Assessing the preparedness of England's natural resources for a changing climate: Assessing the type and level of adaptation action required to address climate risks in the 'vulnerability hotspots'

SRUC

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Final report

July 2013

Executive Summary

Climate change is expected to have significant impacts on the stock of England's natural resources, yet the overall picture on these impacts is surprisingly under-researched in terms of the comparative magnitude of impacts on different categories of resources and the likely returns to appropriate adaptation interventions.

This report considers climate impacts on a set of resource categories of interest to the UK Adaptation Sub-Committee (ASC) in terms of their perceived contribution to the provision of ecosystem services, and identifies a number of corresponding no-or low-regrets adaptation options that can be subject to economic appraisal. The study was also asked to consider adaptations with long lead times where action might be required in the next five years. This analysis compares notional adaptation costs with anticipated benefits, the latter arising over the time horizons up to 2100. The decision making perspective is largely public, implying that costs and benefits are assumed to be economic rather than financial values. Key sectors considered are agriculture (including a variety of plant and animal impact subcategories and water/soil management), forestry, biodiversity conservation (protected areas), peatland (restoration), and coastal zone management (managed realignment).

No- regret or low-regrets is one of several criteria used to define 'robust decision-making', together with flexibility/reversibility; including safety margins, soft strategies and reduced decision time horizons. Low-regret measures have minimal negative trade-offs, and that are sensible across a range of future climate change scenarios. Low-regret actions should also be cost-beneficial or cost-effective, which is what this project sets out to explore. These criteria are more clearly identifiable and applicable in some contexts (e.g. crop or animal disease surveillance) than in others (e.g. on- farm water storage reservoirs). The low-regrets, long lead time rationale is outlined in further later in the report.

The challenges faced with *ex ante* cost-benefit analysis are typically around the nature of uncertain future payoffs, and these are amplified in the context of adaptation where the benefits are the anticipated avoided damage impacts. Estimating these impacts requires the integration of downscaled climate information, with impact and vulnerability assessments and credible monetary valuation of potential damages.

The analysis in this project was initially to be informed by the output of a sister project[1] that aimed to use existing data sets to identify and characterise priority areas or 'hotspots' in England, which were defined in terms of acute vulnerabilities to specific resource categories . The spatial extent of these hotspots was intended to provide a basis for aggregating both impact costs and adaptation benefits. Timing discrepancies between the two projects ultimately prevented these linkages.

[1] Environmental Change Institute et al. (2013) for the Adaptation Sub-Committee.

Each impact category presented specific information challenges, largely related to the patchy scientific evidence on one or more stages of the integration of information for impact valuation. In some cases however, the nature of specific adaptations were contested, either on the basis of scientific evidence on 'adaptation effectiveness', or more mundane data gaps on the cost of measure implementation and its spatial applicability for 'scaling up'. More generally, impact assessment was hampered by a clear view of how alternative climate signals lead to precise and distinct impacts that could be valued. With current scientific data it is generally not possible to be completely precise about the scope of damages, reinforcing the requirement for robust adaptation actions. All that is possible is to provide illustrative examples for the cost-benefit comparison accompanied with reasonable sensitivity analysis.

Each report section provides a more complete rationale of why the category is either no/low regrets or has a long lead time, and more detailed analysis as well as the cost benefit analysis (CBA). Observations arising from the analysis are summarised as follows, and results are presented where possible in a summary table following the sectional summaries.

Peatland restoration

Peatlands are selected as a no regrets adaptation because of the range of ecosystem services that are delivered through conservation or restoration. There is a general consensus that existing levels of degradation impair the flow of many ecosystem services from peatlands and that climate change is likely to increase degradation pressures across much of the existing upland area of blanket bog. Equally, there is consensus that restoration activities have the potential to reinstate at least some impaired ecosystem services and to delay if not halt the onset of climate-induced degradation. Yet quantification of both the ease (cost) with which and the degree (effectiveness) to which ecosystem services can be reinstated through restoration is difficult and contested. Equally, estimating the relative rates of climate-induced degradation with and without restoration is challenging due to confounding factors and time-lags.

Analytically, demonstrating the economic case for restoration rests on being able to quantify and value the relative flows of ecosystem services arising from degraded and from restored sites under climate change scenarios, which in turn rests on the availability of data to describe the biophysical differences and costs of different management activities. Given the general absence of such data and continuing uncertainty over current and future rates of degradation (including emission losses), definitive cost-benefit analysis of peatland restoration is not currently possible.

Nevertheless, results from a simple simulation model illustrate a possible joint distribution of costs and effects and show that a case for restoration may be made – but not uniformly or universally. Results are sensitive to assumed costs – including opportunity costs – and to assumed differences in service flows from restored and unrestored sites. Such illustrative results may serve to focus scrutiny on the robustness of assumptions and the heterogeneity of peatland sites, plus to guide policy attention to the likely conditions required to make restoration a worthwhile activity.

Coastal managed re alignment

Managing coastlines adapt to inundation risks can have a range of ancillary costs and benefits that in some circumstances qualify measures as low regrets. But analysis demonstrates how similar to peatland restoration, a number of variables can drive the efficiency of managed realignment (MR) of coastal defences relative to holding the line against tidal inundation or taking no active intervention. There is significant potential for implementing schemes but their efficiency is largely dependent on both scale and location-specific conditions, including installation costs, topography, existing habitats, land values , which are in turn driven by land uses (either agricultural or residential). The area of target habitat created under managed realignment at a particular stretch of coastline is a key indicator of the (economic) efficiency of schemes . These analytical permutations complicate our ability to generalise about the economic efficiency of this adaptation.

To investigate this further, a schematic analysis of hypothetical MR schemes was conducted, varying the area inundated under managed realignment while keeping the length of defences before and after scheme implementation constant at 1km. A second analysis allowed for built residential property to be affected by the scheme, varying the number and value of affected dwellings. In both cases, the hypothetical managed realignment schemes were compared to holding the line. While the results need to be interpreted carefully due to their sensitivity regarding assumptions about costs of constructing and replacing defences and defence length before and after managed realignment, some useful insights can be gained. First, smaller managed realignment schemes may not be economically efficient even if opportunity costs related to income foregone from agricultural land use and maintenance costs are low. Thus, smaller schemes should be particularly scrutinised in terms of economic impacts in the planning phase. Second, the present value of agricultural land being inundated as a consequence of managed realignment has a moderate impact on the size of the scheme required to prefer managed realignment over holding the line. In other words, opportunity costs related to income forgone from agricultural land use are an important but insufficient indicator of economic efficiency. Other indicators are environmental benefits, reduced construction costs (and replacement costs) of realigned defences and reduced maintenance costs. Third, inclusion of built residential property results in positive net present values only for very large managed realignment schemes relative to the length of the initial coastline. This indicates that MR schemes call for careful investigation of economic welfare impacts if a scheme affects residential property.

Protected areas and biodiversity

For biodiversity and protected areas the aim of adaptation is to ensure protected area resilience against climate impacts. Resilience is likely to be higher where sites (designated sites of special scientific interest (SSSIs)) are in favourable condition. Adaptation should therefore be initially focussed on sites in unfavourable condition since such sites are more vulnerable to change associated with climate change. The benefits of adaptation would then be in terms of the immediate improvement in the sites and increased resilience against on-going and future impacts, i.e. current flows of benefits are increased and future flows are safeguarded. Clearly there is an associated need to ensure that sites currently in favourable condition do not lose their favourable status, but the rationale for initially focussing on unfavourable sites, is that the favourable sites would be expected to be more resilient to climate driven impacts and hence the unfavourable sites are a higher priority for action.

The number of different habitat types combined with the variety of site locations including their condition and extent and the variety of potential adaptation actions means that there is not a simple set of adaptation measures for which costs and benefits can be assessed. A spreadsheet model was developed to allow users to select combinations of habitats, their spatial extent and adaptation measures.

A worked example considers lowland calcareous grassland in the South East of England. We assume that 20 years of restoration activity will delay the onset of climate related degradation by 60 years and that subsequent degradation takes 100 years (both assumptions can be altered for sensitivity analysis). We find that the present value of the benefits of restoring 25% of the 4686ha currently in unfavourable condition come to £40.3m which compares to present value costs of £3.3m.

The spreadsheet model assumes a counterfactual of no adaptation or management measures; but there is existing management in place for SSSIs, which form the UK's contribution to the wider European Natura 2000 network. The Government's Biodiversity Strategy for 2020[2] requires that 50% of SSSI sites in England will be in favourable condition and 95% of sites will be in either favourable or recovering condition. In addition, there is an obligation on the UK to maintain priority habitats and species associated with the Natura 2000 network. Consequently, actions that will help to achieve adaptation should be taking place. Our model together with information on vulnerability can be of use in selecting habitat types, extent (the strategy refers to sites not area) and location that could be targeted to optimise the adaptation benefits whilst meeting the Biodiversity Strategy.

An important element that is not captured in the spreadsheet model is the context of habitats within a wider landscape and how these interact to support biodiversity and a range of other ecosystem services. These should be considered when developing scenarios for adaptation at landscape or regional scales.

Crop diseases

Disease surveillance qualifies as low/no regrets since detection of climate-driven threats may well be an outcome of existing or slightly modified best-practice or surveillance activities. The section on crop disease assesses a broad range of potential adaptations for reducing the future impact of two diseases on winter wheat. The analysis initially calculates the future area suitable for the two diseases, using climate envelope mapping, and then estimates the impact of the adaptations in terms of the avoided damage per hectare. Benefits of these adaptations all outweigh the costs over the time period, with Net Present Values (NPV) ranging from £0.8m to £12.3m. The two diseases considered in this analysis are in fact likely to decline over the period considered as the changing climate will no longer be suitable for them, but this analysis shows that even with a decline in severity due to climate change, management measures are still cost-beneficial. This would suggest that NPVs would be even higher for

[2] https://www.gov.uk/government/publications/biodiversity-2020-a-strategy-for-england-s-wildlife-and-ecosystem-services

diseases that are likely to increase with climate change. This analysis only covers two diseases, and it is likely that other diseases will emerge while others may decrease in significance. It is therefore difficult to estimate a definitive value for crop disease - but this section has highlighted some of the adaptations available and illustrated their economic value.

Animal disease

The animal disease section assesses the costs of increasing the current disease scanning surveillance programme to improve detection time of exotic disease incursions. The benefits are calculated as the avoided damage incurred from a disease outbreak, based on current disease outbreak costs and assuming an increase in disease outbreaks under climate change. The costs assume a 100% increase in scanning surveillance costs above baseline levels, as well as increases in import testing, targeted surveillance for specific exotic pathogens, and infrastructure costs. The results and sensitivity analysis indicate positive NPVs across the majority of possible parameter values, with potential for a very high return. As climate change is already leading to new and exotic diseases arriving in the UK, it would seem prudent to increase surveillance and awareness to detect these in the near future, as well as ensure that control strategies are up to date and effective.

Intensive livestock systems: transportation

The section on transport systems in the pig and poultry sector considers the costs of moving to mechanically ventilated vehicles as an adaptation against rising temperatures under climate change, and the associated mortality and meat quality costs. Mortality and meat quality impacts are estimated in relation to threshold temperatures in existing literature. This impact is perhaps one of the only cases where there is a more reliable link between climate scenarios and impacts. The costs of new and replacement vehicles are calculated at current prices. This adaptation also generated a positive NPV so would be worth undertaking. While purchasing new vehicles does not have a long lead time and could in principle be undertaken at any time, the replacement of an entire fleet of vehicles does have a large upfront cost so transport firms would be wise to consider planning financially in advance for this adaptation.

Livestock system losses – dairy cattle and heat stress

Livestock will be directly exposed to increasing thermal challenges with negative impacts on productivity, health and fertility, with one of the main challenges being heat stress from increasing temperature or/and humidity. Currently dairy cows do not experience heat stress under normal English climatic conditions. We show that losses from systems that house dairy cows will begin to be significant by the middle of this century, with present value damages up to £3.34 billion over the century (high emissions scenario). However, most of these losses could be offset by relatively simple changes to animal management systems, e.g., moving cows outdoors during heat stress periods, increased health and fertility management as a climate adaptation. As heat stress is not currently a common event for English livestock systems there is likely to be a need for targeted knowledge transfer or education on the impacts of climate and weather on animals and livestock systems. Also on the best ways of overcoming them, including animal management options but also buildings/system design specifications for consideration at times of capital reinvestment in the systems. Further research on the other climate change impacts and adaptations for all livestock systems is required to map out the most coherent and integrated adaptations for English livestock production.

Soil management

Six adaptations on a number of different crops are considered for soil management. This section proved particularly challenging among the adaptive management options because of a lack of evidence on the relationships between climate change and yield, soil health, and in particular soil organic matter. Furthermore, where there may be localised evidence, this does not necessarily scale up to the regional or national level due to other influencing factors – including local weather conditions, soil type, topography, as well as crop management. Given these caveats, and the fact that the visual soil assessment methods are related to crop production, yield was used as a proxy for soil fertility, and the adaptations chosen were selected for their expected effect on improving soil quality. Under these assumptions, all the adaptations analysed (with one exception) generate positive NPVs, some large (up to £1744m for winter wheat compacted soils). None of these adaptations require long lead times and all have positive ancillary benefits. But the challenge will be to encourage farmers to adopt them. Further research is required to provide evidence for the relationships as discussed above.

Agricultural water use

Water adaptation focusses specifically on agricultural use and initially considered one supply side option of on–farm reservoirs, and several demand side options including alternative irrigation technologies, (trickle versus spray), potential alternatives for crop cover to prevent water loss from soil, and crop switching (drought tolerance). Use of market-based approaches (i.e. water pricing and tradable abstraction permits) was not considered in this report. For the illustrative analysis the demand side measures were ruled out due to a lack of evidence on their low regrets potential. This was particularly surprising in the case of irrigation technologies applied to high value crop potatoes, which showed no significant water saving. At best, these technologies return a modest cost saving on energy use (thus emissions) so could be low regrets. Appraisal of crop cover and switching (to drought resistant varieties), was handicapped due to our inability to develop meaningful scenarios on the type of crops, their schedule for development (through private or perhaps public research and development (R&D)) and the likely uptake.

On-farm reservoirs save on abstraction costs in the summer (as winter abstraction costs to fill reservoirs are much lower) and provide farmers an option value on their own secure supply. But farmers must incur significant up-front construction costs, while the social benefits of reservoirs in terms of reduced abstraction externalities, accrue more widely and possibly over a longer time span. Illustrative examples take an economic perspective to compare private costs to social benefits for 100 years. These show impressive NPVs for installations of varying capacity. But it is important to interpret this result with reference to private investment time horizons likely to be adopted by farmers. From this perspective, public benefits are not considered in decision making and crop returns are more relevant. This private perspective can make installation returns more marginal. Hence, an important consideration in the context of reservoirs concerns the reasons why the adaptation is important; i.e. a private benefit, a social benefit or some combination. There is some convergence of rationales in that prior to making such investments, farmers may also be logically comparing installation costs with costs for continued river abstraction. Until the latter increase, the autonomous uptake of reservoirs is likely to be retarded. Hence a more rational adaptation in the meantime might ultimately reside in better demand side measures.

Forestry

The forestry analysis identified a number of adaptations but eventually considered two for further analysis: planting different species and developing new cultivars more suited to the future climate. The forestry sector has long rotations and therefore adaptations do often have long lead times. Robust adaptations are crucial in this sector as identifying species for a particular climate that may not eventuate could have very negative impacts on the sector. Both the avoided damages (benefits) and effects of the adaptations were calculated from existing literature, constraining the choice of adaptation options and assumptions. Both the adaptations considered generate positive NPVs when considered out to the end of the century. While benefits are mostly observed in the second half of the century, the research to develop new cultivars needs to be put in place now.

Results and general observations

Indicative NPVs for the sectors are summarised in Table E1. The analysis makes no *a priori* assumptions about the relative importance of the sub sectors, but there is clearly a potentially significant indicator in terms of the relative magnitude of likely impacts under climate change. We are unaware of any similar studies outlining rates of return to adaptation measures, even in more routine engineering (i.e. less biologically complex) sectors such as the built environment. The table also indicates limitations on the estimates and it is important to exercise caution in their interpretation at this point. Data gaps in relation to both costs and benefits render the estimates more contestable in some cases.

Each section in this report outlines the methodological challenges, assumptions and data sources used to calculate these values . The process of undertaking this study and the indicative results highlight a need to narrow down specific sectoral data gaps, and also highlights a methodological requirement for more practical examples implementing alternative or supplementary methodologies to cost-benefit analysis, including real options analysis, portfolio analysis, robust decision making and iterative adaptive management. The pros and cons of these alternative methods were not considered within this project.

Table E1: Summary NPVs for each sector (where possible) calculated to 2100

Sector	NPV (£m)	Comments
Peatland		Site and assumption specific
Managed realignment		Entirely site-specific. Spread sheet model allows NPV to be calculated once site-specific

		data has been entered.
Protected areas	37	For the South East Region of England
Crop disease	1.1-12	A range of 8 different adaptation options - covering wheat at the national level
Animal disease (exotic incursions)	1280 (median value)	National (England) level. Potential benefit is very assumption specific; see figure 14 for a full range of values.
Transport	36	National level
Animal productivity	0.82 – 3279	National level
Soil management	-122 – 1744	A range of 6 different adaptation options – covering a range of crops
Water	1 – 21	Covers a range of water storage capacities
Forestry	222 – 470	National level

Contents

1 Introduction & background

This report develops an understanding of the actions that will make the natural environment, agriculture and forestry sectors in England more resilient to climate change. These sectors combine the natural capital stocks that provide flows of ecosystem services identified and quantified in the National Ecosystem Assessment[3] that will be challenged by climate change, and it is important to identify low- or no-cost adaptation options in the near term, as well as those adaptations that have long lead times where planning would need to begin in the next five years.

