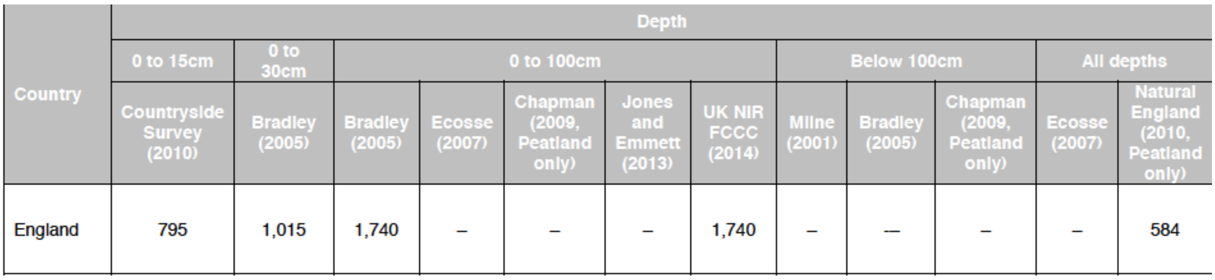
Figure 1 Projected change in temperature and precipitations for the UK region from 1981-2000 to 2041-2060 for RCP 2.6 and RCP8.5 using the probabilistic projections. (Lowe et al, 2018)

There will be potentially greater impacts from changes in extremes. Heavy precipitation is a major factor in soil erosion rates, and this is generally projected to increase under climate change, as identified in UKCP18. There is also the potential for dry spell duration and drought to affect soil erosion, for example, during such periods, loss of structure can be exacerbated, increasing erosion (GFS, 2017).

The pathways for vegetation cover and soil processes, and the effects on other soil health are not sufficiently well understood to project the effects of climate change.

There is also some data on soil carbon. AECOM (2015) present a range of quantitative data on the carbon stock held in soils in England, summarised in Table 1.

Table 2 Collated recent estimates of the soil carbon stock in England



Country	Depth										
	0 to 15cm	0 to 30cm	0 to 100cm					Below 100cm			All depths	
	Countryside Survey (2010)	Bradley (2005)	Bradley (2005)	Ecosse (2007)	Chapman (2009, Peatland only)	Jones and Emmett (2013)	UK NIR FCCC (2014)	Milne (2001)	Bradley (2005)	Chapman (2009, Peatland only)	Ecosse (2007)	Natural England (2010, Peatland only)
England	795	1,015	1,740	–	–	–	1,740	–	—	–	–	584

Note: (Units Mt = Tg, see also Figure 3.1). Dashes indicate that the stated report or authors did not produce an estimate for the country in question.). Source: (AECOM, 2015)

There are also studies that estimate the change in soil carbon stock from climate change. The estimates usually include two key factors: (1) the change in soil carbon due to soil erosion; and (2) the change in soil carbon due to land use change. The total change in soil carbon by AECOM (2015) is based on an aggregation of these two factors (Table 2 below)

Table 3 Baseline soil carbon in 2010 and annual change in carbon due to erosion in soils up to a depth of 100 cm (MtC and MtCO2e)

Region	Baseline soil carbon (Million tonnes)	Annual change (Million tonnes)	Annual change (Million tonne CO2 eq)
England	1,740	-0.0446	-0.1637

A further dimension is that higher temperatures are likely to increase the production (and thus release) of Dissolved Organic Carbon (DOC) from soils (Evans et al. 2005 in AECOM 2015). For upland landscapes with substantial coverings of frost and/or snow in winter, higher temperatures will increase soil exposure to ultraviolet photo-degradation (Stasko et al. 2012 in AECOM 2015). Additionally, any increase in the frequency of fires will leave soil carbon vulnerable to erosion and thus runoff losses of DOC. However, a more substantial impact of climate change could be through changes in the frequency of short-duration drought events and changes in the intensity of rainfall.

It is stressed that this whole area is extremely challenging and data are highly uncertain. For example, whilst data from the repeated surveys of the National Soil Inventory Monitoring Programme (1978 and 2003) indicate that top soils in England and Wales (0 – 15cm depth) are losing carbon at a rate of 0.6% (4 million tonnes) per year (AECOM, 2015), a study using vegetation modelling demonstrated that climate change might only have contributed to 10-20% of the reported loss (Smith et al. 2007 in AECOM 2015). Furthermore, estimates derived from Countryside Survey locations (1978 and 2007, Carey et al. 2008 in AECOM, 2015), showed no change in topsoil carbon over this period. NEA (2011) concluded that up to 2050'future changes in land use could have as much impact on ecosystem services as the direct effects of climate change' (NEA 2011). It is therefore critical that the implications of changes in land use/cover be taken into account when assessing carbon stocks.