The Climate Change Risk Assessment (CCRA 2012) identified a number of biophysical impacts that are likely to affect the continued provision of these ecosystem services, affecting not only the natural environment itself, but the economy and society more broadly. To minimise the damage, and to take advantage of any potential opportunities from climate change, it will be necessary to put in place processes of adaptation to the impacts, and in some cases make transformational changes to the way natural resources including land are used (Park et al. (2011). Previous work (e.g. Moran et al. 2009; Morecroft et al. 2012) has identified a long list of possible adaptations for the natural resource, agriculture and forestry sectors, but not all of these will meet the criteria of 'low regrets' which are broadly defined as measures that are beneficial or which make stakeholders no worse off, whatever the climate outcome. The ASC specified that adaptations considered for analysis were either to be low-regrets, or have long lead times where action would need to begin in the next five years. This project therefore narrows the list of possible options down to those that meet these low-regrets or long lead time criteria, and then undertakes an economic appraisal of these adaptation measures where possible under alternative climate scenarios.

Economic analyses of adaptation are particularly challenging because they are typically *ex ante* appraisals, comparing the costs and benefits of adapting to uncertain events. In this context these comprise the private costs (including opportunity costs) and potential social (or public) costs of measure implementation. These adaptation costs, which can be delineated further as private or public sector expenses, then need to be considered relative to future benefits, where the latter are the best picture of future impact or 'endpoint' damages to be avoided. Appraisal uncertainly in this context includes the spatial and temporal heterogeneity of both measure costs (particularly ancillary impacts) and the magnitude and value of benefits. This level of uncertainty is typically not confronted in normal government appraisals and can be explored using sensitivity analysis.

While basic adaptation appraisal guidelines have been drafted[4], specific sector applications are rare, particularly in the natural environment sector. An application to the natural environment, agriculture and forestry sector is particularly challenging because much of the endpoint impact is non-market in

[3] Service categories being supporting , regulating, provisioning and cultural http://webarchive.nationalarchives.gov.uk/20130123162956/http://uknea.unep-wcmc.org/Resources/tabid/82/Default.aspx

[4] http://www.ukcip.org.uk/wordpress/wp-content/PDFs/Costings_Implementation.pdf

nature and because of the extent of ancillary impacts[5]. This means that this project needs to undertake careful interpretation and use of non-market value information (e.g. from the UK National Ecosystem Assessment, NEA 2011). Elsewhere, the assessment of adaptation responses requires insights into other sectors (e.g. the implementation of water pricing).

1.1 Climate impacts on the natural environment

The UK Climate Change Risk Assessment (CCRA), published in January 2012, provides an assessment of the magnitude and timing of impacts caused by changes in climatic conditions, variability and extremes in the UK. It also provides an indication of the levels of certainty in relation to the predicted impacts.

The work focuses on risks and opportunities in five 'themes': agriculture and forestry, built environment and infrastructure, business and services, health and wellbeing, and the natural environment. The following key messages were highlighted:

1. The global climate is changing and warming will continue over the next century. The UK will experience increases in summer and winter temperatures, increases in winter rainfall, decrease in summer rainfall, more intense rainfall events and sea-level rise.

2. The UK is already vulnerable to extreme weather, including flooding and heat waves.

3. Flood risk is projected to increase significantly across the UK.

4. UK water resources are projected to come under increased pressure.

5. There are health benefits as well as threats related to climate change, affecting the most vulnerable groups in our society (e.g. premature deaths due to cold winters will decrease while premature death due to heat waves is likely to increase)

6. Sensitive ecosystems are likely to come under increasing pressure.

7. Potential climate risks in other parts of the world are thought to be much greater than those directly affecting the UK, but could have a significant indirect impact here (e.g. migration and changes in the geographical spread of diseases).

8. Some changes projected for the UK as a result of climate change could provide opportunities for agriculture and other businesses, although not outweighing the threats.

9. Despite the uncertainties related to future climate change and its impacts, the evidence is now sufficient to identify a range of possible outcomes that can inform adaptation policies and planning.

10. Significant gaps in evidence still exist.

[5] Wider implications of greenhouse gas mitigation measures in English agriculture - Defra AC0226

Following from the CCRA, the Economics of Climate Resilience (ECR 2013) project was established to develop a framework to assess the economic case for adaptation in the UK. The aim of the project is to assess the extent to which individuals and organisations are likely to adapt to climate change effectively and whether further action by government, other organisations, or individuals is needed. The analysis investigates current and likely adaptation actions and identifies the key barriers and enablers to actions being implemented widely, effectively; in a timely way, and proportionate to the challenges facing the UK. The project will inform the National Adaptation Programme, which is due to be published in July 2013.

1.2 Criteria for measure selection

Adaptation in the natural environment can be divided into two distinct categories of actions, first a broad category of planned or unplanned (i.e. climate-induced) **land-use changes**, and second, changes to **management regimes** including timing of agricultural practices and improving disease surveillance. Low or no-regrets' adaptation and long lead-time actions can be identified within both these categories.

An example of the latter are breeding programs for animals and plants that might require long lead times in term of research and development by both private and public sectors. Low-regrets actions will provide benefits regardless of how the climate evolves; removing the need to wait for improved climate information. Low-regrets is one of several criteria used in 'robust decision-making', together with flexibility/reversibility; including safety margins; soft strategies and reduced decision time horizons (Hallegatte 2009).

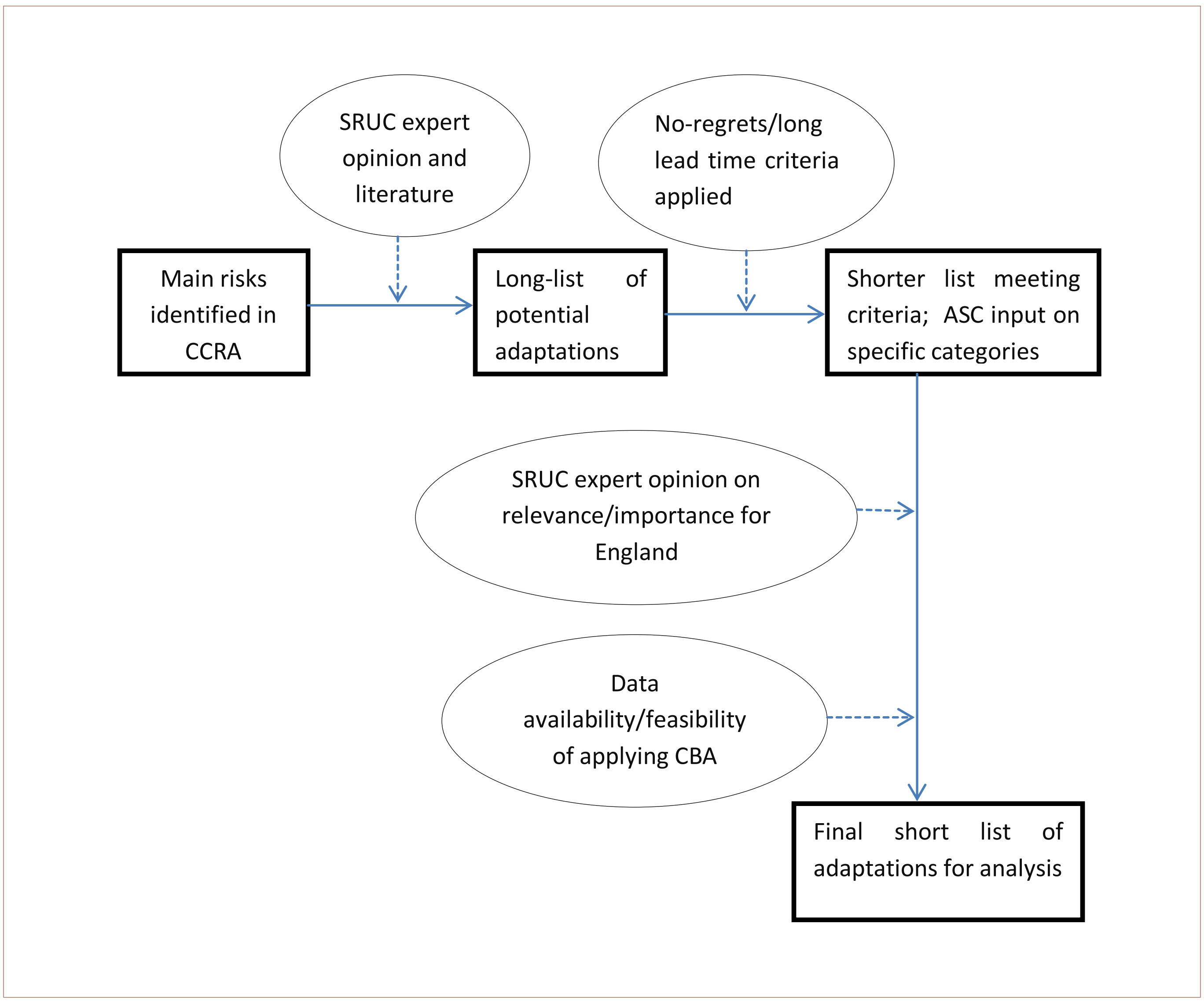
1.3 Reasoning behind adaptations selected for further analysis.

Identification of adaptation options for analysis drew on a combination of sources. In the first instance, the CCRA provided the main climate risks likely to be faced by England for the natural environment sector. . The risks that were identified as being either high or medium risk in the by 2020 or 2050 were prioritised. Following consultation with SRUC experts and a wider literature review, this list was amended with some categories of risk added. For example, SRUC experts considered the risks to livestock production from diseases and increasing temperatures to be greater than were indicated in the CCRA.

This list of main risks was then used to identify a range of possible corresponding adaptation options. Adaptations were identified from literature as well as the expert opinion of the project team. Adaptation is highly site-specific and the vulnerability of a particular area or sector is a function of the interactions between exposure (i.e. the extent to which the system is exposed to the climate risks identified), its sensitivity to the risks or impacts, and its adaptive capacity. While one area or system may be highly vulnerable to the climate impacts due to the aforementioned factors (exposure, sensitivity and adaptive capacity), another area may be relatively resilient to these risks. Therefore a "one size fits all" approach to adaptation is often misleading. Bearing this in mind, a range of adaptations that could generally be adopted in order to address each climate risk was identified. These main climate impacts and broad adaptation categories are shown in Table 1.

The low or no-regrets and lead-time criteria were then applied to the list of adaptation options in order to derive a shorter, more specific list of adaptations to take forward for further analysis. This shorter list was then screened further in conjunction with SRUC experts as well as the project steering group of the ASC to develop a final list of adaptations. This last stage of screening considered the relevance of the adaptations to England, their proven effectiveness, as well as the feasibility of conducting a CBA on them considering both the nature of the adaptation as well as the availability of data. At this point also, the preferences of the ASC were made clear in terms of pre-specifying its interest in peatland restoration and managed realignment. The latter could be clearly interpreted as providing potential low regrets returns. The former was initially more debateable but ultimately accepted as an option linking adaptation with socially beneficial ecosystem services such as water quality, flood control, biodiversity and emissions mitigation. Figure 1 illustrates the process followed from identification of main climate risks through to the final list of adaptations taken forward for further analysis. Further detail and rationale on the choice of adaptations finally selected are provided in each section.

Figure 1: Illustrating the process of adaptation identification



Climate risk	Adaptation category
Agriculture	
Increase in water demand for crop irrigation	Water demand and supply side measures
Number of unsustainable water abstractions	Water demand and supply side measures
Drier soils	Irrigation, cover crops, minimum tillage / shallow ploughing
Flood risk to high quality agricultural land	Managed realignment/holding the line
Heat stress to animals	Animal husbandry and transport; selective breeding and genetics
Crop pests and diseases	Disease surveillance
Animal diseases	Disease surveillance
Biodiversity and ecosystem services	
Species unable to track changing 'climate space'	Habitat enhancement and connectivity
Changes in species' migration patterns	Habitat connectivity to some degree
Biodiversity risks due to warmer rivers and lakes	Water cooling (riparian shading)
Risks to species and habitats due to coastal evolution	Managed realignment due for inter-tidal habitats
Risks to coastal habitats due to flooding	Managed realignment
Generalist species more able to adapt than specialists	Habitat enhancement and connectivity to some extent
Risk of pests to biodiversity	Disease surveillance
Risk of diseases to biodiversity	Disease surveillance
Changes in soil organic carbon	Peatland restoration

Risk to species and habitats due to drier soils	Peatland restoration, soil management (agriculture)
Wildfires due to warmer and drier conditions	Peatland restoration
Forestry	
Forest extent affected by red band needle blight	Disease surveillance
Decline in potential yield of beech trees in England	Management changes; species choice
Wildfires due to warmer and drier conditions	Management changes
Forest extent affected by green spruce aphid	Monitoring
Loss of productivity due to drought	Management changes; water supply and demand measures (from the agricultural sector)

Based on these risk categories and adaptation responses, the analysis in the remainder of this report is divided into the sections below. We briefly list the types of adaptations selected for further analysis, which are all assessed to be low-regrets or require planning for long lead-times now, and further detail is provided in each respective report section.

- Peatland – this section assesses the costs and benefits of peatland restoration measures (such as re-seeding of bare peat with sphagnum, blocking drains/gullies to raise water levels) and the cessation of activities causing degradation (such as heather burning, over-grazing and peat cutting).
- Coastal managed realignment – assesses the costs and benefits of coastal defences and counterfactuals of managed retreat involving impacts to land and buildings and the creation of ecosystems.
- Biodiversity and protected areas – the section explores the costs and benefits involved with adapting a number of different habitat types in different site locations – the complexity of these interactions means there is not a simple set of adaptation measures for which costs and benefits can be assessed.
- Crop disease – assesses the costs and benefits of a variety of adaptation options including increased disease surveillance, changes in sowing dates, new fungicide developments, disease resistant seed, precision agriculture, expert advice and breeding resistant cultivars.
- Livestock disease – assesses the costs and benefits of an increased surveillance programme.
- Intensive livestock transportation – assesses the costs and benefits of interventions combatting heat and water stress in broiler transport, such as increased ventilation and mechanical cooling.
- Dairy system losses – this section values the costs and benefits associated with the increased labour required to move animals in and out of shelter to address heat stress.

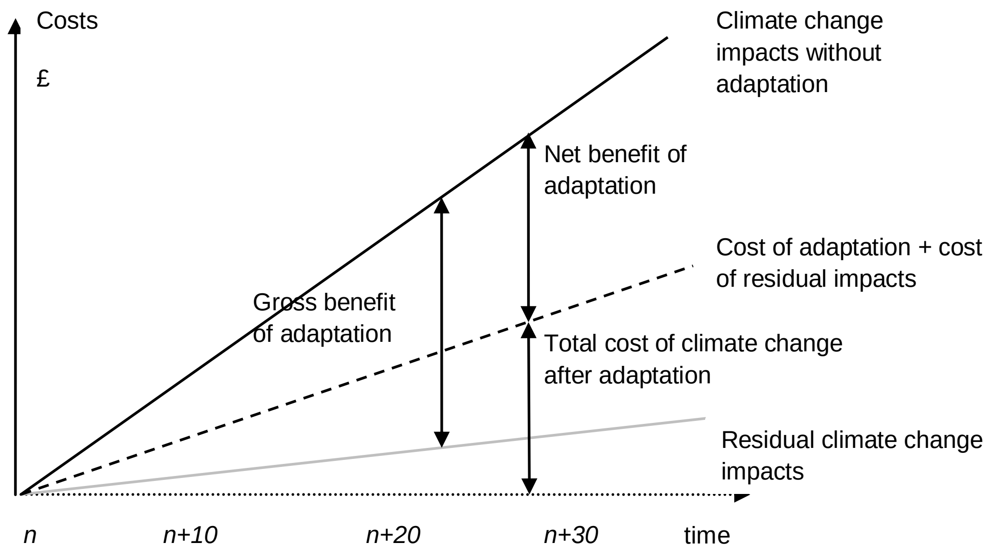
- Water management – assesses the costs and benefits associated with alternative water storage in on-farm reservoirs.
- Soil management – assesses the costs and benefits of a range of adaptation options including soil drainage, cover crops, shallow ploughing, spring cultivation, contour ploughing and dealing with compacted soils.
- Forestry – assesses the costs and benefits of restocking with varieties projected to have higher yields in the latter half of this century, and developing new species or subspecies more likely to be suited to the new climate.

1.4 Methodology

This analysis is an *ex ante* cost-benefit analysis (CBA), or in some cases, cost-effectiveness analysis. CBA is useful for comparing diverse impacts using a single metric. In this context it is most effective when climate risk probabilities are known, the climate sensitivity is likely to be small compared to the total costs and benefits, and when good quality data exists for the major cost and benefit components. Clearly these conditions will not always be met and it is questionable whether CBA is always the most effective tool. However, the analysis in this report presents a first step in quantifying the costs and benefits of adaptation. Cost-effectiveness analysis is also used in some sections of this report where benefit data are unavailable.

Figure 2 illustrates the role adaptation plays in reducing the impacts of climate change. The grey line represents the baseline or residual costs of climate impacts, even without future climate change. These costs generally increase over time due to increases in the value of vulnerable assets through increased income growth, and increased exposure. Adaptation is already occurring, in many cases without being named as adaptation, and this provides challenges in determining what a baseline is. The solid black line represents the costs over time as the climate changes. The dashed line illustrates the potential effect that adaptation actions can have on reducing the impacts over time. It is important to recognise that even once adaptation actions are put in place; it is unlikely that they will lead to complete elimination of any risk. We currently tolerate a certain level of weather-related damage: how much we tolerate is a societal judgement and will vary over time and between different societies, but in most cases adaptation will not reduce this to zero.

Figure 2: impacts, adaptation and residual impacts



The true benefits of adaptation are therefore the impacts of climate change minus the impact once the adaptation has been put in place (e.g. wheat yield under climate change minus the wheat yield following the adaptation, provides an estimate of the benefit of adaptation). Some impacts can be valued using market prices (e.g. the value of livestock or crop productivity), but most are non-market in nature (the potential loss of habitat or a decline in perceived recreational water quality). For each adaptation measure or combination, the analysis will need to be specific about the nature of impact and the data on current and future valuation.

It will usually be necessary to estimate the climate change impact initially in order to determine the effect that adaptation has had, but it should be noted that this report is not primarily about impacts, which were initially planned to be provided by a sister report that was initially tasked with defining climate hotspots.

Costs are estimated by calculating the one-off capital costs, variable costs, and opportunity costs, where appropriate. Where possible, specific alternative land uses will be specified to estimate foregone revenues or welfare flows.

Non-market costs and benefits can be valued using an existing willingness to pay (WTP) estimates derived using revealed and stated preference studies. More recent estimates are recorded in the UK National Ecosystem Assessment 2011[6], and the challenge here is to transfer these judiciously to reflect the climate damage and adaptation scenarios. This includes matching existing value estimates to likely damage cost scenarios, and decisions on how these values should change through time depending on the relative abundance or scarcity of environmental assets.

[6] Note the NEA has some significant gaps including in terms of e.g. animal health and welfare.

Both costs and benefits are characterised by levels of uncertainty pertaining to the nature and extent of future climate change impacts, measure cost, effectiveness, and adoption levels[7]. In the latter case, the technical effectiveness of any measure is contingent on the extent of its adoption by target groups. For example, water quality outcomes can only be technically effective if all farmers in a catchment adopt measures collectively and to a certain standard. Hence, uncertainty should be extended to overall adoption scenarios, which can be informed by emerging evidence on behavioural intentions and climate change adaptation and mitigation[8].

Costs and benefits are discounted at the social rate of time preference prescribed in the UK Treasury's Green Book (Green Book 2011) of 3.5% for 0-30 years and 3.0% for 31 – 75 years and 2.5% for 76 – 125 years.

It is important to note that CBA can give a misleading impression that adaptation can follow a series of discrete technical measures implemented to arrive at an 'adapted' state. In reality adaptation is an on-going iterative process. There will be some level of residual impacts, and in this project we use the expert opinion of our project team as well as expert opinions from those involved in the relevant stakeholders groups (e.g. NFU, RSPB, Natural England) to provide some ground-truthing of likely uptake and effectiveness to enable an assessment of the residual impacts to be made.

Where possible, two climate scenarios will be used: UKCP09 low emissions (P10) and high emissions (P90). More detail on the specific methods used for each adaptation category is provided in the relevant sections.

1.5 Report Outline

The remainder of this report is divided into 9 sector chapters, each providing sector background, climate risk information, and cost-benefit analysis. A final chapter summarises the main findings from the report, highlighting issues for consideration and directions for further research.

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[7] Note that we could potentially add policy uncertainty or more generally the uncertainty around underlying socio-economic storylines, which could include how planning guidance, Common Agricultural Policy and energy prices will change land use change.

[8] Much of what is known is being researched under SRUC's program of farmer and land manager advice Farming for a Better Climate http://www.sruc.ac.uk/farmingforabetterclimate

2 Land Use Change Measures

2.1 Assessing peatland restoration as an adaptive response to climate change.

2.1.1 Introduction

The restoration of damaged peatlands is currently attracting considerable research and policy interest. This reflects acknowledgement of the range of ecosystem services associated with functioning peatlands and the current widespread degradation of such services due to a combination of pollution, land management practices and climate change, with anticipated further climate change likely to exacerbate degradation pressures.

Although the evidence base is far from complete, restoration is generally anticipated to improve at least some ecosystem service flows. Moreover, the possibility that functioning peatlands are themselves able to adapt to climate change via biotic responses means that restoration benefits could be durable.

In particular, if restoration avoids on-going degradation-induced carbon losses from the peat store and possibly leads eventually to new carbon sequestration, then restoration has significant potential to help meet challenging greenhouse gas (GHG) emission reduction targets (e.g. Schaefer, 2009; NEA, 2010b, Moxey, 2011).

In addition, the potential effect of restoration on other ecosystem services means that it can also be viewed more broadly as an adaptive response. For example, protection and enhancement of upland habitats may assist the retention and movement of threatened species and biodiversity that would otherwise have less scope for adapting to climate pressures.

Equally, restoration may reduce the need for other adaptive measures to cope with the consequences of climate-induced changes to hydrological functions. For example, restoration may partially off-set and/or delay the need for downstream flood control and water treatment installations by lessening the effect of both continuous incremental degradation and more extreme rainfall events on peak flow rates and water contamination.

However, since restoration activities incur effort, the balance of costs and benefits needs to be considered in order to assess the net benefit to society. Notwithstanding considerable uncertainty about quantification of relationships and rates of change, this short report attempts to illustrate potential net benefits for restoration of blanket bog peatlands under climate change pressure in the English uplands. The results presented are subject to a number of caveats and serve primarily to highlight the circumstances under which restoration would be worthwhile and thus where further research to clarify relationships would be helpful.

2.1.2 Basis for assessment

Several recent review exercises helpfully summarise the state of peatlands in England, including current understanding of peatland degradation and restoration processes. For example, see reports by the IUCN (Bain et al., 2010; Labadz et al., 2010; Lunt et al., 2010., Worral et al., 2010), RSPB (Lindsey, 2010), Natural England (2010a) and the JNCC (2011). More detail on specific aspects of peatland functionality, degradation, restoration and climate change is offered by the wider literature (see section 6 Annex A), interpretation of which was aided by personal communications with a number of academic and practitioner experts (see Annex B).

Although drawing heavily on the literature and informed views of experts, the analytical approach adopted for this report – a spread sheet simulation model - necessarily invokes a number of simplifying assumptions.

The following sections outline data and assumptions used before some selected results are presented and discussed. Scope for further research is identified and some general conclusions drawn.

2.1.3 Degradation and restoration evidence

Efforts to map the area, depth and condition of UK peatlands are on-going. However, Natural England (2010a) reported the extent of blanket bog in England together with estimates of areas under different land covers and management practices. Although the categories are not mutually exclusive, the reported estimates indicate that out of a total area of c.355 000 ha only c.10k ha of blanket bog are undamaged or restored, leaving c.345k ha in a damaged state. More detailed assessments on sub-sets of the total area suggest that the condition of areas covered by Biodiversity Action Plans is declining slowly and that for designated/protected sites, such as Sites of Special Scientific Interest (SSSIs), only 58% is in favourable condition[9] (JNCC, 2011).

In an undamaged or near-natural condition, peatlands are capable of delivering a range of ecosystem services. Most notably, they can actively sequester and store atmospheric carbon plus can influence both the quality of and rate of flow of water downstream. They also serve as an important habitat for biodiversity Upland peatlands also have cultural value through recreational opportunities, preservation of archaeological artefacts, and sustaining rural traditions and communities (Haines-Young & Potschin, 2009; Eftec, 2009; Kimmel & Mander, 2010; Grand-Clement et al., 2013).

If damaged, for example through drainage and/or changes to vegetation cover through grazing, fertilisation or burning, the capacity of a peatland to deliver such ecosystem services is reduced. In particular, carbon sequestration may cease and stored carbon may be emitted back to the atmosphere as CO_2 and/or into water courses as DOC or POC[10], plus terrestrial and aquatic biodiversity may be reduced. Drainage and changes to vegetation cover may also alter hydrological relationships, affecting both base and peak flows of water downstream with possible implications for flood management.

[9] A reviewer suggests that, in addition to not relating to areas outside of designated sites, the assessment methodology for site condition may itself underestimate the degree of actual ecological damage.

[10] Respectively, Dissolved Organic Carbon (which turns water brown) and Particulate Organic Carbon (sedimentation), both of which can incur water treatment costs.

Unlike some other ecosystems, cessation of damaging activities is not necessarily sufficient to allow a damaged peatland to recover and further positive restoration action may also be required. For example, re-wetting by blocking drainage grips and re-vegetating bare peat. If undertaken properly, restoration is anticipated to recover at least some of the original ecosystem functionality over a period of time (Lunt et al., 2011).

However, the degree to which a restored site will equate to an undamaged site is uncertain. For example, although re-establishment of representative plant species within a period of five to ten years is widely reported, desired changes to GHG balances, wider biodiversity, water quality and hydrological functionality are harder to discern conclusively or consistently. This partly reflects time-lags in the system in that restoration is an on-going process and it may take decades for some functionality to recover and to be observable, plus full functionality may not necessarily be achieved (Lucchesea et al., 2010; Mills et al., 2010; JNCC, 2011; Grand-Clement et al., 2013). That is, insufficient time has passed to allow full interpretation of “success” or “restoration” of function.

It also partly reflects the conditionality of observed effects on not only the restoration undertaken but also confounding factors such as initial site conditions and size (e.g. extent & depth of peat), conditions on neighbouring sites and natural year-on-year variability. For example, different degrees of degradation vary in the ease with which they can be alleviated and severely damaged sites will be harder and take longer to restore than lightly damaged ones. Moreover, changes at a given site need to be viewed in the wider context of landscape mosaics and catchment or landscape scale hydrological and habitat linkages.

For example, even if restoration of a damaged site does raise base flow rates and lower peak flow rates[11], the relevance of this to (e.g.) flood management down-stream is affected by the flow contribution of the restored site relative to other parts of the catchment and the extent to which down-stream reaches of a river have been modified. Similarly, even if restoration does reduce the emission of DOC & POC into water courses[12], the impact at a catchment-scale depends on the relative contribution of that site against other parts of the catchment. Similarly, biodiversity gains may depend on circumstances and changes beyond the restoration site itself.[13]

Even in the case of carbon, there is conflicting evidence about the net effect of restoration on GHG emissions over short and longer-term periods – reflecting uncertainty over the emissions from both damaged sites and from restored sites. In particular, re-wetting can increase methane emissions and the time-taken for bog species to achieve peat-forming capability is uncertain, meaning that net emissions may increase for a while before probably decreasing subsequently. The intensity and

[11] This appears to be highly site-specific, with some sites responding but others not, possibly due to natural “pipes” forming below the surface but also due to variation across sites in terms of topography and the degree to which natural vegetation can slow surface run-off e.g. (Conway & Millar, 1960; Holden et al., 2005; Holden et al., 2006; Grayson et al., 2010; Holden et al, 2011; Wilson et al., 2010, 2011a & b; Ballard et al., 2012).

[12] Again, this appears to be highly site specific and confounded by rising DOC levels due to reduced sulphur pollution (Armstrong et al., 2012; Fenner et al., 2011; Turner, 2012).

[13] See, e.g., van Deineng et al., (2006); Carrol et al., (2011), Ramchunder et al., (2011, 2012), Watson et al. (2012).

duration of a methane “spike” is uncertain, as is the timing and long-term potential of sequestration (or at least protection of stored carbon). DOC & POC losses are similarly uncertain.

Consequently, despite the presentation of indicative emission factors (e.g. Natural England, 2010; Alonso et al., 2012), there is on-going effort to debate and refine emission factors that are acknowledged to vary between years at a given site as well as between sites (e.g. Bussel et al., 2010; Artz et al., 2010 & 2012). Indeed, Worral et al. (2011) stress the absence of reliable emission factors and Evans et al (2011) suggest a research programme (elements of which are now in place) to fill data gaps.

In summary, although there is a general consensus that restoration could recover at least some lost ecosystem service capacity, precise quantification of both the rate of recovery and the ultimate degree of recovery is subject to some uncertainty. A further complication is imposed by the need to consider climate change effects.

2.1.4 Peatlands and climate change

Upland blanket bogs are associated with cool and wet climatic conditions which maintain a high water table and inhibit decomposition. As such, predictions of warmer and drier climatic conditions may be expected to place existing peatlands under additional degradation pressures (Orr et al., 2008). Indeed bioclimatic envelope modelling of likely climate change suggests that many domestic (including most, if not all, of the English upland blanket bog area noted earlier) and international peatland sites will find themselves outside of their presumed comfort zone (Acreman et al., 2009; Clark et al., 2010; Gallego-Sala et al., 2010; Essl et al., 2012; Gallego-Sala & Prentice, 2012).

This is generally interpreted as likely to accelerate the degradation of already damaged sites by increasing the likelihood of peat drying-out and thus its proneness to oxidisation and colonisation by non-bog species. In addition, extreme rainfall events are likely to exacerbate erosion losses from bare peat, increasing the formation of gullies & haggs and increasing DOC & POC emissions. Quantification of such acceleration is difficult for complex and variable peatland ecosystems (e.g. Moore et al., 1998), with the existence of threshold effects and variation in local conditions both meaning that predictions need to be based on site-specific data. Agreed, definitive emission factors, or indeed rates of degradation for other ecosystem services, are not available – either with or without climate change effects.

Nevertheless, as a generalisation, it seems likely that more extreme climate change will induce more rapid degradation than modest climate change, both in terms of the speed with which a given site moves outside of its presumed bioclimatic envelope and the severity of particular climate pressures. Within this, the relative effect of climate change on undamaged or restored sites is also uncertain. That is, whilst a restored site is likely to resist climate-induced degradation better than an unrestored site, the magnitude and duration of any such differential is effectively unknown. That is, there are uncertainties in both the modelling of climate change and in the modelling of peatland responses to climate change.

A functioning peatland is itself potentially capable of adjusting to changing conditions and need not necessarily be adversely affected by warmer and drier conditions (Dise, 2009; Lindsey, 2010).

Specifically, paleoecological evidence from the peat archive stretching back c.9k years suggests that peatlands can not only survive but actually thrive under warmer and drier conditions. This may be due to subtle changes in the mix of peat-forming *Sphagnum* sub-species and/or altered rates of plant growth (e.g. Flanigan & Syed, 2011; Swanson, 2007; Lindsay, 2010; Waddington et al., 2011; Charman et al., 2012). Such biotic responses are not captured by current bioclimatic envelope models, the interpretations of which may thus be too pessimistic in their predictions of potential peatland decline.[14] Yet restored sites may not behave as pristine sites did historically.

However, even if restoration cannot prevent the eventual demise of a peatland it may still be of value in at least slowing the rate of subsequent degradation. Of course, if restoration recreates a functioning peatland capable of self-adjusting to climate pressures, benefits may be even more durable. Hence restoration merits consideration under either possibility. To do so, however, requires assessment of the economic value of ecosystem services retained and/or enhanced through restoration plus the economic costs of restoration efforts.

2.1.5 Restoration benefit values

Although there is an extensive literature on economic valuation of (what are now termed) ecosystem services, Wichtmann et al. (2013) note that economic valuations for ecosystem services associated with peatlands and peatland restoration are relatively scarce. Moreover, reported valuations often differ markedly, reflecting differences in methodologies but also the specific services and scenarios considered.

Conducting a bespoke valuation exercise was beyond the scope of this study. However, published "benefit transfer" guidelines facilitate the use of values from other studies. Possible candidate sources include upland reports by Eftec (2009 & 2010), the recent National Ecosystem Assessment (Bateman et al., 2011) and values for Biodiversity Action Plan impacts (Christie et al., 2011).

The use of valuation figures offers a convenient metric to allow comparisons across different ecosystem services. However, it is imperfect for a number of reasons. First, the values are not linked explicitly to biophysical measurement of changes in service flows – although given the absence of definitive data on these, the alternative is not clear. Second, valuation of headline services such as GHG emissions and water treatment are different to estimates derived by other means such as the DECC carbon prices. Third, the scenario descriptions underpinning values are not necessarily the same as those considered here in terms of in terms of peatland areas and changes to their condition - most notably, climate change and the possibility of post-restoration degradation are not generally considered. Fourth, projecting values forward over an extended time-frame ignores the effect of, for example, possible demographic and per capita income changes.

Nevertheless, Harlow et al. (2012) demonstrated the use of valuation estimates as applied to an upland catchment in Northern England, using detailed local data and expert judgements on land use changes. Two approaches were used, the first deployed values taken from Christie et al (2011) whilst the second

[14] Although it is important to note here that (e.g.) Clark et al. 2010 do not themselves state that rapid degradation and loss will necessarily occur, merely that the pressures on peatlands will increase.

combined values taken from Bateman et al (2011) together with DECC carbon prices and water treatment costs[15].

For the values taken from Christie et al (2011), aggregate values reported in the Biodiversity Action Plan (BAP) study were converted to per hectare values[16]. Two sets of values were derived. First, a value of +£136/ha/yr for enhancements delivered through restoration and -£275/ha/yr for losses imposed by degradation. This includes a broad range of ecosystem services.[17] Second, a value of +£94/ha/yr for enhancements and -£170/ha/yr for losses. This reflects a more conservative view of the ecosystem services affected, excluding flood management since there is some uncertainty around the impact of restoration on this. In both cases, the value of restoration comprises the "avoided loss" of further degradation plus the "enhancement gain" of improved site condition and thus ecosystem service delivery.

For values taken from Bateman et al (2011), a headline marginal valuation of £304/ha was arbitrarily split in two to give +£152/ha/yr for enhancements and -£152/ha/yr for degradation. These values were then combined with carbon values derived by combining published DECC unit carbon prices (low/central/high £/tCO_{2e} for non-traded carbon out to 2100, with values varying by year) with estimated changes in GHG emissions derived from the application of a biophysical model using site-specific data. The NEA valuations encompass a narrower range of ecosystem services than the BAP values.

2.1.6 Costs

The costs of restoring a damaged peatland site fall into three main categories, capital, subsequent monitoring/management and opportunity costs. Previous attempts to collate such costs have been hampered by variation in project circumstances and ambitions plus a lack of standardisation in the reporting of cost items (e.g. Holden et al., 2008; Bonnett et al., 2009). Nevertheless, it is possible to identify indicative ranges for costs likely to be incurred.

Capital costs

Capital costs relate to upfront investment such as dams for blocking drainage grips and gullies, re-vegetation of bare peat, clear-felling of trees and fencing for stock control. Precise costs will depend on site conditions and location – the more damaged and/or the more inaccessible/remote, the more expensive. For example, drainage grips vary in terms of their density per hectare (ha) and slope, with steeper slopes and higher densities requiring more dams. Similarly, the use of helicopters for inaccessible sites is very expensive whilst accessible sites prone to public access can incur health & safety expenditures.

[15] Although water treatment costs are not reported explicitly due to commercial confidentiality restrictions.
[16] This in itself invokes a number of assumptions including accuracy of area totals, uniformity of Willingness To Pay values across all sites and the validity of applying marginal unit values to large changes.
[17] Specifically: wild food; non-food products; climate regulation; flood risk management; sense of place; charismatic species; and non-charismatic species. Note the exclusion of provisioning services.

Holden et al. (2008) report capital costs varying between a few hundred and several thousand pounds per ha depending on site condition and accessibility plus the method, scale and ambition of restoration. Median capital costs are inferred as c.£880/ha[18] whilst Matthews (2012) reports typical capital costs of £1260/ha. These two values straddle a rule-of-thumb figure of £1000/ha reported by practitioners. This order of magnitude may be taken as a guide for the central value to use in broad-brush analysis that does not distinguish between different site conditions and restoration techniques.