As identified in CCRA2 (Brown et al., 2016), in some locations, there may be potential opportunities from climate change, due to increased organic matter and biodiversity due to warmer temperatures and higher primary productivity.

CCRA2 also highlighted that for all the potential effects above, the impact of climate change will be strongly influenced by management measures, and whether these maintain vegetation cover and good soil structure: in the absence of such actions, soil will become more susceptible to water erosion and potentially wind erosion. As an example, high carbon soils with good structure can hold more moisture and be more drought-resistant (GSF, 2017).

Overall, climate change will therefore affect soil quality, and thus is an important component in the soil health metrics. In the absence of additional adaptation, soil health could decline (at least for the component vulnerable to climate change) which could mean it is more challenging to achieve the outcome of improved soil health (though the effect will depend on the soil health definitions and soil metrics agreed by Defra). Beyond this, climate change will affect the sustainable management of soils, with detrimental effects on the ecosystem services soil provides.

Thresholds and Lock-in

The case study has considered the potential for threshold risks for soil quality and also the potential for lock-in. There are a large number of potential thresholds risks associated with soil quality and soil health, but these thresholds are extremely complex. There are also some potential lock-in risks from unsustainable soil management, i.e. which could lead to the irreversible damage of soil (for productive use). These are not, however, primarily associated with climate change. The one area where climate could have more of an influence on thresholds and lock-in (from inaction) is with long-term soil erosion, though even here, land management practice will continue to be important.

It is highlighted that there the potential risks of thresholds risks has been identified by the Global Food Security programme (2017). The study provided an example of a potential illustrative but plausible tipping point in East Anglia where climate change could lead to a dustbowl (similar to that seen in the US in the 1930s). In this case, an unprecedented drought could cause the loss of peat and a reduction in soil organic matter, with long-term detrimental effects on crop yield, and the potential susceptibility to major erosion of soil (leading to an East Anglian dustbowl).

Step 3. What are the economic costs of climate change, i.e. the effect on the outcome?

There are potential economic costs from not meeting the outcome, i.e. not managing soils sustainably, and from declining soil health. The two most obvious economic costs that can be quantified are the loss of agricultural productivity as a result of soil erosion, and the loss of soil carbon, increasing GHG emissions. The first is a market impact and the second a non-market impact.

There is a general literature which reports on the impacts and economic costs of soil erosion and land degradation, relating this to the reduction in (long-term) agricultural productivity, with values that are often estimated at several % of agricultural GDP.

It is also possible to estimate the impacts of soil erosion using replacement costs (e.g. from the costs that would have to be incurred to replace a damaged asset such as the annual marginal costs of fertilizer applications to compensate for the loss of soil nutrients due to erosion) or in terms of loss productivity (the value of the lost crop production valued at market prices, with future losses discounted by market interest rates), though there are issues with both methods[2]. Not surprisingly, the aggregation to national level involves many assumptions, and there are important issues with the boundary of the analysis (not least because upstream soil erosion can sometime lead to benefits downstream).

The loss of soil also has a further economic cost in relation to the increase in carbon emissions, from reduce soil carbon stock.

Two studies – Defra (2012) and NEA (2011) – present some relevant cost information.

The 2012 report for Defra estimated the annual costs of soil degradation in England and Wales at between £0.9 and £1.4 billion, as below.

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[2] For example, replacement costs, which consider additional fertilizer use to compensate for loss in nutrients, may not captures the full loss from soil erosion, though it may also not reflect the opportunity cost. Loss productivity involves assumptions about yield rates with and without erosion, and does not reflect the costs of irreversible losses.

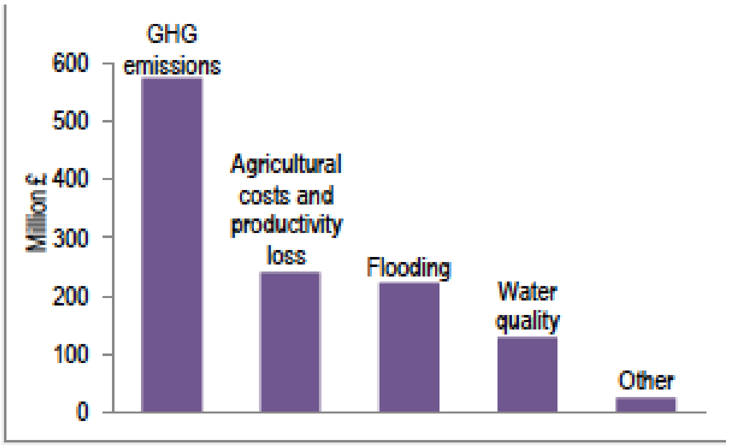

Figure 2 Annual costs of soil degradation in England & Wales

Source: POST (2015).

Defra (2012) identified that the costs of erosion include: (i) the onsite costs of the decline in agricultural and forestry yields caused by the reduction in soil depth, the cost of a reduction in the stock of C, and the cost of replacing losses in N, P and K, and (ii) the offsite cost associated with impacts on environmental water quality, drinking water quality, and iii) greenhouse gas regulation. The total annual cost of erosion in England and Wales for all soil-scapes was estimated at about £177 million yr. Onsite costs (£40 million per year) comprise loss of yield potential due to loss of soil and loss of soil nutrients, but these were valued at their nutrient replacement cost (not the market cost). Offsite costs comprise mainly the treatment cost of nutrient removal from drinking water, the damage costs of nutrients passing to the water environment, sediment removal from rivers and lakes, sediment removal from urban drainage systems. final major category was the GHG loss linked to erosion.

The cost of compaction was considered to include: the onsite cost of agricultural and forestry yield decline caused by impaired rooting medium and reduced water holding capacity, the extra draught power associated with ploughing and cultivation operations, and the cost of losing applied N, P, and K because of extra runoff. The off-site costs included the impact of compaction induced additional N, P and K in the water environment and the environmental burdens associated with increased soil tillage. An estimated 3.9 million ha are at risk of compaction in England and Wales, highest on clay soils during wet periods. The estimated total current cost of compaction is £472 million per year, about half of which are on-site, and half are offsite.

The loss of soil carbon has both onsite implications for agricultural production and offsite implications for global warming. Soil organic matter, for which soil organic C is a proxy, is critical for good soil structure. The annual cost of the loss of organic matter in the soil as measured by loss of organic carbon was calculated to be £3.5 million per year, based on the cost of replacing it with organic manures. The off-site cost in terms of GHG emission was much larger. Using the ratio of 1 to 3.67 for soil C to CO_2 in the atmosphere, the central estimated annual cost, assuming a CO_2 value of £51 CO_2e/t is £566 million mostly associated with clay and peat soils, ranging between low and high estimates of £360 million and £700 million per year respectively.

The National Ecosystem Assessment (NEA 2011) provided estimates of the land cover in the year, 2060, based on various socio-economic scenarios. AECOM (2015) selected three of the NEA scenarios and used Bradley et al. (2005) 'land types' to assess the effect of land cover changes on carbon stocks in both: a) the soil, and b) the vegetation. By using a land cover dataset that also accounts for the indirect effect of climate change, this study quantified how climate change effects, such as increased drought events or the abandonment of agricultural land, drive changes in land cover and thus changes in carbon stock.

The three NEA scenarios used in AECOM (2015), reflecting different societal attitudes towards the environment, ranging from a society relatively concerned with the surrounding environment ('Local stewardship'), to one mainly concerned with trade ('World markets'). The 'Green and pleasant land' scenario is one where the conservation of traditional landscapes is a dominant driving force in society. This aesthetic imperative drives a renewal in tourism and recreation but also has clear benefits for biodiversity.

Each NEA scenario was matched with two climate change scenarios: 'low' and 'high'. These are loosely based on the results for mean temperature and precipitation changes under the UKCP09 low (SRES B1) and high (SRES A1FI) emissions scenarios for 2050–2079, (AECOM, 2015). These low and high scenarios are projected to drive changes in global mean temperature of +1.8°C (likely range +1.1 to +2.9°C) and +4.0°C (likely range +2.4 to +6.4°C) respectively (IPCC 2007). UK NIR (2014) assume that it will take anything from 50 to 750 years for a land cover change to be reflected in the soil carbon stock of the area in question (Table below), and as a rule of thumb, losses are often assumed to occur over shorter timescales than gains - principally due to disturbance of the soil.

The resulting changes in carbon stock levels for England are presented below. AECOM, (2015) found that 'Local stewardship' and 'Green and pleasant land' appear similar in policy terms and both result in substantial gains in soil carbon throughout lowland Britain. However, the areas of highest gains identified under each scenario are substantially different. In 'Local stewardship', the highest gains come in upland periphery areas, where afforestation and changes from improved grassland to semi-natural grassland drive a long-term increase in carbon amounts.