Information within Holden et al (2008) can also be used to infer indicative costings at a more detailed level. For example: Stabilisation costs £88/ha to £1700/ha; (Gulley) Re-profiling costs £600/ha on average; Reseeding costs £90/ha to £900/ha; Planting costs £2700/ha on average; Gulley blocking costs £2500/km; Grip blocking costs £1000/km to £6500/km; Scrub clearance costs £400/ha to £3000/ha; Mowing (on-going management) costs of £128/ha to £200/ha; Vegetation removal (e.g. clear felling) costs £1000/ha to £10000/ha.

These specific techniques and costs may be applied to a site individually, but also in combination under headings of "vegetation management", "hydrological management" and "re-vegetation". Allowing for +/-50% in capital costs (as per Worral et al., 2009) and making some assumptions about management combinations suggests the following possibilities.

Re-vegetation (of bare peat) may entail one or more of: Stabilisation, Reseeding and replanting. This implies capital costs of £(88+90)=£178/ha to £(1700+900+ 4050)=£6650/ha, with an average of perhaps £4089/ha.

Hydrological management may entail grip blocking, gulley blocking and gulley reprofiling. Neglecting variation in the category of grip (i.e. its depth, width, slope & condition) and the intensity per ha, suggests figures of perhaps £300/ha to £1950/ha (although the latter probably includes gully re-profiling). Including gulley blocking and profiling would give figures of £(300+300+375) = £975/ha to £(1950+900+1125)=£3975, with an average of perhaps £2475/ha.

Vegetation management may entail removal of livestock (with zero capital cost), but also scrub clearance and vegetation removal. Hence capital costs might vary from £0 to £400/ha to £3000/ha for non-afforested sites, but £1000/ha to £5500/ha to £10000/ha for afforested sites.

All of the above values are merely indicative since they are drawn from a limited number of empirical observations that varied considerably in their scope and objectives as well as lacking an agreed methodology for recording and reporting costs. The estimates are also a little dated and "learning-by-doing" as restoration projects have continued may have led to unit costs reductions as techniques have been refined, but equally capacity constraints on skilled labour and specialist equipment may have raised unit costs. Moreover, combinations of individual activities have been inferred using various assumptions. Nevertheless, the figures are sufficient to reveal likely orders of magnitude and variation. Relative to the rule-of-thumb figure of £1000/ha (see para 33), it is apparent that some (difficult) sites

[18] They actually cite a median budget of £1600/ha, of which 55% is for capital works (see also Chapman et al., 2013).

will easily cost more but that less challenging sites would be accommodated at lower cost. Of course, any given site could itself encompass parcels of land with different characteristics and thus different restoration costs.

On-going monitoring & management

Once initial capital works have been completed, further, subsequent costs are incurred by the need for regular monitoring to check that a site is recovering as anticipated and to reveal any needs for repairing or supplementing capital items plus adjusting land management practices. For example, dams can fail or vegetation covers not develop as hoped. As with initial capital costs, monitoring & management costs can be hard to generalise since they will vary considerably with project scale and ambition, not to mention reliance on volunteers or land managers rather than salaried staff. Some on-going costs may not necessarily be incurred each and every year, but can be approximated as an annual cost.

Holden et al. (2008) suggest monitoring accounts for 10%-20% of budget costs, implying an annual figure of perhaps £16/ha to £32/ha[19] – although this may be skewed upwards by measurements of water quality. Matthews (2012) cites, albeit for Scottish raised bogs, figures of £600 per site for monitoring, implying around £26/ha/yr[20]. Matthews (2012) also cites on-going grazing management costs of £40/ha/yr, consistent with the use of agri-environment scheme payments as cost estimates in Natural England (undated) and Harlow et al. (2012). Again, these orders of magnitude may be taken as a guide for the central value to use in simulation modelling and sensitivity analysis, although the duration of on-going costs is as yet largely unknown.

Opportunity costs

Commercial activities such as farming, forestry and grouse shooting are undertaken across large parts of the English uplands. If peatland restoration displaces such activities it will impose opportunity costs in terms of lost provisioning services and private income. However, as with evidence for the effectiveness of restoration, the evidence for displacement effects is somewhat inconclusive due to complexity of the underlying relationships, time-lags between cause and effect and confounding variability across different sites and different years.

On-the-one-hand, measures such as burning, fertilisation/liming and drainage have historically (and often with policy encouragement) been undertaken with the explicit intent of improving land productivity in terms of commodity production. As such, it would perhaps be surprising if the reversal of such interventions did not have some negative impact on commercial activities. For example, lower sheep stocking rates due to reduced grazing values or lower grouse numbers due to reduced heather cover. Indeed, anecdotal accounts of such cases can be found. Yet evidence for the absence of negative impacts can also be found, for reasons that include the following.

[19] Again, taken as 10% - 20% of £1600/ha, spread-out over an assumed project life of ten years.

[20] As £450 per site for monitoring & maintain dams plus £150 per site for monitoring and managing scrub, with an average restorable area per site of 23ha.

First, the expected long-term productivity gains attributable to land improvement measures may have been exaggerated. Specifically, there is a limit to how much improvement can actually be achieved and sustained since diminishing marginal returns set in fairly rapidly and effects may be rather short-term. For example, grazing quality may perhaps (at some expense) be improved to support higher stocking levels, but equally can rapidly deteriorate again and lead to over-grazing and erosion problems (Wilson et al., 2013).

Second, in the case of upland grazing and forestry, much of the historical expansion was driven by policy support via subsidies and/or tax-breaks for not only improvement measures but also coupled production volumes. Subsequent policy changes mean that the incentives for commercial activities in the uplands have altered and thus whereas restoration might have been in conflict previously it is less likely to be so now. For example, stocking rates have already declined and new afforestation is extremely limited (Thomson, 2008 & 2011).

Third, restoration may actually bring some modest production benefits. For example: the grazing value of re-vegetated sites is higher than that of bare peat; wetter conditions improve the availability of water and invertebrates for chicks; and blocking grips removes a drowning hazard for sheep and chicks. Fears of increased peat and disease incidence arising from wetter conditions are being researched but do not seem to have been realised (Wilson et al., 2013). For example, many uplands sites are too cold and acid for liver flukes to become a problem (although climate change may alter this). As such, whilst not compatible with historical production intensities, restoration may be compatible with current (lower) intensities or even marginally higher production intensities. Moreover, shepherding and game-keeping play a useful role in on-going management and monitoring such that restoration sites benefit from retention of some provisioning activities.

Fourth, a peatland area will typically be characterised by spatial variation – a mosaic of land parcels. This suggests that the degree of any displacement of current activities will not be uniform and, potentially, that land managers may have scope for substituting between individual parcels of land to minimise overall displacement effects. Over time, displacement effects – and thus opportunity costs – may perhaps be reduced through adaptive management of both restoration and affected commercial activities.

For the purposes of this exercise, although higher values are also modelled, it is assumed that restoration is generally compatible with current upland agriculture and that opportunity costs will generally be zero[21]. This is on the basis that net and even gross margins for upland grazing enterprises are often negative and even in favourable years are only ever modest (Harvey & Scott, 2011; Nix, 2006 – 2012; SAC, 2006 – 2012). This is not to say that some farming operations could not be more adversely affected (and higher costs are considered below), particularly where improved grassland cover has been

[21] This assumes that returns to upland livestock farming will remain low into the future, whereas it is possible that food prices and/or policy incentives and/or system-wide effects of climate change could increase returns. More immediately, it also assumes that RPA farm inspections will not rule some elements of restored bogs (e.g. open pools) as permanently ineligible features and thus excluded from receipt of the single farm payment – if they did, farmers' opportunity costs would rise.

established, merely that on average the displacement effect of restoration will be limited. By contrast, Morris et al. (2010) note relatively high opportunity costs for lowland peats, reflecting the higher intensity of production on such sites (which may also apply to cultivated land and temporary or improved grassland here too).

For grouse shooting, the absence of routinely published and standardised performance figures means that the opportunity costs of partial or total displacement are harder to infer. Rotational burning is a traditional management practice but effects on peatland condition and, for example, carbon emission or DOC levels are uncertain. Equally, the effects of (e.g.) rewetting and reducing/halting burning on grouse populations and subsequent shooting revenues are also controversial. Scientific understanding of such relationships is imperfect and hindered by both inter-year and inter-site variability (Grant et al., 2012).

Figures for the net margin of grouse shooting on a per hectare basis are not readily available. Variation in per hectare values is likely to reflect structural and management differences across different shooting estates in terms of (e.g.) intensity of shooting and number of birds bagged, yet (as with upland grazing) many enterprises apparently run at a loss (FAI, 2010). As such, indicative opportunity costs can at best be considered as a range.

On a per ha basis, grouse bags vary year-on-year but a figure of 0.4/ha may be reasonable in England.[22] FAI (2010) report that the fee per brace varies over time and also according to the type of shooting (driven, walking, over-pointer) but a value of £15 to £65 per bird may be reasonable. If restoration led to complete displacement, this implies an opportunity (revenue) cost of perhaps £6/ha to £26/ha per shoot, or £24/ha to £104/ha over a year. Alternatively, FAI (2010) analysis for Scotland implies a contribution to GDP of around £13/ha to £18/ha[23]. However, FAI results also imply c.£21.6k per FTE of employment supported by grouse shooting. Combining this with employment figures of 1520 cited by the Moorland Association suggests a GDP contribution of c.£33m[24] across c350k ha in England & Wales, again implying values approaching £100/ha.

For forestry, current guidelines discourage planting on peat and it is assumed here that restoration imposes no additional opportunity costs for new plantings. However, in contrast to the possibility of partial or zero displacement for grazing and shooting, restoration entailing the clear-felling of standing timber clearly imposes complete displacement of existing forestry. The opportunity cost that this represents in terms of timber income foregone will depend on how prematurely the trees are harvested and their anticipated remaining growth potential. If close to the planned harvest time and/or of a low yield-class, then foregone income may be minimised (Morrison, 2013). For example, current timber

[22] See http://www.gwct.org.uk/research__surveys/wildlife_surveys_and_ngc/national_gamebag_census_ngc/birds__summary_trends/230.asp

[23] Inferred from an estimated £7m contribution to GDP from responding estates with a total area of c.551k ha of which c.384k ha were heather cover. As with upland grazing, it is also apparent that grouse shooting operates at a loss in some years.

[24] The Moorland Association cites a figure of c.£70m, but this is for output or expenditure rather than value added. http://www.moorlandassociation.org/economics3.asp

prices[25] are c.£14/m^3 standing or c.£37/m^3 felled, implying that harvesting prematurely on yield class 10 would forgo perhaps £370/ha/yr on average, although this would decline the closer to maturity a stand was. There may also be opportunity costs in terms of disruption to other ecosystem services. For example, soil carbon stores will be disturbed, woodland habitat and biodiversity will be lost and the landscape will be altered[26] (Vanguelova et al., 2012), but such values are not considered explicitly here.

As a final consideration, upland areas also host recreational activities such as walking, mountain biking and wildlife watching. In principle, restoration could displace some of these activities if portions of sites become inaccessible and/or it is necessary to exclude visitors to protect certain areas. In practice, this is unlikely to affect large areas and/or could be mitigated by best practice in visitor management.[27] Moreover, biodiversity gains would be anticipated to increase visitor numbers. Hence it assumed that there are no net opportunity costs in terms of lost recreational opportunities.

In all cases, estimates of economic value added or net margins delivered by different land uses are only a partial measure of their local significance to rural economies where employment opportunities are often limited and/or traditions of upholding private property rights over land are cherished. Consequently the perceived or actual displacement of activities by restoration will be politically contentious in some places regardless of estimated aggregate impacts and engagement to acknowledge and/or accommodate local interests will be essential (Bullock & Collier, 2011; Bullock et al., 2012).

2.1.7 Previous studies

Explicit attempts to quantify the economic value of upland peatland restoration in the UK remain relatively scarce. For a catchment in the North Pennines, Worral et al (2009) used local data with a carbon model to estimate emissions under different management patterns and concluded that restoration was generally worthwhile for a range of carbon prices and cost assumptions over a medium-term time-horizon of 30 years (although they note the divergence between regulated market prices for carbon and the much lower voluntary carbon market prices, with the latter being insufficient to justify restoration).

Harlow et al (2012) also focused on a northern catchment, using a combination of non-market valuations, DECC carbon prices (using local data with a carbon model to estimate emission profiles) and water treatment costs to assess the benefits of restoration actions. Again, the study concluded that (over a 25 year time-horizon) restoration was worthwhile.

[25] See http://www.forestry.gov.uk/pdf/tpi201209.pdf/$FILE/tpi201209.pdf

[26] Although this may have positive as well as negative impacts, for example in terms of habitat edge effects for biodiversity.

[27] For example, through the use of boardwalks or even perhaps encouragement for the use of (e.g. Yowie) snowshoes.

Moxey (2011) used a far simpler approach[28] to conclude that, over a period of 20 years, the cost-effectiveness of restoration via grip-blocking was at least comparable to other GHG mitigation activities being promoted by current government policies.

More comprehensively, Natural England (2010a) reported the results of cost-benefit analysis (over a 40 year time-period) for restoration of different types of degraded sites at the national (England) level. The precise cost and efficacy assumptions underpinning the analysis are unknown, but the results suggest that most restoration options would be worthwhile under forecast (DECC) carbon prices. Subsequent refinement of the analysis (Natural England, 2010b) to apply discounting to the flow of future benefits altered the precise figures but not the conclusion.

With the exception of Harlow et al (2012), the supportive results in these studies were achieved without including values for non-GHG effects. Inclusion of such “ancillary” or “co-benefit” effects will increase the positive findings. Similarly, although none of the above studies considered the effect of climate change, it seems unlikely that extension of the analysis to consider climate change effects would alter the overall conclusions. That is, unless climate change increases the costs of restoration and/or reduces the efficacy of restoration, the overall pattern of results will be similar.

For example, despite the possibility of restoration offering durable effects, none of the studies considered time-horizons beyond 40 years, meaning that even if climate change were to reduce the longevity of restored sites any such curtailment would have to be very severe to overturn the cost-benefit results (i.e. limit any positive effects to a handful of years, which seems unlikely even under extreme climate change scenarios).

Similarly, although climate change may reduce the efficacy of restoration, climate change will also accelerate degradation and emission losses at unrestored sites. Consequently, unless the differential between restored and unrestored sites narrows significantly, restoration will still convey some relative emission savings.

The next section reports selected results from a spread sheet simulation model designed to explore interaction of the above factors with a range of other influences.

2.1.8 Some simple simulation results

Assessing the economic merits of peatland restoration requires basic information on rates of ecosystem service degradation (including, explicitly, emission losses) with and without restoration. These can be combined with unit values to estimate the aggregate difference in service flow values from restored and unrestored sites. Carbon can be valued using DECC carbon prices whilst other ecosystem services can be valued using results of various non-market valuation exercises. If information on how climate change affects the time-profile of service flows is available, this can be accommodated too.

To account for differing time-profiles, the value of service flows and of costs should be discounted back to give a Net Present Value (NPV), using standard discount rates (as per HMT Green Book guidance).

[28] Specifically, assuming a single "typical" cost of restoration and constant "typical" emission savings per hectare across an assumed total area

Choice of a time-horizon over which to discount values is somewhat arbitrary, but values of 20 to 40 years are used in other studies whilst 80 years would extend the time-horizon to approximately that used in bioclimatic envelope models.

Worral et al (2011) highlight the uncertainties surrounding emission factors, citing imperfect understanding of complex carbon pathways. Moreover, emission factors can be subject to interaction effects. For example, drainage and grazing may combine to increase emissions whilst drainage alone may reduce emissions. Artz et al (2012) and Smyth (2013) echo these points, noting the relative scarcity of long-term empirical measurements for many categories and the need for further monitoring.

Annual variation in emissions around "typical" values is also likely, and site-specific factors can exert considerable influence. For example, the level of (reduced) emissions achieved through restoration and the time taken to achieve them can vary depending on the initial conditions prior to restoration – it depends on what is being restored to what. In addition, the effects of climate change depend at least partially on threshold effects that are difficult to predict without knowledge of current localised conditions, notably proportionate bare peat coverage. Consequently, although refinement of emission factors is anticipated as current research activities and restoration projects report over the next few years (and revised IPCC guidance is published), current suggestions for emission factors vary somewhat – as illustrated in Table 2 below.

Table 2: Suggested emissions factors (t CO2e/ha/yr) for different peatland categories

Peatland/management type	NE (2010a)	Artz et al (2012)	Smyth (2013)
Cultivated & temporary grass	22.42	9.2 to 15	
Improved grassland	8.68		
Extracted	4.87		
Rotationally burnt	2.56		-0.7 to 2.4
Afforested	2.49	0.1 to 1.9	
Restored	2.78	-8.1 to 2.8	
Bare peat	0.06	0 to 5.5	31.0*
Gripped	-0.2	-0.05 to 3.9	2.8
Hagged and Gullied	-0.2		-0.7 to 31.0*
Overgrazed	0.1		-0.7 to -1.2
Undamaged	-4.11	-2.8 to -0.7	-3.0

*Includes POC and DOC losses, which may or may not enter the atmosphere immediately (see also Harlow et al, 2012, for an approach to handling this issue).

Such variability and uncertainty make it difficult to conduct economic analysis with any great confidence. Nevertheless, the above table of suggested emission factors is sufficient to identify an illustrative range of possible differentials between restored and unrestored sites.

Whilst restoration of cultivated land and temporary grass offers an emission differential of perhaps 10 to 20t CO2e/ha/yr, most other differentials appear to lie in the 2.5t to 5t range. In some cases, such as gripped drainage[29], the differential could be negative – although Worral et al (2011) suggest that even in this case rewetting may be desirable for other reasons.

Although knowledge of the absolute emission levels is desirable, and indeed is necessary for Inventory purposes, the differential is sufficient to calculate the value of emission savings for comparison with the costs of achieving them. Table 3 below summarises the results of a spread sheet simulation comparing the net benefits of restoration for a range of illustrative differentials combined with a range of recurrent (management/monitoring/opportunity) costs, carbon prices and time horizons.

The results are expressed in terms of a Net Present Value (NPV) that excludes up-front capital costs. This means that the results can be compared with the indicative capital costs described earlier to identify the circumstances under which different levels of restoration would be worthwhile. Although offering some analytical advantages, indicative differentials need to be interpreted with care. As Table 4 shows, estimated emission factors for a given peatland category vary somewhat and thus different differentials may be calculated under different assumptions.