In 'Green and pleasant land', the largest gains come where the potential for habitat restoration is high: in the mountainous areas where substantial reversions of enclosed farmland to semi-natural habitat are projected for this scenario. The large difference between the low and high climate scenario versions is driven by an increase in semi-natural grassland under high climate, which generally replaces enclosed farmland in England.

In 'World markets', broad-scale industrialisation of farming results in large net losses in soil carbon as more semi-natural and wild habitats are brought into cultivation. Unlike the other two NEA scenarios, for 'World markets' there is estimated to be less change to soil carbon stocks under high climate change than under low climate change. This is due to increased losses of arable land to higher temperatures, leading to increased drought and abandonment of unproductive land. Thus, reversion to woodland or semi-natural grassland reduces estimated loss.

Table 4 Percentage change in soil carbon stock under various scenarios of land cover change for 2060

	NEA Scenarios					
	Low Climate Change			High Climate Change		
	Local Stewardship	Green & Pleasant Land	World Markets	Local Stewardship	Green & Pleasant Land	World Markets
England	+8.05	+13.79	-11.51	+8.72	+18.15	-10.20

The AECOM (2015) study estimated the monetary value of changes in carbon stored in soil and vegetation stocks under the range climate scenarios over the period 2010 to 2060. Thus, the annual change in tonnes of CO_2 equivalent was multiplied by the central non-traded DECC carbon prices for the period 2010 to 2060. These values were then discounted using a rate of 3.5% for the first 30 years and 3.0% thereafter in order to estimate the Present Value (PV) of the change. A comparison of the value estimates is presented in Table 4. The results suggest that the total value of the change in soil carbon stocks across England over the period 2010 to 2060 ranges from a low of -£33 billion in the 'World markets' (low emissions) scenario, to a high of £50 billion in the green and pleasant land (high emissions scenario).

Table 5 Present Value of soil carbon stocks from 2010 to 2060 (£ billion, 2014 prices)

	NEA Scenarios					
	Low Climate Change			High Climate Change		
	Local Stewardship	Green & Pleasant Land	World Markets	Local Stewardship	Green & Pleasant Land	World Markets
England	22	38	-33	24	50	-29

These results equate to undiscounted, annual, totals of approximately (minus) £1 billion to (plus) £2 billion – a mid-point of these appears to be broadly consistent with the current annual loss of carbon of £566 million for England and Wales, reported above; equivalent to £480 million for England alone.

There are no robust estimates of the future economic costs of climate change on soil quality or stocks. However, it is possible to provide some indicative estimates by deriving annual totals for the climate change impacts of erosion and compaction. For example, applying the 20% change identified from the impact of climate change on erosion (Cooper et al. (2010) to the current economic costs of soil erosion presented above (from Defra, 2012) would indicate potentially large economic costs.

Step 4. What are the potential additional adaptations options to address impacts?

The CCRA2 Evidence report (Brown et al., 2016) identified risks to soils from increased seasonal aridity and wetness and highlighted that further action was needed for this risk, i.e. there was an adaptation gap, but since this time there has been the publication of the 25YEP and NAP2.

The current soil management policy and soil metrics from these policies are still being developed, and this makes it difficult to know how much climate change adaptation is being factored in, and thus what additional adaptation might be needed.

At the simplest level, an obvious first action is to ensure that the soil health metrics being developed include attributes that could be affected by climate change, and then to ensure that climate information and soil health quality over time are monitored and evaluated (with the linkages between the two being explicitly considered). For example, specific factors that relate to climate change related impacts include soil erosion rates and soil carbon content.

However, the current actions set out (see Table 1) for soil health in NAP2 are primarily focused on research and monitoring (developing soil metrics). For this to be useful, there will be a need to scale this up, and incentivise the farming sector to act on the information this provides. There is also an opportunity to use this information (on monitoring of soil health) at the national scale, to help inform new policy development, as part of an adaptive management (iterative) approach for developing national agriculture policy, and for influencing the incentives in agriculture farm payment systems.

Moving to soil management actions, the types of actions that will conserve soil quantity and quality are well known (see below), though there is very little information available about the level of uptake of these actions by land managers in England. NAP2 sets out a general action to incentivise good soil management practices (to enhance soil's ability to deliver environmental benefits through future environmental land management schemes to ensure soils are healthy and productive) – but not specifically how this will be done. An obvious vehicle for incentivising the right measures is the Environmental Land Management scheme, being developed as part of the Agriculture Bill currently going through Parliament.

Such actions have been advanced through a large international literature on climate smart agriculture (FAO, 2013). Such practices aim to deliver triple outcomes of increased productivity (income growth), reduced GHG emissions (mitigation) and enhanced climate resilience (adaptation). Most of these measures are forms of sustainable agricultural land management (SALM) practices, which improve soil water infiltration and holding capacity, as well as nutrient supply and soil biodiversity. They are generally considered to be low-regret (rather than no-regret, because they often have opportunity or transaction costs (FAO, 2011: ECONADAPT, 2017).

Soils vary on national, regional and field scales and appropriate management practices will vary from place to place, depending on soil type, land use and climate. Possible measures that are judged likely to reduce the climate change risks identified above include (POST, 2015):

- Organic matter (OM) addition to agricultural land confers benefits on most aspects of soil health. Adding OM can increase soil carbon content for up to 20 years before it plateaus. It can be several years before benefits are apparent in crop yields or farm profits.
- Cover crops (or green manures), such as clover and vetch, protect soil from erosion and nutrient leaching over winter and can be tailored to suppress weed growth and improve soil structure. They are then killed off or ploughed in, adding OM to the soil. Benefits to soil health vary with crop and weather and can take three or more years to become apparent
- Longer crop rotation and intercropping. Varied cropping permits soil recovery and may reduce pesticide requirement. The benefits of increasing rotation complexity depend on the crop species used. Growing two or more crops alongside each other (intercropping) can suppress pests and weeds, covers the soil, protecting it from erosion and can increase nutrient supply to the main crop, although mechanical harvesting can be difficult.
- Non-inversion or reduced tillage improves soil structure, can reduce erosion, cultivation time and fuel costs, and encourages earthworms. A flexible management approach to tillage, according to climate and crop, is most financially profitable.
- Tree planting in strategic areas increases water infiltration and reduces erosion and run-off of sediment and water. Low density forestry can sometimes be effectively combined with animal grazing. However, commercial forestry on upland carbon-rich soils such as peat can cause significant erosion.
- Informed decision-making regarding the timing of agricultural operations, the type of operations used (e.g. minimum tillage), and by erosion control measures such as buffer strips could help reduce negative impacts on soil structure, erosion and runoff.
- Careful planning of the amounts and timing of applications of fertilisers and pesticides could help minimise increased nutrient and pesticide losses in winter.
- Coastal management options should consider measures to protect aquifers from saline intrusion due to sea level rise where appropriate.
- Investment into research in improved soil management methods, in combination with outreach initiatives to land managers, and monitoring.

There are issues on how to increase the uptake of such measures. While improved awareness will be important, a key issue will be the incentives introduced through farm payments.

Step 5. What are the benefits and potential costs of adaptation?

There are some previous studies on sustainable soil management, although the evidence base is relatively modest. While many studies highlight the benefits of these approaches (e.g. see the multi-criteria analysis of a range of climate smart agriculture initiatives in Canada (British Columbia, 2013), most economic studies report benefit to cost ratios are modest. As examples:

- Ex-ante economic analysis (Ferrarase et al 2016) of 32 country-level projects in IFAD's Adaptation for Smallholder Agriculture Programme estimated average BCR of 1.8:1 (median).
- There was also an analysis of the costs and benefits of conservative/low tillage in Germany (UBA, 2012), though this found benefit to cost ratios were low and uncertainty was high.
- Social Returns on Investment (SROIs) of 1.3 - 4.7: 1 for representative investments channelled through the private sector are reported (IFAD 2018).

Importantly, the literature reports that climate smart agriculture (CSA)measures often include important opportunity, transaction and implementation costs (FAO, 2011). Positive EIRRs are usually conditional on including all non-market benefits and low discount rates, the latter because schemes take time to mature and deliver benefits. Modelled returns are often contingent on widespread adoption by farmers, which do not always materialise.

For individual practices, measures are often highly site-specific, reflected in large BCRs differences for similar interventions in different places. There is varied evidence on practices as viable standalone adaptation strategies.

There is also emerging information (ICRAF have prepared large database of climate smart agriculture interventions) which finds that in practice, it can be difficult to get triple wins (mitigation, adaptation, and productivity), i.e. there is often a trade-off involved.

These findings are supported in the limited UK information that exists.