Much depends on the extent to which restored sites may, over time, approximate the behaviour of undamaged sites, with emissions eventually falling to zero or becoming negative through active sequestration. Moreover, the figures in Table 4 are "typical" values that may not reflect annual variations due to weather conditions nor indeed longer-term trends. The latter may include, for example, degradation accelerating at different rates for different peatland categories. Time-varying emissions may also occur at restored sites due to short-term increases (spikes) in methane emissions arising from rewetting – meaning that some characterisation of net emission or differential profiles over time is required.[30] Such further considerations were also addressed, albeit simplistically, with the spread sheet model and selected results (using a 2.5t differential for illustrative purposes) are presented in Table 4.

[29] Although NE (2010a and b) cite this negative value, the reported positive cost-benefit result for grip blocking implies that either another emission factor was used for at least part of the time period considered and/or that a different (more strongly negative) restoration emission factor was used.

[30] It is not clear whether the estimated emission factors presented in Table 4 for restored peatlands relate to a steady-state end-point or to transition phase or to some average – hence it is not clear whether a methane spike is accounted for or not. However, the precise figures in Table 4 are only used here as a guide to upper and lower bound differentials to simulate

Tables 5 & 6 (and the two associated bar chart Figures) attempt to sketch-out possible combinations of restoration effectiveness (expressed as emission differentials) and recurrent costs under different carbon and NPV assumptions. In reality, the joint distribution (spatial co-incidence) of emission differentials and recurrent costs (and capital costs) is unknown, not simply between peatland categories but also within a given category (and indeed a given site). That is, heterogeneity of local conditions (e.g. site access & topography, management history) and management regimes (e.g. objectives, competence) mean that identical restoration activities may yield different results at different sites.

However, the use of differentials rather than absolute values avoids the need for specific details and allows consideration of a range of "what if?" results. That is, individual cells in Tables 5 & 6 represent estimates of different positions in the joint distribution and inspection of the range of values reveals the circumstances under which restoration is most likely to be merited or least likely to be merited – with the boundary between these highlighting where sensitivity to underlying assumptions demands better information and understanding.

Overall, the simulation results show that the level of capital investment merited increases as the assumed differential and/or unit carbon price rise but decreases as recurrent costs rise. Importantly, NPVs also increase as the time-horizon lengthens[31]. This partially reflects the (assumed) durability and thus continuing positive effect of restoration but also the fact that recurrent costs are more affected by discounting than carbon prices are since the latter increase over time whilst (in the absence of a forecast for future costs) the former are simply held constant in nominal terms.

For example, the NPV (capital investment merited) for 1.0t at low carbon prices with recurrent costs of £25 is £0.6k over 40 years but £1.2 over 80 years, whilst the equivalent figures for 2.5t are £2.2k and £4.2k. If recurrent costs were £50, the 1.0t NPVs drop to £0k and £0.5k whilst the 2.5t NPVs drop to £1.7k and £3.5k. High carbon prices raise the values to £2.2k & £5.4k and £7.2k & £15.6k respectively.

Including non-market valuation of restoration/adaptation gains for other ecosystem services (Table 6) further improves any given NPV. For example, the 2.5t NPV figure for low carbon prices over 40 years with £25 recurrent costs increases from £2.2k to £6.2k. Similarly, the same figure increases from £2.2k to £2.5k if the initial differential is assumed to widen by 0.5% per year and to £3.3k if the differential is assumed to widen by 1.5% per year. These last two assumptions approximate to degradation rates as characterised by Cranfield University (2013) for the Adaptation Sub-Committee for lowland peatlands under "P10 low" and "P90 high" climate change scenarios in a parallel report to the ASC. In both cases, widening of differentials under climate change implies that unrestored sites' rate of degradation accelerates faster than that of restored sites.

[31] Strictly, as shown by the bottom-left hand corner of Table 5, extending the time-horizon does not necessarily increase the NPV. Specifically, it can worsen if the annual costs exceed the annual value of carbon savings for a significant part of the time period – as occurs for low differentials with high recurrent costs.

Table 3: Maximum (break-even) initial capital cost (£k/ha) justified under different CO_{2e} differentials, carbon values, recurrent costs and NPV periods

(No other ES WTP values)		Differential between restored and unrestored sites (tCO_{2e}/ha/yr)									
(No methane spike)		1.0		2.5		5.0		10.0		20.0	
(No climate change effect)		NPV Years		NPV Years		NPV Years		NPV Years		NPV Years	
Recurrent Costs	DECC prices	40	80	40	80	40	80	40	80	40	80
£25/ha/yr	Low	0.6	1.2	2.2	4.2	5.0	9.1	10.5	19.0	21.5	38.7
	Central	1.7	3.7	5.0	10.3	10.5	21.3	21.6	43.3	43.7	87.4
	High	2.8	6.1	7.7	16.4	16.0	33.5	32.6	67.7	65.8	136.1
£50/ha/yr	Low	0.0	0.5	1.7	3.5	4.4	8.4	9.9	18.2	21.0	37.9
	Central	1.1	2.9	4.4	9.6	10.0	20.6	21.0	42.6	43.2	86.7
	High	2.2	5.4	7.2	15.6	15.5	32.8	32.1	67.0	65.3	135.4
£100/ha/yr	Low	-1.1	-1.0	0.6	2.0	3.3	6.9	8.8	16.8	19.9	36.5
	Central	0.0	1.5	3.3	8.1	8.9	19.1	19.9	41.1	42.1	85.2
	High	1.1	3.9	6.1	14.2	14.4	31.3	31.0	65.5	64.2	133.9
£150/ha/yr	Low	-2.2	-2.4	-0.5	0.5	2.2	5.5	7.7	15.3	18.8	35.0
	Central	-1.1	0.0	2.2	6.6	7.8	17.7	18.8	39.7	41.0	83.8
	High	0.0	2.5	5.0	12.7	13.3	29.8	29.9	64.0	63.1	132.5
£200/ha/yr	Low	-3.3	-3.9	-1.6	-0.9	1.1	4.0	6.7	13.9	17.7	33.6
	Central	-2.2	-1.4	1.2	5.2	6.7	16.2	17.7	38.2	39.9	82.3
	High	-1.1	1.0	3.9	11.3	12.2	28.4	28.8	62.6	62.0	131.0
£400/ha/yr	Low	-7.7	-9.7	-6.0	-6.8	-3.2	-1.8	2.3	8.0	13.3	27.7
	Central	-6.6	-7.3	-3.2	-0.7	2.3	10.3	13.4	32.4	35.5	76.5
	High	-5.4	-4.8	-0.5	5.4	7.8	22.5	22.4	56.7	57.6	125.2

Table 4: Maximum (break-even) initial capital cost (£k/ha) justified under 2.5t CO_{2e} differential without and with other assumptions

		As Table 5		With other assumptions[32]							
				WTP value		Mth. Spike		P10		P90	
Recurrent		NPV Years		NPV Years		NPV Years		NPV Years		NPV Years	
Costs	DECC prices	40	80	40	80	40	80	40	80	40	80
£25/ha/yr	Low	2.2	4.2	6.2	8.2	1.7	3.6	2.5	5.2	3.3	8.1
	Central	5.0	10.3	9.0	14.3	3.9	9.2	5.6	12.7	7.1	20.0
	High	7.7	16.4	11.7	20.4	6.1	14.7	8.7	20.3	11.0	31.8
£50/ha/yr	Low	1.7	3.5	5.6	7.4	1.1	2.9	2.0	4.5	2.7	7.4
	Central	4.4	9.6	8.4	13.5	3.3	8.4	5.1	12.0	6.6	19.2
	High	7.2	15.6	11.2	19.6	5.5	14.0	8.1	19.5	10.4	31.1
£100/ha/yr	Low	0.6	2.0	4.6	6.0	0.0	1.4	0.9	3.0	1.6	5.9
	Central	3.3	8.1	7.3	12.1	2.2	7.0	4.0	10.5	5.5	17.8
	High	6.1	14.2	10.1	18.2	4.4	12.5	7.0	18.1	9.3	29.6
£150/ha/yr	Low	-0.5	0.5	3.5	4.5	-1.1	0.0	-0.2	1.5	0.5	4.5
	Central	2.2	6.6	6.2	10.6	1.1	5.5	2.9	9.1	4.4	16.3
	High	5.0	12.7	9.0	16.7	3.3	11.1	5.9	16.6	8.2	28.2
£200/ha/yr	Low	-1.6	-0.9	2.4	3.1	-2.2	-1.5	-1.3	0.1	-0.6	3.0
	Central	1.2	5.2	5.1	9.2	0.0	4.1	1.8	7.6	3.3	14.9
	High	3.9	11.3	7.9	15.2	2.2	9.6	4.9	15.1	7.1	26.7
£400/ha/yr	Low	-6.0	-6.8	-2.0	-2.8	-6.6	-7.4	-5.7	-5.8	-4.9	-2.8
	Central	-3.2	-0.7	0.8	3.3	-4.5	-2.0	-2.6	1.8	-1.1	9.0
	High	-0.5	5.4	3.5	9.4	-2.4	3.5	0.5	9.3	2.8	20.9

[32] NEA WTP value of +£152/ha/yr; Methane spike of 2.5t CO2e per year for 10 years; 2.5t differential widened by 0.5% per year (P10 low) or 1.5% per year (P90 high) under climate change. Assumptions applied individually, not cumulatively relative to Table 5.

Figure 3: Capital investment (£k/ha) merited under different GHG differentials (tCO2e/ha/yr) and recurrent cost (£/ha/yr) levels, assuming DECC central carbon prices and a 40 year time horizon

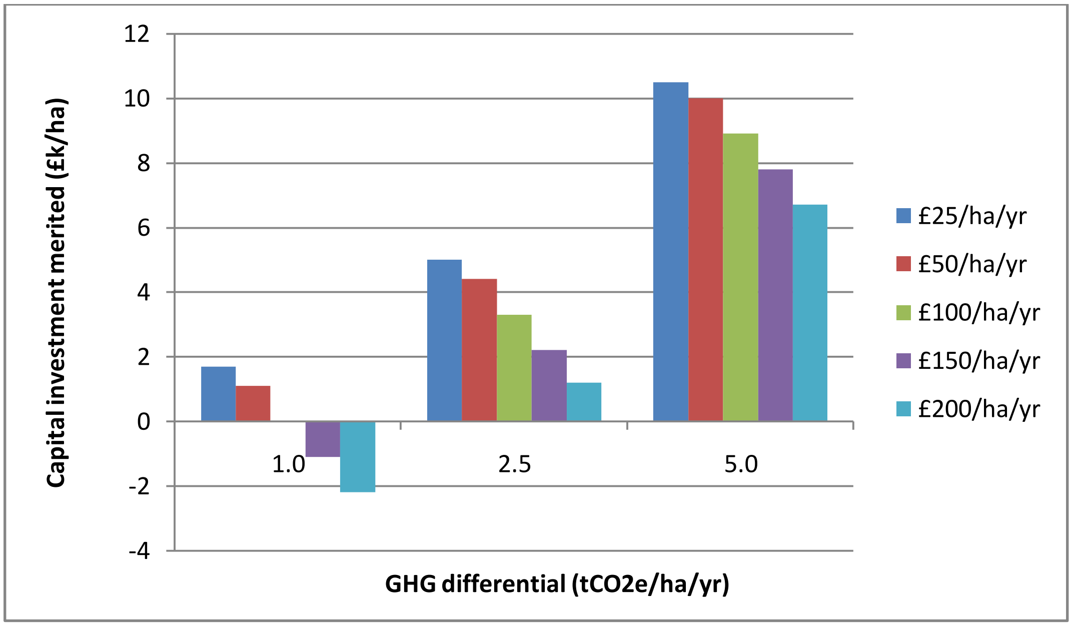
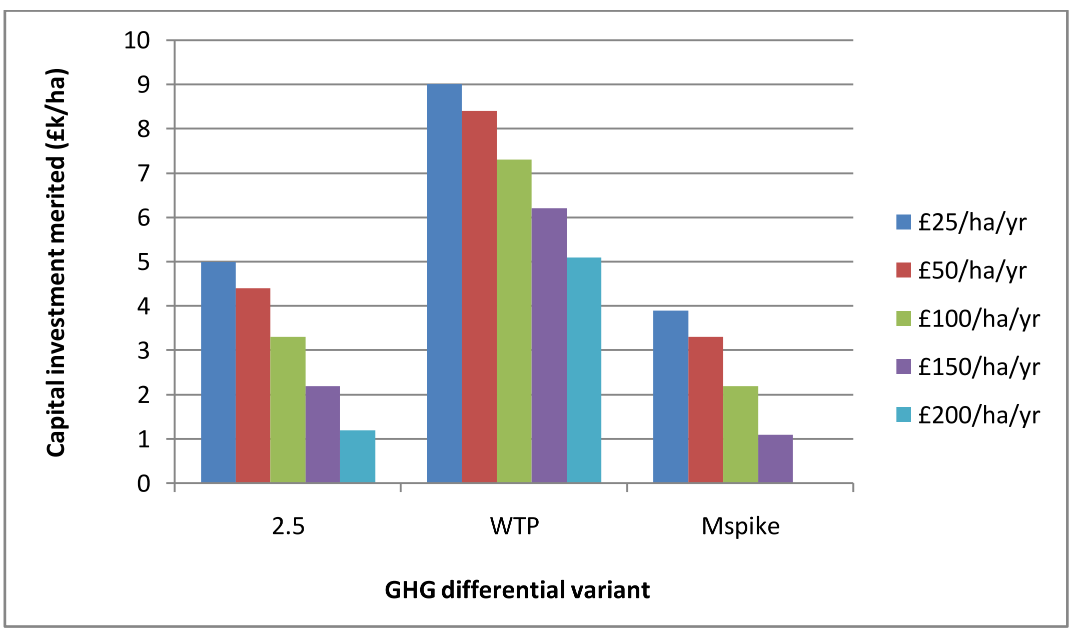


Figure 4: Capital investment (£k/ha) merited under 2.5t GHG differential (tCO2e/ha/yr) with different recurrent cost (£/ha/yr) levels, without and with WTP values and methane spike included, assuming DECC central carbon prices and a 40 year time horizon



Allowing[33] for a short-term methane spike to reduce differentials immediately after restoration lowers NPVs. For example, the £2.2k figure drops to £1.7k, reflecting the greater weight given by discounting to effects in earlier years.

The magnitude of variations reported across Table 3 and Table 4 depends on a number of assumptions. In each case, the validity of an assumption to a specific site may be debatable. For example, methane spikes may not arise in all restoration projects either due to the absence of certain vegetation species and/or careful management to avoid open pools of water. Similarly, the widening of differentials over time may depend on how climate change impacts are felt locally. Underlying uncertainty about emission factors and differentials has already been noted, but lack of detail on the time-profile is a major impediment to formal economic analysis.

On the valuation side, although DECC forecasts are the standard for carbon prices, the difference between low and high prices is significant in terms of its influence on net benefits. Moreover, as Worral et al (2009) note, actual carbon prices in compliance and voluntary markets are somewhat lower than DECC ones. The inclusion of WTP values for other ecosystem services is also potentially problematic in that available WTP values themselves vary and the relevance of restoration to specific ecosystem services is not necessarily uniform or indeed proven.

The positive effect of lengthening time-horizons is perhaps less contested, although it does rest partially on year-on-year increases in DECC carbon prices.

Relative to the rule-of-thumb capital costs of £1k/ha, it is apparent that restoration will be worthwhile in many cases. However, crucially (and especially for differentials in the perhaps more plausible ballpark of 2.5t) the results are sensitive to variation in recurrent costs and to the inclusion or not of a methane spike. In situations where current land uses are profitable and would be significantly displaced by restoration, the case for restoration becomes less clear. Unfortunately, information on such opportunity costs remains scarce, particularly for grouse shooting.

2.1.9 Some specific interpretations

The illustrative results presented in Table 3 and Table 4 can be interpreted in terms applicability to different types of peatland condition and management found across blanket bogs in England.

Specifically, the NPV values can be compared with the indicative capital costs derived from Holden et al. (2008) and the different peatland categories[34] reported by Natural England (2010). For example, 440ha of blanket bog are estimated to be under cultivated land or temporary grass. The opportunity costs of restoration are likely to be high, but the potential emission savings are also high – meaning that restoration of such land probably lies in the bottom right hand corner of Table 3. This suggests that relatively high initial capital costs would be justified, even under low carbon prices and short time-

[33] The characterisation of a methane spike here is undeniably simplistic (Baird et al. 2009) but - in the absence of firm guidance - a 2.5t annual spike for ten years is sufficient to show the sensitivity of results to a spike

[34] Although the reported categories overlap to some extent so areas affected are not cumulative.

horizons. As such, even relatively complex and expensive restoration activities are likely to be worthwhile.

Similarly, 5629ha are under improved grassland. Again, opportunity costs of displaced agricultural activities are likely to be high but the potential emission savings are likely to be reasonable. Hence restoration of improved grassland probably lies towards the bottom and middle of Table 3. This suggests that modest capital costs would be merited under low carbon prices and short time-horizons. Higher costs would be justified by higher prices and/or longer time-horizons. As such, the case for restoring improved grassland is less certain and more complex and expensive restoration activities might be too expensive.

Other peatland categories have less potential for emission savings. Afforested peatland covers 23579ha, and restoration might yield modest emission savings (although this is uncertain). However, depending on the time to harvest maturity, premature felling of standing timber can incur very high opportunity costs. Hence, restoration of afforested sites probably fall in the bottom left of Table 3. As such, even high carbon prices and long time-horizons justify only modest capital outlays. Yet restoration of afforested sites is acknowledged to incur significant initial capital costs and thus is unlikely to be merited.

Restoration of semi-natural habitats (177942ha), purple moor-grass dominated sites (3217ha) and scrub cover (2900ha) may realise limited emission savings per ha. However, the opportunity costs of restoration are also probably low. Hence restoration of such sites probably lies towards the top left of Table 3, and the top rows of Table 4. The same probably applies to gip blocking (73604ha). This suggests that modest levels of capital outlay may be merited in such cases, and this is consistent with the simpler types of activities likely to be undertaken (although scrub clearance can be expensive). However, the possibility of methane spikes needs to be considered carefully since this will reduce considerably the capital cost that can be justified.