Frontier Economics (2013) reported that there was little evidence on the costs and benefits of soil management techniques in England. They presented a qualitative picture of economic appraisal. They give a cost rating of 'low-medium' and a benefit rating of 'medium', suggesting a positive cost-benefit balance, overall. To support this, the report state that the 'net value of soil organic management in Europe is €30-80/ha/year' though no source was identified. However, the report also identifies that up-take of measures to better manage soil in the farming community is relatively low; the authors cite a survey that finds that 23% of respondents are adapting to increased soil erosion. This is thought to be the consequence of the fact that the minimum time-frame before improvements are seen in soil structure is 5 years whilst farmers are more concerned with the short-term disruption to production. Additionally, two other factors are thought to deter take-up of adaptation measures. The first is that there remains scepticism regarding the underlying science and information on benefits realized from good soil management. Furthermore, whilst the costs of the measures would be borne primarily by the land-owner, the majority of the benefits are gained by others in the area who benefit from – for example – reduced flood risk. The incentive to invest in the measure is therefore substantially reduced.

Some additional data on costs and benefits can be derived from Kuhlman et al., (2010), who collated data for a range of alternative measures that address erosion, organic matter and compaction. It should be noted that the benefit estimates are derived on the basis of costs avoided rather than gains in agricultural, forestry and ecosystem productivity. The data indicate that for the contexts where erosion, soil organic matter and compaction risks co-exist, the benefit-cost ratios vary and are strongly influenced by whether the off-site benefits – that do not accrue to the land manager making the investment in the measure – are included or not.

Table 5. Costs and benefit-cost ratio data on alternative soil adaptation options

Climate risk	Adaptation Measure	Cost per ha per year for measure (£)	Benefit-cost ratio
Serious erosion, SOM loss, compaction	Conversion of arable land into forest; conversion of arable land into pasture; terracing; buffer strips; residue management; cover crop; conservation tillage	256	0.9 (on-site & off-site benefits) 0.7 (on-site benefits only)
Moderate to serious erosion, SOM loss, compaction	Buffer strips residue management cover crop conservation tillage	120	No benefits data
Moderate erosion, SOM loss, compaction	Linear elements contour ploughing residue management cover crop conservation tillage	103	No benefits data
Level areas, SOM loss only	Residue management cover crop conservation tillage application of EOM	100	1.5 (on-site & off-site benefits) 0.6 (on-site benefits only)
Specific anti-compaction measures	Low-pressure tyres	4	5.6 (on-site benefits only)

Source: derived from Kuhlman et al. (2010)

These findings seem to broadly support the conclusions of Frontier Economics, (2013), that in order to realise the benefits from soil protection these benefits need to be better understood and measured, and the costs of adaptation spread across those who benefit.

SRUC (2013) for the CCC also looked at soil management, considering six adaptations on a number of different crops. They report this proved particularly challenging, because of a lack of evidence on the relationships between climate change and yield, soil health, and in particular soil organic matter. Furthermore, they report that while there may be localised evidence, this does not necessarily scale up to the regional or national level due to other influencing factors. The study used yield as a proxy for soil fertility, and the adaptation options included those that had a projected effect on improving soil quality. Under these assumptions, all the adaptations analysed (with one exception, for cover crops) generated positive NPVs. These did not require long lead times and had positive ancillary benefits, but the study still identified the challenge would be to encourage farmers to adopt them. They recommended further research to provide evidence for the relationships.

Table 6 Adaptation options. Source SRUC (2013).

Measure	**Impact on soil fertility**	**Impact on soil organic matter including carbon**
Drainage	Reduce waterlogging	May have some small effect because of yield increase and therefore increased root growth and hence residue return. May also have negative effects due to leaching of SOC (Baker et al, 2007).
Reduce soil compaction	Increase ability of air and water and roots to move through the soil.	May have some small effect because of yield increase and therefore increased root growth and hence residue return
Cover crops	Improve soils structure due to return of residue, and reduce risk of nutrient and soil loss over the winter period.	Possible return of residue
Shallow ploughing	Reduce risk of water loss for droughted soils, but may lead to compaction over time.	
Spring cultivation	Reduce risk of nutrient and soil loss over winter period.	
Contour ploughing	Reduce risk of nutrient and soil loss over.	

Therefore, while sustainable soil management approaches have potential for reducing climate impacts, their uptake requires these barriers to be addressed. These are likely to go beyond information and awareness raising, though there are obvious opportunities to provide additional incentives through revision of the current farm payment schemes.

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