By contrast, although restoration of rotationally burnt heathland (105233ha) may yield some emission savings[35], it may (or may not) incur higher opportunity costs through displacement of grouse shooting. As such, restoration of heathland could lie towards the left middle of Table 3 or the middle rows of Table 4. This implies that restoration may not be justified unless high carbon prices and/or long-time horizons are assumed (particularly if a methane spike occurs), and even then only modest levels of capital investment will be merited.

Although perhaps incurring very low opportunity costs, restoration of overgrazed land (30222ha) appears unlikely to yield any significant emission savings. As such it lies in (or beyond) the top left of Table 3 and merits very low or no capital outlays and is unlikely to be merited (although it may be through interaction with other degradation pressures).

[35] Although it may have more effect on DOC and POC than emissions to air from the site, although the degree to which DOC & POC may subsequently convert to emissions to air is uncertain.

Finally, modest emission savings may be realised by restoring bare peat (4199ha) and haggs/gullies (49290ha). Given that such areas are unproductive, restoration will incur limited opportunity costs. As such, it may lie in the middle of the top rows in Table 3 and Table 4. This suggests capital costs sufficient for addressing haggs and gullies may easily be justified, but that the very high costs often incurred by restoring bare peat will require other motivations – most obviously the impact of POC and DOC losses to water bodies.

The various uncertainties described previously preclude translating the above interpretations into predictions about the scale of worthwhile restoration in each peatland category. Nevertheless, the background literature cited and the simulation results presented are sufficient to demonstrate that the conditions required to render restoration economically worthwhile are likely to occur widely. As such, there is a case to be made for promoting restoration activities more widely, but not uniformly or universally. This inference applies with or without climate change, but climate change adds further support to the case. Care should be made not to exaggerate the case for restoration and further research is clearly needed.

2.1.10 Conclusions

There is a general consensus that existing levels of degradation impair the flow of many ecosystem services from peatlands and that climate change is likely to increase degradation pressures. Equally, there is a general consensus that restoration activities have the potential to reinstate at least some impaired ecosystem services and to delay if not halt the onset of climate-induced degradation. Hence restoration may have some merit as an adaptive response to climate change.

Yet quantification of both the ease (cost) with which and the degree (effectiveness) to which ecosystem services can be reinstated through restoration is difficult Equally, the relative rates of climate-induced degradation with and without restoration are effectively unknown, partly because of uncertainty over the long-term effects of restoration but also because of uncertainty over the response of both degraded and functioning peatlands to climate change – the prediction of which is itself subject to considerable uncertainty.

Restoration may well be merited in many situations, but the case for this needs to be made with clarity about the assumptions invoked. Moreover, engagement with land managers is essential to discuss impacts on their livelihoods and lifestyles and, where possible, to identify supportive incentive structures to capture some of the apparent gains to society.

Analytically, demonstrating the economic case for restoration rests on being able to quantify and value the relative flows of ecosystem services arising from degraded and from restored sites under climate change scenarios, which in turn rests on the availability of data to describe the biophysical differences and costs of different management activities. Given the absence of such data and continuing uncertainty over current and future rates of degradation (including emission losses), definitive cost-benefit analysis of peatland restoration as an adaptive response to climate change is not currently possible.

Nevertheless, the illustrative results presented may serve to focus scrutiny on the robustness of assumptions and to guide policy attention to the likely conditions required to make restoration a worthwhile activity. Restoration may not be worthwhile in all cases, and the sensitivity of net present values (NPVs) to certain parameters implies that a site-by-site approach to assessments may be prudent – a finding that echoes suggestions made elsewhere (Acreman et al., 2011; Vanguelova, et al., 2012).

Construction of the agricultural marginal abatement cost curve (MACC) for the CCC (Moran et al., 2008) pre-dated the collation and publication of much of the peatland restoration data now available. For example, the cost survey by Holden et al. (2008) and the various reviews undertaken within the IUCN Commission of Inquiry on Peatlands (Bain et al., 2011). Moreover, the focus at that time was primarily on technical or management adjustments rather than wholesale land use changes. Consequently, few expert consultees suggested peatland restoration as a mitigation option and there was insufficient empirical evidence to support its inclusion in the MACC back in 2008. However, any MACC is unlikely to remain constant over time in terms of either the mix of options or their specific profiles as technologies and scientific data evolve. Hence, although scientific understanding remains imperfect and there are still significant data gaps, peatland restoration would now be included.

2.2 Coastal managed realignment

Future climate change is predicted to cause further sea level rise, increasing pressure on existing coastal defence structures. Sea level rise results in 'coastal squeeze' between existing coastal defence lines and the encroaching sea, implying that loss of some of the existing habitat is inevitable. Managed realignment (MR) has been suggested as an adaptation response to these changes. MR refers to deliberately breaching existing sea defences to create or restore areas of intertidal habitat helping to dissipate wave energy, and reducing pressure on adjacent artificial coastal defence structures. The retreat may imply the creation of a new defence line further inland, or making use of areas of higher ground that can serve as a natural flood defence. Widening floodplains may reduce pressure on adjacent existing and newly created defences. MR is a controlled process (active retreat), often linked with the aim of creating new coastal habitat, and thus passive retreat, i.e. waiting for existing defences to fail (do nothing; no active intervention), is not considered MR.

MR schemes can provide benefits related to habitat conservation and biodiversity, which is an important driver of MR development, and may have positive impacts on recreation, fisheries, and amenity values (Eftec 2010). Furthermore, it has been shown that the newly created habitat types, i.e. salt marshes, mudflats or saline lagoons can effectively sequester carbon, even after taking fluxes of other greenhouse gases into account (Adams et al. 2012). Saltmarsh habitat can also be an important nursery ground for juvenile fish, and may thus support the provision commercial fish species (Fonseca 2009). However, it should be noted that inter-tidal habitats may not be formed immediately after the deliberate breaching of the coastline; and that even after several years the habitat quality may not be comparable to existing intertidal habitats that have formed over decades (Spencer et al 2008).

In terms of costs, MR schemes are likely to require the construction of a new defence line that needs to be maintained over time. Compared to holding the line (HTL), there may be maintenance cost savings after MR, because the habitat created after MR may reduce the erosive power of waves, and therefore their erosive impact on flood defences (Edwards and Winn 2006). Further, costs of maintaining and improving existing defences are expected to increase as sea levels rise. Existing defences are also likely to need replacement at the end of their design life, and the timing and extent of replacement needs can have a significant impact on whether MR or HTL is the preferred alternative from an economic efficiency perspective. Finally, the opportunity cost of MR schemes needs to be considered, i.e. the income foregone from land that is allowed to form intertidal habitat.

This section identifies relevant costs and benefits of MR schemes against a baseline for comparison and combines them in a tool that can be used flexibly for appraisal across different schemes. The baseline selected was as HTL. The tool enables users to assess whether HTL represents an efficient allocation of limited resources in comparison to MR. For the purpose of this project, HTL involves maintaining the existing defences at a satisfactory standard (1:100), and the potential loss of habitat in front of defences due to coastal squeeze is not considered in the cost-benefit tool developed here.

Presentation of the cost-benefit analysis tool

Economic appraisal of adaptation responses through MR requires hypothetical MR 'projects', against which to compare a baseline. This is challenging, as the economics of MR are highly dependent on their spatial context (Turner et al 2007). This is supported by Tinch and Ledoux (2006), who find that comparisons across MR schemes are difficult because "[e]ach case has special characteristics related to the geography and economics of the area. Together, these facts mean that it is not possible to draw general conclusions specifically about the choice between MR and other options based on the cases analysed." Furthermore, there is a wide range of alternatives for MR even for individual stretches of coastline. Therefore, a clear set of criteria needs to be applied for site selection, and the actual outline of the hypothetical MR scheme needs to be informed by the local spatial context and engineering knowledge in terms of defence construction.

Reporting a CBA of MR in the Humber estuary, Turner et al. (2007), suggest the use of a number of criteria used for GIS-based identification of suitable MR sites (Box 1). While some of the criteria and constraints may be modified to align with the specific needs of this project, the criteria listed in Box 1 reflect important spatial constraints to MR schemes and highlight some site-specific factors (size, shape, elevation, proximity to other inter-tidal habitat areas) that will increase the likelihood that MR schemes pass a cost-benefit test. For an analysis on a national scale, sites that contain features or infrastructure of regional or national importance could also be excluded.

Box 1. GIS-based realignment site location criteria, based on Turner et al (2007)

Criterion 1 – The Area below the High Spring Tide Level

The high spring tide level is the highest point at the coastline that is reached by the sea during a spring tide. The area below this represents the maximum area of intertidal habitat that could be created, before other factors are considered.

Criterion 2 – The Present Land Use of the Area

Sites of Special Scientific Interest (SSSI), Special Areas of Conservation (SAC) and other similarly protected areas together with historically significant buildings should be excluded from the realignment areas.

Criterion 3 – The Infrastructure of the Area

The transport network – including roads, railway lines and canals – should be assumed to be protected and therefore precluded from realignment.

Criterion 4 – The Historical Context of the Area

Realignment *may* be constrained to areas that had been previously reclaimed.

Criterion 5 – The Spatial Context of the Areas

Size: A threshold for size could be applied. For example, only areas greater than 5 ha in size could be considered for realignment to enhance habitat benefits. Alternatively, intertidal habitat of any size could be created.

Shape: The optimum shape for realignment areas could be described as a trade-off between creating a wide intertidal area to maximise benefits, while ensuring that the length of realigned defences to protect the surrounding land is no greater than those which already exist.

Elevation: All of the scenarios assumed setback to an elevation above the high spring tide level where possible to make use of topographical features acting as a natural defence.

Proximity to existing intertidal habitats: Intertidal habitats could be created where they best fit in with the overall vegetation succession to facilitate the movement of species between habitats.

Since MR schemes involve foregoing valuable assets, they are at risk of meeting opposition from affected private land owners and communities. A transparent approach to the decision making process is required, but there are factors that may reduce the potential for conflict in identifying appropriate sites for MR. As suggested by Turner et al. (2007) a sequential approach could be taken, where consideration is first given to MR schemes that have relatively low opportunity costs. In line with this a set of criteria could be established to spatially identify the scope for MR schemes. Criteria could be directly linked to opportunity costs (e.g. identifying appropriate areas below a certain threshold value), or be factors that are likely to influence opportunity costs, such as:

- Grade of agricultural land forgone – MR schemes that would flood lower grade land are prioritised
- Number and value of built residential properties
- Number and value of built commercial properties.

Arguably when the potential for conflict lines along ethical and social justice concerns is greater, the decision becomes more difficult, and the economic efficiency criteria becomes less decisive in guiding decision and policy making. Cost-benefit analysis outputs could be produced for instance in a tableau format (Krutilla 2005), illustrating winners and losers as well as transfers between affected parties and governments in order to facilitate discussions about, for example, potential compensation needs. The cost-benefit tool developed here does not take any equity considerations into account. Cost-benefit analysis should ideally also be supplemented by multi-criteria approaches, feeding into a transparent, inclusive and participatory decision-making process that can be adapted over time to changes in societal demand and shifts in policy objectives. The planning process set out in shoreline management plans (SMPs), together with Defra’s ‘Pathfinder’ initiative, contain elements of the above and therefore appear to be a good platform to build upon in terms of future adaptation to increasing pressures on the coastline and coastal defence.

MR schemes are ideally evaluated on a case-by-case basis, considering the wider context of coastal management at appropriate (ecosystem) management units (e.g. whole estuaries) – see Turner et al. (2007). Because of issues of social acceptance and the higher opportunity cost value of residential and commercial property and land for construction, an approach towards prioritising MR schemes across wider stretches of coastline should focus first on sites where the creation or restoration of inter-tidal habitat would only affect land used for agricultural production. While this approach may seem to artificially constrain the area available for consideration of MR, it is in line with the goal of identifying 'low-regret' options for adaptation that can be implemented in the short-term.

As noted, spatial context is important for identifying suitable sites. Additionally, both costs and benefits can vary substantially across locations. Illustratively, a review of costs of 41 existing MR schemes (Rowlands et al. unpublished), reports total costs per ha to be £34,500 (2011 prices) on average, with a standard deviation larger than the mean (£37,500). A similarly large variation in capital and maintenance costs is reported (together with caveats related to comparing these) in Tinch and Ledoux (2006) for a smaller set of existing MR schemes. Benefits may vary depending on, for example, access to sites for recreational use, the type and quality of habitat provided, and the relevance of newly created habitat to support local economic activity, for example commercial fishery. Luisetti et al. (2011) find evidence of diminishing marginal utility with increasing habitat areas created through MR in the Blackwater estuary. The magnitude of benefits also depends on the affected population ('economic jurisdiction', i.e. the population that hold economic values for the environmental effects considered; see Eftec 2010), which may differ depending on the importance of non-use values related to the implementation of particular MR scheme, which in turn may depend on aspects such as uniqueness of the site and scale and magnitude of environmental change (Eftec 2010). A related case-specific phenomenon is 'distance decay', where the Willingness to Pay (WTP) decreases with increasing distance to a site. Distance decay, may in turn, be related to the availability of substitutes (Schaafsma 2012), which again is site-specific. These considerations represent caveats to applying uniform per ha benefit values as, for example, reported for wetlands in Brander et al. (2008).

A key element of this work is the development of a flexible tool that can be used for cost-benefit appraisal of MR schemes against HTL as a baseline. But difficulty in defining the specificities of a hypothetical MR project and a HTL baseline is one of the limitations of this tool.. Equally, costs and benefits applied are subject to assumptions that may be problematic given the observed degree of variation between existing schemes. Consideration of a generic cost benefit-tool cannot therefore replace a more detailed case-by-case analysis to guide efficient decision making on coastal adaptation. Any figures generated using the tool should only be interpreted as a first approximation that requires validation through further in-depth analysis.

Nonetheless, the cost-benefit tool may be used to illustrate the sensitivity of results to a range of assumptions about costs and benefits, and to changes in important factors affecting those. Further, the tool also allows comparisons of HTL with 'doing nothing' ('No Active Intervention or NAI), although this function has not been used for this project. This may be of interest for appraising stretches of coastline that are subject to (cliff) erosion, an issue that is not discussed here.

For the economic appraisal, a comparison of the present value (PV) of an existing protection scheme ('hold the line' or HTL) with a MR scheme will be undertaken.

The PV for HTL can be estimated as follows (see Turner et al 2007 and Luisetti et al 2011):

$$PV_t^{HTL} = -\sum_{t=0}^{T} \frac{1}{(1+r)^t} \left[(l^{HTL}, C_{m,t}^{HTL}) \right]$$

where: PV_t^{HTL} is the present value of total costs of current defences (£) as there are no future (additional) benefits in the status quo scenario, *r* is the discount rate, l^{HTL} is the length of defences, and $C_{m,t}^{HTL}$ are the maintenance costs (£/km/yr). This equation may be refined to take the condition and design life of current defences into account:

$$PV_t^{HTL} = -\sum_{t=0}^{T} \frac{1}{(1+r)^t} \left[(l^{HTL}, C_{m,t}^{HTL}, C_{r,t}^{HTL}) \right]$$

where $C_{r,t}^{HTL}$ are the replacement cost of defences that need replacement (end of design life) at time t (£/km).

The PV of the managed realignment (MR) scheme is:

$$PV_t^{MR} = \sum_{t=0}^{T} \frac{1}{(1+r)^t} \left[\left(a_h^{MR} B_{e,t}\right) - l^{MR}\left(C_{k,t}^{MR} + C_{m,t}^{MR}\right) - \left(a_t^{MR} L_{agr,t}^{agr}\right) \right]$$

where: PV_t^{MR} is the present value of the MR scheme (£), *r* is the discount rate, a_h^{MR} is the area of inter-tidal habitat created, $B_{e,t}$ are the ecosystem value benefits (£/ha), l^{MR} is the legth of managed realignment, $C_{k,t}^{MR}$ are the capital costs of realignment, $C_{m,t}^{MR}$ are the maintenance costs, a_t^{MR} is the agricultural land lost, and $L_{agr,t}^{agr}$ is the forgone agricultural land value, adjusted for transfer payments.

The costs of implementing the scheme usually include the capital costs of realigning defences whenever a secondary line of defence was necessary further inland; opportunity costs associated with any agricultural land that would be converted in inter-tidal habitat. Other costs relate to maintenance costs of old and new seawalls.

The net present value (NPV) of MR compared to HTL at time *t* is given by $PV_t^{MR} - PV_t^{HTL}$.

This case assumes that no residential or commercial properties and assets are affected. The terms in square brackets of PV_t^{MR} may be amended by terms reflecting the present value of residential built properties (number of built property affected at time *t* x value of built property) per type of built property affected; the present value of housing land (area of housing land affected at time *t* x value of housing land); and the present value of affected commercial property at the time *t* of being lost.

Equally, on the benefits side, per hectare values can be added for the net greenhouse gas effect and impact on fisheries arising from habitat creation at time *t*.

Values populating the cost-benefit analysis tool

<u>Habitat ecosystem benefit</u>

In the cost-benefit tool, per ha habitat benefit values developed in Eftec (2010) are used, which are based on the meta-analytical function reported in Brander et al (2008). The distribution of values is skewed with a long tail of high values. It thus seems appropriate to use median values, as reported in Eftec (2010). For details on the estimation and assumptions made, the reader is referred to Annex 2 in Eftec (2010). Per ha habitat values do not include the value of net changed in greenhouse gas emissions resulting from the creation of intertidal habitat. The types of values considered are: ecosystem service provision of water quality improvement; recreation (non-consumptive); biodiversity; and (only for lower bound values) aesthetic amenity. As mentioned above, it should be noted that generally the benefit transfer of (adjusted) unit values may not be appropriate and needs to be considered carefully on a case-by-case basis.

Per hectare values can be adjusted for: average population density for England and Wales (345 per km^2); ii) the availability of or access to non-consumptive recreation at site; iii) the presence of non-consumptive amenity values. The tool distinguishes two types of inter-tidal habitat: mudflats and saltmarsh. It is assumed that the habitats develop immediately after implementation; typically, this will be a process spawning over several years, and habitat quality depends on previous land use and/or preparation of land in the course of MR implementation, which is assumed not to take place.

Further, values can be adjusted for the availability of substitutes. The meta-analytical function used in Brander et al (2008) specifies the relevant spatial area for considering the influence of substitute (alternative) wetland sites on the economic value of wetland ecosystem service provision as a 50 km radius from the wetland site (i.e. an area of 7,854 km^2), and estimates a relationship between Willingness To Pay (WTP) and availability of substitutes within this area. Accessibility and availability of substitutes are indicators of scarcity of an environmental good. The theoretical expectation is that WTP for an improvement at a given site should decline as the availability of suitable substitutes increases. Eftec (2010) report two series of values, depending whether 0-100 ha or >100 ha of substitute wetlands are present within the 50 km radius from the MR site under consideration. It should be noted that there is no clear definition of what constitutes a substitute site – it may refer to wetlands in general, or only to certain intertidal habitat areas; however, a reasonable assumption is that substitutes are defined as the area of intertidal habitat. As noted in Eftec (2010), values decrease by approximately 5% if > 100 ha of substitute habitat areas are available.

Per hectare habitat values also depend on the scale of change represented by the area of habitat that is newly created in a MR scheme. This follows the theoretical expectation on diminishing marginal utility for increase in the area of habitat created (Luisetti et al 2011). The WTP for any additional hectare of intertidal habitat decreases with an increase in the total area of habitat created through MR. Eftec (2010) thus report decreasing per ha values for the following categories of habitat size: up to 10 ha; 11-30 ha; 31-50 ha; 51-100 ha; ~500ha; ~1000ha. In the cost-benefit tool, the last two categories are interpreted as 101 – 750 ha, and > 750 ha. All habitat values have been adjusted to 2012 prices using GDP deflators.

The cost-benefit tool allows the user to consider potential impacts of saltmarsh creation on fish productivity, with values related to impacts on commercial fisheries. These values are derived from Luisetti et al (2011). . The mean value per ha of £ 11.5 is derived using the average wholesale price of £7/kg reported by Luisetti et al (2011). Upper and lower bound values are considered in the tool. It should be noted that i) strictly speaking the reported values apply to wild-caught seabass only; ii) market prices used for valuation are volatile and can therefore have changed since; iii) the fish production function used draws on Fonseca (2009) and may be site-specific and related to the habitat condition of saltmarsh. Impacts on fisheries are considered only from year 5 after MR implementation. The tool allows impacts on fish productivity to be considered for a certain percentage of newly created saltmarsh only; this may be of relevance if the tool is used in an appraisal that treats several distinct MR schemes as a single project.

Habitat carbon storage benefit

The cost-benefit tool allows for the consideration of net carbon gains related to the creation of mudflat or saltmarsh areas. Net GHG fluxes expected for mudflat and saltmarsh habitats are based on Adams et al. (2012), who report results of an assessment of GHG fluxes from mudflat or saltmarsh sediments following MR in the Blackwater estuary. The reported annual net GHG flux is approximately 2.2 t CO_2 eq/ha for mudflats and 2.4 t CO_2 eq/ha. Thus intertidal habitat serves as a net GHG sink. GHG emission reductions are then multiplied by carbon prices (non-traded) published by DECC (2011) and adjusted to 2012 prices. It should be noted that the tool assumes a zero net balance of GHG fluxes from (agricultural) land behind existing defences. This assumption may not hold. In fact, depending on land use, agricultural land may act as either a GHG sink or a GHG source.

Construction and maintenance costs for hold the line and managed realignment

As noted above, capital costs of MR implementation may be highly variable and site specific; also, economies of scale may play a role. DEFRA (2004) guidance lists costs for linear structures (revetments, seawalls) as £2.7million/km; for beach management schemes as £5.1million/km; for groyne fields as £0.6million/km.

In their cost-benefit analysis of MR in the Humber and Blackwater estuaries, Luisetti et al (2011) use capital costs per km of realigned defence based on Halcrow (2000) of £0.88million/km (2005 prices) for the Humber estuary, and 0.93million/km (2007 prices). The cost-benefit tool has an option to enter other capital costs associated with MR scheme implementation, for example related to site preparation and pre-implementation, which are sometimes listed in viability assessments related to Shoreline Management Plans (SMPs). Also, other capital costs associated with HTL schemes in year 0 can be considered, for example related to urgent changes in existing defence structures to safeguard a certain standard of flood protection.

Replacement needs of existing unsatisfactory defences (as they approach the end of their design life) can be considered for HTL in the tool at three distinct points in time (at project start, after 25 years and after 50 years). Turner et al (2007) and Luisetti et al (2011) report per km costs of replacing unsatisfactory defences as £0.67million/km in a cost-benefit analysis of MR in the Humber estuary. Costs of replacement are highly site-specific, and may have a significant impact on the NPV of MR compared to HTL. Costs of replacement may also increase over time as higher/improved defences are needed to meet standard of protection given sea level rise. Note, however, that this is somewhat already considered in the application of adjustment factors, further described below.

Unit capital costs for construction and replacement for the tool were derived from the Environment Agency's 'Flood Risk Management Estimating Guide (update 2010)': £2.1 million per km of sea defence (for HTL defence lines), and £1,152/m for river embankments, considering that realigned defences tend to be constructed as earth embankments.

Maintenance costs under both MR and HTL are site-specific and are thus likely to vary. Although some caveats for comparison apply, including the fact that the MR schemes compared are very small, Tinch and Ledoux (2006) report largely varying maintenance costs for existing MR schemes. Luisetti et al (2011) apply an annual value of £3,560/km for the Humber estuary MR, and £866/km for the MR scheme considered in the Blackwater estuary. Defra (2004) guidance suggests maintenance costs of £10,000 for linear structures and groynes, and £20000 for beach management. In the cost-benefit tool, maintenance costs are assumed to be the same every year for the lifetime of the defence - in reality they may increase over time. Further, the tool allows for an adjustment to be made to account for a percentage reduction in maintenance costs of MR relative to HTL. This reduction can arise, because the habitat created after MR may reduce the erosive power of waves, and thus the erosive impact on flood defences (Edwards and Winn 2006, Moeller 2006). There is an option to add additional maintenance costs unrelated to tidal defences in the MR scheme; for example, to account for recurring costs of habitat management. Additional annual maintenance costs can be added, which may, for example, be related to electricity costs of pumping stations.

Agricultural land value

Present values of MR include the opportunity costs related to income foregone from land that is being flooded in as a result of controlled (MR). The cost-benefit tool distinguishes four uses of land that are given up in case of MR: i) agricultural use; ii) use of residential built property; iii) use of residential building land; and iv) commercial use. All are valued using market prices as an approximation of the present value of income streams arising from these uses over time.

Agricultural land is valued using average prices for England, differentiated by grade (grades 1-2, grade 3, grades 4-5 and not graded). The 2004 values reported by Defra (http://archive.defra.gov.uk/evidence/statistics/foodfarm/farmgate/agrilandsales/index.htm) are adjusted to 2012 prices using GDP deflators. It is worth pointing out that in this database per ha values of grade 3 land are higher than those of grade 1-2. Alternatively, income streams (rents) derived from land in perpetuity could have been used to estimate present value. Some exploratory calculations in this direction revealed that present value estimates did not differ much from using land prices. Using income streams adds further levels of complexity in terms of deriving appropriate gross margin estimates, in terms of accounting for subsidies paid to land, in terms of other capital requirements necessary to farm the land, and in terms of making further assumptions about appropriate discount rates. It should also be noted that Defra land price values are easily accessible for different regions, thus reflecting some spatial heterogeneity.

Following recent Defra supplementary guidance on the treatment of agricultural land (http://archive.defra.gov.uk/environment/flooding/policy/guidance/project-appraisal.htm), £600 are subtracted to account for transfer payments and subsidies. For the calculation in the cost-benefit tool, it is assumed that there is no (agriculturally related) income, for example related to livestock grazing on saltmarsh or habitat conservation 'payments'. Statistics for agricultural land prices are also available per region, but are not reported for both land grade and region. It should be noted that the 'value' of agricultural land and thus the opportunity costs of MR schemes may rise substantially to meet growing demand for food. Such effects are not considered here.

Built property value

The approach used to derive the present value of built property is the same as that adopted for agricultural land. Market prices are used as an estimate for present value, instead of income streams (rents) derived from the properties in perpetuity. Prices for residential built property for different dwelling types, and an 'average' dwelling, are obtained from government statistics (https://www.gov.uk/government/statistical-data-sets/live-tables-on-housing-market-and-house-prices). Residential building land is valued using government statistics of valuations per ha (https://www.gov.uk/government/statistical-data-sets/live-tables-on-housing-market-and-house-prices) Note that these prices do not distinguish new and preoccupied properties. House price statistics are reported for 2010. The values were not adjusted since more recent information on house price development suggests that since 2010 house prices in many parts of the UK have been increasing less than the rate of inflation. The value of commercial property being affected by MR schemes should be calculated separately, because valuations are complex and require the consideration of a large number of factors for different types or uses of commercial property. Indicative values for different types can be found here: http://www.voa.gov.uk/dvs/propertyMarketReport/pmrJan2011.html. It is also possible to consider using rates and values as displayed in the Multi Coloured Manual (Penning-Rowsell et al. 2005) - or an update of those.

Economic assumptions

Further assumptions made refer to the use of discount rates, adjustment factors that account for sea level rise, and the consideration of 'optimism bias'. Discount rates follow current guidance for long-term appraisals (HM Treasury Green Book) and are 3.5% up to year 30, 3% up to year 75 and 2.5% beyond year 75. Luisetti et al. (2011) explore implications of different approaches to discounting on NP for MR schemes, including the use of a constant discount rate of 3.5%, declining discount rates (as applied in the cost-benefit tool), and gamma discounting (Weitzman 2001). The gamma discounting applies lower discount rates for longer time horizons, and thus resulted in a higher present value of benefits from MR.

Allowance is made for an increase in costs due to climate change and resulting sea level rise. Defence structures need to become higher, deeper and more resilient to increased exposure. This follows guidance on Defra (2004) and Penning-Rowsell et al (2005). A factor of 1.5 is applied to defence-related capital and maintenance costs for years 21-50, and a factor of 2 is applied from year 51 onwards. Optimism bias should in accordance with Defra guidelines (Defra 2003) be applied to all costs (at 60%) to reflect uncertainty in broad level analysis and prevent an overly optimistic ex-ante assessment of project costs when compared to actual values observed ex-post projects. For small scale projects with reliable data or ex-post assessments, it can be reduced or set to zero. Note that only capital and maintenance costs associated with defences are made subject to optimism bias here, not other maintenance costs that are, for example, related to pumping stations or habitat management.

A full list of variables and factors used as inputs for the cost-benefit tool can be found in Annex C.

As emphasised above, it is not recommended that CBA is performed on a large scale bundling many individual MR schemes into a single 'project'. If the cost-benefit tool is used for such an analysis with little information on actual MR sites, Annex D spells out some key assumptions required, and suggests some key factors and assumptions that should be included in tests of sensitivity of NPV.

A key determinant of economic efficiency is the area of habitat created under managed realignment at a particular stretch of coastline. To investigate this, a schematic analysis of hypothetical MR schemes was conducted, varying the area inundated under managed realignment, while keeping the length of defences before and after scheme implementation constant at 1km. A second analysis allowed for built residential property to be affected by the scheme, varying the number and value of affected dwellings. In both cases, the hypothetical managed realignment schemes were compared to holding the line.

Table 5 summarises assumptions about all key variables entering the cost-benefit tool for estimation.

Table 5. Assumptions for schematic analysis of impact of land value and residential property on NPV across varying MR sizes relative to length of initial defence line

Case 1: impact of land value on NPV
Length of defences before project (km)
1
Length of defences after project (km)
1
Length of realigned defences (km)
1

Habitat value (SM=Saltmarsh; MF=Mudflat; SM and MF are created on 50% on land inundated each)

Area of substitute wetlands within ~50km radius (ha)

100<X<500

Population density (50km radius) > UK average (345 per km2), eg London (yes/no)

no

MR/NAI: Recreation access to site (site NOT accessible to informal recreation) (yes/no)

no (i.e. site is accessible)

Site (MR/NAI) is NOT judged to provide aesthetic amenity (yes/no)

no (i.e. site has amenity value)

Values (£/ha/yr)	lower	central	Upper
SM 0-100	437	562	687
SM > 100	415	540	666
MF 0-100	426	540	655
MF > 100	404	513	622

MR: Amount of carbon stored (t CO2 eq/yr)

Saltmarsh net t CO2 eq / ha / yr	2.4
Mudflat net t CO2 eq / ha / yr	2.2

Carbon values

see ‘cost-benefit tool’' documentation

Fisheries impact

no

Cost of constructing new defences (MR) (£/km)

1,152,000

Cost of defence replacement (HTL&t=50) (£/km)

2,100,000

Maintenance cost after realignment compared to HTL (%)

50

Adjustment factors (sea level rise) for Construction and maintenance costs at time t

t=0-19	1
t=20-49	1.5
t=50-99	2

Discount rate applied (%)

t=0-29	3.5
t=30-74	3
t=75-99	2.5

Case2 (additional): impact of residential property affected by MR on NPV

Land area under agriculture

residual of total area inundated minus number of properties x housing land per dwelling

Land value (agriculture) (£/ha)

6000

Optimism bias

no

Housing land (per single dwelling)

200m^2

Housing land value (£/ha)

2,000,000

Interpretation of results

The results need to be interpreted carefully due to their sensitivity to assumptions about costs of construction, replacing defences and defence length before and after managed realignment, but some useful insights can be gained. Figure 5 and Figure 6 illustrate these. First, smaller managed realignment schemes may not be economically efficient even if opportunity costs related to income foregone from agricultural land use and maintenance costs are low. Thus, smaller schemes (in terms of habitat area created per kilometre of existing defence) should be particularly scrutinised in terms of economic impacts in the planning phase.

Second, the present value of agricultural land being inundated as a consequence of managed realignment has a moderate impact on the size of the scheme required to prefer managed realignment over holding the line. In other words, opportunity costs related to income foregone from agricultural land use are an important but insufficient indicator of economic efficiency. Other indicators are environmental benefits, reduced construction costs (and replacement costs) of realigned defences and reduced maintenance costs.

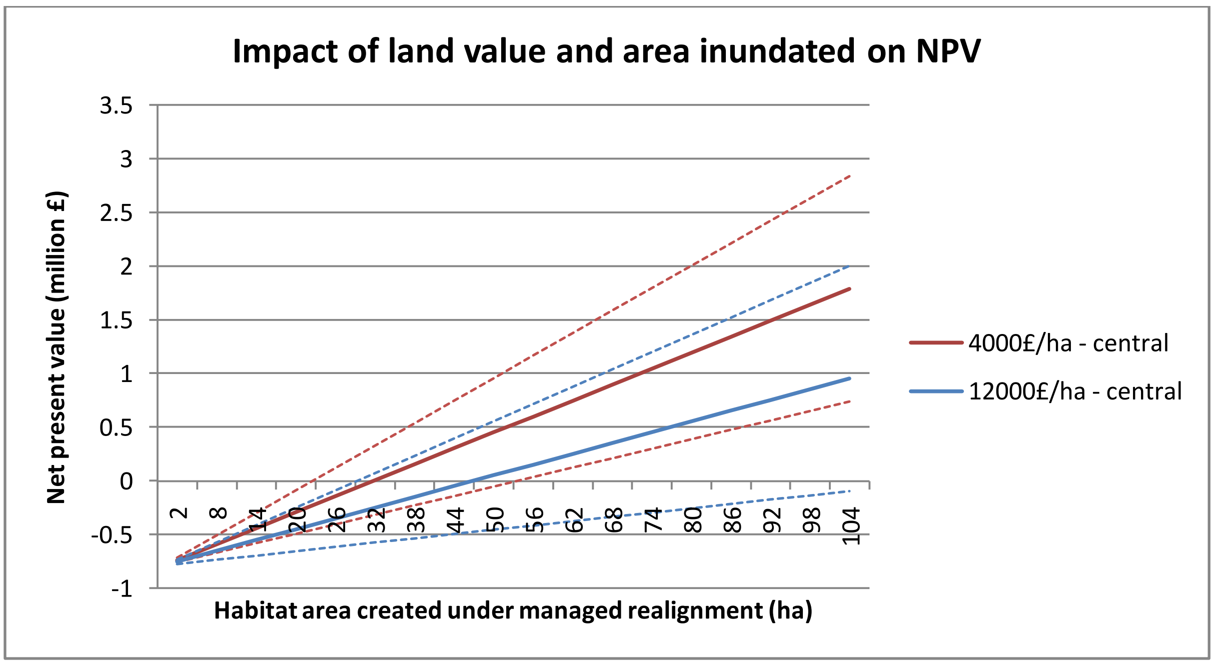


Figure 5. Impact of land value and area inundated on NPV. The dashed lines represent upper and lower estimates based on upper and lower bounds for habitat and carbon values. A low value for maintenance costs applies for HTL defences (£2,000 km/yr). No optimism bias applied.

Third, inclusion of built residential property results in positive net present values only for very large managed realignment schemes relative to the length of the initial coastline. This indicates that MR schemes call for careful investigation of economic welfare impacts if a scheme affects residential property.

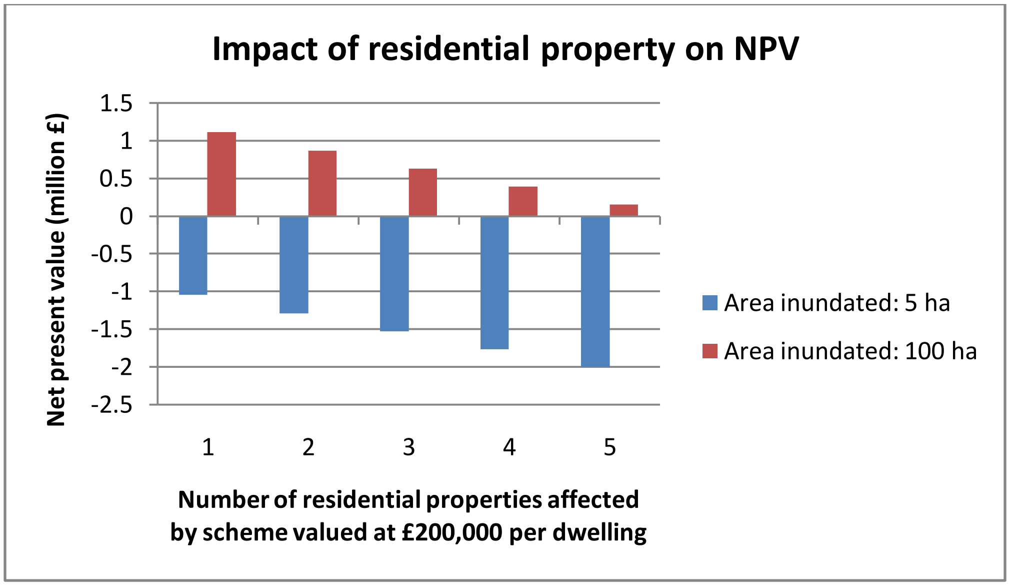


Figure 6. Impact of residential property on NPV. Maintenance costs for HTL defences are assumed to be £6,000 km/yr.

2.3 Costs and benefits of adaptation for biodiversity and protected areas

There are many ways that climate change would be expected to impact on biodiversity. For example, changes in species distribution and abundance; changes in the timing of seasonal events and associated habitat use by different species; changes in the composition of plants and animal communities within habitats; changes to habitats and ecosystems themselves through changes to water regimes, increased rates of decomposition and changes to plant growth rates; rising sea levels and direct impacts on coastal habitats; increases in occurrence and severity of extreme weather events. In addition, changing land practices and land use in response to climate change are also expected to impact directly and indirectly on biodiversity.

But it is unclear in most cases where (and to what degree) such changes will occur and hence what the actual impacts will be on habitats and species in general and protected areas in particular. What does seem clear is that the most vulnerable habitats/species are those where there is no facility in the UK for the climate envelope they require to 'move' to other UK locations (e.g. high altitude montane habitats and associated species) or those where it is clear there is a high potential for loss through the climate change impacts that are already evident (e.g. coastal habitats affected by rising sea levels and the increase in storm events).

The speed and scale of climate change is such that it is not possible to wait until there is greater certainty as to how and where impacts will occur – since delay will result in more severe impacts, a reduction in the adaptation options available and increased costs of damage and intervention. The basic approach that therefore needs to be taken involves putting a particular focus on conserving protected areas and other high quality habitats through adaptation action in the protected areas themselves and in the wider countryside. In particular actions are needed aimed at:

- Reducing the sources of harm to biodiversity that are not linked to climate change, i.e. reducing the additional pressures such habitats are under
- Maintaining and increasing the ecological resilience of such areas by maintaining and increasing the condition of the habitats, i.e. by increasing habitat diversity and condition in the protected areas and reducing damaging activities within their immediate vicinity
- Maintaining and increasing ecological connectivity between such areas by providing opportunities for species to move between sites
- Increasing the size and number of protected areas

This section addresses adaptation options for protected areas, specifically those sites that have been designated as Site of Special Scientific Interest (SSSI). We use SSSIs as these are the primary protected designation in the UK, they form the UK's contribution to the wider European Natura 2000 network (under which there is an obligation to maintain priority habitats and species associated) and they are also subject to on-going monitoring and condition assessment by Natural England. To assess the costs and benefits of adaptation in SSSI we have developed a spread sheet model that allows users to select from a menu of adaptation actions for each habitat type, with associated costs, these are then applied over an area selected by the user and compared to estimates of the benefits for the selected habitat.

2.3.1 Data sources

Condition assessments are regularly published by Natural England at National, Regional or County level[36]; these describe the name, location, habitat type, area and condition of each SSSI. Condition is assessed as either 'Favourable'; 'Unfavourable recovering'; 'Unfavourable no change'; 'Unfavourable declining'; 'Part destroyed'; or 'Destroyed'. With respect to climate change impacts we can assume that sites in 'Favourable' or 'Unfavourable recovering'[37] condition are likely to be more resilient to impacts, depending on habitat type and the nature of the impact. Therefore, early adaptation actions might be most effectively targeted at sites in 'Unfavourable no change' and 'Unfavourable declining' condition.

The main adaptation actions we have included in our SSSI spread sheet were identified from a series of Natural England reports published under the Character Area Climate Change Project38. The currently available reports cover habitats in the Norfolk Broads, the Cumbria High Fells, the Dorset Downs and the Shropshire Hills (Natural England 2009a, 2009b, 2009c and 2009d).

The adaption measures identified by the Natural England studies were then mapped onto appropriate measures from the Environmental Stewardship Higher Level Scheme (HLS). The costs for these adaptation measures are as per HLS payment rates which are determined on a cost basis (Natural England, 2013). The spread sheet used for this analysis these costs can be varied for sensitivity analysis, creating low, medium and high values, or can select more or less costly HLS measures. Users can select multiple adaptation measures and the area over which each measure is applied as a percentage of the total area. This allows for response to multiple climate induced impacts. Further sensitivity can be assessed by selecting alternative measures such as 'maintain', 'restore' or 'create' with different payment rates.

The benefits of adaptation are based on a stated preference study undertaken by Christie et al. (2011), which valued the range of ecosystem services provided by different SSSI habitats. The approach used by Christie et al was to elicit the general public's values for different levels of ecosystem services using a discrete choice experiment. Christie et al then attributed these values to each habitat type based on an expert assessment of the combinations of ecosystem services they provide. This approach avoided the need to value each habitat individually (and their range of ecosystem services), but it doesn't capture the influence of context on values. For example, the public may have different preferences for similar watershed services provided by peatland versus woodland.

The Christie et al valuation exercise explored two scenarios, which we have adopted to reflect potential losses from climate induced degradation and gains from adaptation. A 'Maintain funding' scenario measured the benefits of maintaining current status of SSSIs relative to a counterfactual of no funding

[36] http://www.sssi.naturalengland.org.uk/Special/sssi/reportIndex.cfm

[37] These sites may be on course to achieve Favourable condition in the near future.

[38] http://www.naturalengland.org.uk/ourwork/climateandenergy/climatechange/adaptation/naturalengland.aspx

for SSSI management. We use this as an estimate of the losses from climate induced degradation. An 'Increased funding' scenario measures the benefits over the current status of additional funding for SSSI management. We use this to reflect the additional benefits of adaptation.

To incorporate potential delays between implementation of adaptation measures and these additional benefits, the SSSI CBA spread sheet allows for the selection of a time lag of up to 10 years. Users are also able to select the period over which management actions are applied, this will vary depending on the ease with which the adaptation can be implemented and the vulnerability of the habitat to change. We have made suggestions for the appropriate duration of management action for each habitat.

The categories of SSSI habitat used by Christie et al (2011) do not directly map onto those used by Natural England in their condition assessments. Consequently we have matched categories as shown in Table 6 below. The main difference is the where Natural England distinguish between upland and lowland areas of the same broad habitat, the value estimates do not make this distinction. We have to assume that these habitats will deliver broadly similar ecosystem services, and hence per hectare values. Some habitats were not included in the Christie et al study; these are either being considered elsewhere in this report (e.g. bogs – or peatland - and water bodies); may be influenced by management for other purposes (arable and horticulture; boundary and linear features; and built up areas and gardens); or are unlikely to be adversely impacted by climate change (Earth heritage and inland rock). Christie et al also estimated values for ‘Purple moor-grass and rush pastures’ and ‘Coastal and flood plain grazing’: these are Biodiversity Action Plan rather than SSSI habitat classes.

These categories should not be considered in isolation for assessing wider habitat adaptations. For example, a typical coastal habitat will consist of supralittoral sediment (sand dunes and shingle); littoral sediment (intertidal mudflats and saltmarsh); and fen, marsh and swamp. The exact composition of each type will vary depending on location and this in turn will influence the dynamics between habitats and their individual and combined response to climate change. Therefore it is impossible to suggest a specific adaptation strategy with associated cost-benefit analysis based on the data we have available. Instead we recommend that any analysis of coastal adaptation uses a hypothetical example based on some combination of the typical extent of these habitats for any given region.

Table 6 Comparison of SSSI habitat categories with habitats used by Christie et al (2011)

Natural England category	**Christie et al (2011)**
Acid grassland – lowland	Acid Grassland
Acid grassland – upland	
Arable and horticulture	
Bogs - lowland	
Bogs - upland	
Boundary and linear features	
Broadleaved, mixed and yew woodland - lowland	Broadleaved, mixed and yew woodland

	Broadleaved, mixed and yew woodland - upland	
	Built up areas and gardens	
	Calcareous grassland - lowland	Lowland calcareous grassland
	Calcareous grassland - upland	
	Coniferous woodland	Coniferous woodland
	Dwarf shrub heath - lowland	Heathland
	Dwarf shrub heath - upland	
	Earth heritage	
	Fen, marsh and swamp - lowland	Fen, marsh and swamp
	Fen, marsh and swamp - upland	
	Inland rock	
	Littoral sediment	Intertidal mudflats and saltmarsh
	Neutral grassland - lowland	Neutral Grassland
	Neutral grassland - upland	
	Rivers and streams	
	Standing open water and canals	
	Supralittoral sediment	Sand dunes and shingle

2.3.2 Selecting regions and habitats for analysis

There are no clear criteria on which to base the choice of region, habitat and extent for adaptation measures. As noted above, with respect to the multiple components of coastal habitats, these choices should be made with reference to wider regional or landscape level conditions. That is, the benefits of adaptation would be maximised if chosen habitats and measures recognise the regional context of the habitat and the connectivity of habitats in supporting biodiversity and other ecosystem services. We emphasise that the analysis can only ever be illustrative of the scale of adaptation costs and benefits.

There are two alternative approaches to stratification of adaptation action based on either a habitat or region centred approach. Under a habitat approach there may be a key threshold such as the proportion of England's total stock (i.e. >10%) present within a region. For example, Table 7 indicates that SSSI lowland calcareous grassland is largely found in the South East (65% of England total) and the South West (65%), whereas SSSI upland calcareous grassland is exclusively found in the North East and North West (73% and 27% respectively). In contrast habitats such as acid grassland and fen, marsh and swamp are more evenly distributed, in which case targeting of adaptation measures would need to reflect spatial vulnerability (as well as initial condition).

Table 7 SSSI Habitat presence in each region as a percentage of England total (all condition levels)

	East Anglia	Midlands	North East & Yorkshire	North West & Merseyside	South East	South West
Calcareous grassland - lowland	6	5	3	1	19	65
Calcareous grassland - upland	0	0	73	27	0	0
Acid grassland - lowland	43	11	4	1	23	19
Acid grassland - upland	0	14	42	18	0	26
Dwarf shrub heath - lowland	8	7	9	2	45	29
Dwarf shrub heath - upland	0	8	0	61	18	13
Fen, marsh and swamp - lowland	24	4	12	7	39	13
Fen, marsh and swamp - upland	0	36	19	16	0	29
Broadleaved, mixed and yew woodland - lowland	15	18	2	1	50	15
Broadleaved, mixed and yew woodland - upland	0	17	29	24	0	29
Supralittoral sediment	17	2	11	21	25	24
Littoral sediment	16	22	14	31	8	9
Coniferous woodland	85	0	0	0	11	4
Neutral grassland - lowland	23	6	4	2	37	28
Neutral grassland - upland	0	3	69	26	0	2

The second approach would be to target adaptation at the region level. Here the relative abundance of each habitat within a region is used to determine which habitats should be targeted. Again 10% may be a reasonable threshold. Table 8 presents the area of each habitat as a percentage of the area of all SSSI habitats within that region. From this we can determine the relative importance of the habitat within the region.

Table 8 also highlights the potential complexity of developing packages of adaptation measures across different habitats at a regional level. For example in East Anglia there are relatively few habitats with areas over our threshold, further those are lowland habitats that might form a landscape of connected habitats. In contrast, the North West and South West have a mix of both upland and lowland habitats resulting in a more complex task for prioritisation of action.

2.3.3 Selecting the area of habitats to apply adaptation

Once the region and habitat (or combinations of these) have been determined it is necessary to identify the area to which adaptation measures will be applied. Again, there are no set criteria for this and local context will be important. The characteristics of each SSSI have developed over time and are often site specific, these sites should also reflect the 'best' examples of the habitat. Consequently they cannot be moved elsewhere and habitat creation is often not an appropriate adaptation action[39].Where compensatory habitat creation is possible then the extent and nature of the new habitat should be determined using appropriate guidance such as that developed be Defra for biodiversity offsetting projects[40].

We suggest that adaptation is applied to areas of habitats that are currently described as being unfavourable. Our rationale is that the aim of adaptation is to ensure resilience against climate impacts and that this resilience may already be a feature of habitats in favourable condition. The adaptation of sites in unfavourable condition is therefore? more likely to of higher priority in the short-term. There is an expectation that on-going monitoring of SSSIs would identify where sites currently in favourable condition are subject to adverse impact (related to location, nature of habitat and nature of impact). Management should be adaptive to ensure that adaptation measures are applied to sites currently in favourable condition should these begin to exhibit signs of decline due to climate change or other drivers.

A further issue is the extent of habitat (and combination of habitats) that should be subject to adaptation measures in a given region. The area subject to management must be sufficient for adaptation to be effective to ensure resilience to impact and continuing ecological functioning. There is no clear guidance here, and relevant habitat thresholds will vary according to habitat and context. The areas subject to management should also recognise connectivity between sites and habitats within a landscape or region.

Table 8 Habitat presence as a percentage of SSSI area in each region (all condition levels)

	East Anglia	**Midlands**	**North East & Yorkshire**	**North West & Merseyside**	**South East**	**South West**
Acid grassland – lowland	3	1	0	0	1	1
Acid grassland – upland	-	3	4	2	-	4
Arable and horticulture	11	-	-	-	0	0
Bogs – lowland	0	0	1	2	0	0
Bogs – upland	-	10	32	23	-	9
Boundary and linear features	0	0	0		0	0
Bracken	0	-	-		0	0
Broadleaved, mixed and yew woodland – lowland	9	11	0	0	28	7
Broadleaved, mixed and yew woodland – upland	-	2	1	2	-	3
Built up areas and gardens	0	0	-	0	0	0
Calcareous grassland –	2	2	0	0	6	17

[39] We have included HLS measures related to habitat creation to allow either sensitivity analysis or in the absence of a ‘restore’ or ‘maintain’ option for some habitats.
[40] https://www.gov.uk/biodiversity-offsetting

lowland						
Calcareous grassland - upland	-	0	2	1	-	-
Coniferous woodland	16	0	0	0	2	1
Dwarf shrub heath – lowland	3	3	1	0	17	9
Dwarf shrub heath – upland	-	11	36	15	-	14
Earth heritage	1	3	3	3	2	3
Fen, marsh and swamp - lowland	5	1	1	1	7	2
Fen, marsh and swamp - upland	-	1	0	0	-	0
Improved grassland	1	-	0	0	0	0
Inland rock	-	0	1	2	0	0
Littoral rock	0	-	0	0	0	1
Littoral sediment	34	46	12	40	16	15
Montane habitats	-	-	0	1	-	-
Neutral grassland – lowland	9	2	1	1	13	8
Neutral grassland – upland	-	0	1	0	-	0
Rivers and streams	0	1	1	1	1	0
Standing open water and canals	5	4	1	2	3	1
Supralittoral rock	0	-	0	0	1	3
Supralittoral sediment	2	0	1	1	3	2

Faded out habitats are not included in the analysis of SSSI adaptation.

2.3.4 Adaptation example: lowland calcareous grassland, South East region

A cost-benefit analysis model can illustrate potential adaptation scenarios. The current condition for the lowland calcareous grassland habitat in the South East region is summarised below.

Condition	Extent (hectares)	% of regional total
Favourable	3,343.03	41.6%
Unfavourable recovering	4,505.55	56.1%
Unfavourable no change	72.37	0.9%
Unfavourable declining	107.91	1.3%
Part destroyed		
Destroyed	2.81	0.03%
Grand Total	8,031.67	

If we assume that sites that have been classified as Unfavourable (recovering, no change and declining) would benefit most from early adaptation measures then the potential area for application of measures is approximately 4686 ha.

The identified HLS options relevant for this habitat are:

HLS code	HLS measure	HLS payment (£/ha)
HK7	Restoration or creation of species-rich, semi-natural grassland	200
HK8	Creation of species-rich, semi-natural grassland	280
HK18	Haymaking supplement	75

Selecting option HK7 – Restoration or creation of species-rich, semi-natural grassland – as the most appropriate adaptation measure and apply this to 25% of our target area of 4686 ha, then the present value cost of adaptation in £ 3,329,966. This is the discounted annual cost of £ 234,300 for management over 20 years.

The benefits of adaptation in terms of an initially improved set of ecosystem services are £469 per ha arising from the improvement in condition due to the adaptation measure (Christie et al's, 'increased funding' scenario). As the benefits of adaptation measures will be subject to a time lag the spread sheet allows users to select an appropriate lag period. The figures below assume a 10 year lag in benefits.

Climate induced degradation of the habitat will result in a loss of ecosystem service benefits. For lowland calcareous grassland this would be £10 per ha (based on Christie et al's 'maintain funding' scenario).

Having determined the habitat, extent, adaptation measures and delay in benefits, users can select the delay in climate induced degradation due to adaptation. Despite adaptation we still assume that there will eventually be 100% degradation in vulnerable habitats. Degradation can be specified as both the time period over which it occurs (intervals between 40 and 160 years) and the delay before degradation begins (30, 60 or 90 years).

In this example we have selected 100% degradation to occur over 100 years, but adaptation delays the onset of degradation by 60 years. Under these assumptions the present values (initial discount rate is 3.5% declining to 1.5% after 200 years) of the benefit and cost items are:

Ecosystem service benefit due to adaptation:	£ 39,890,108
Ecosystem service loss due to degradation:	£ 413,925
Costs of adaptation measure:	£ 3,329,966
Net benefit of adaptation:	£ 36,974,067

Therefore under the assumptions made there is a £37m net benefit to adaptation in this example.

2.3.5 Research gaps and uncertainties

Our analysis of the cost and benefits of adaptation for protected areas relies on the key assumptions that climate vulnerability can be reduced through increasing the resilience of habitats and that this is linked to site condition. Consequently, adaptation should initially be focused on sites currently in unfavourable condition with the aim of increasing their resilience to change. With respect to benefits we have used existing estimates based on values for the portfolios of ecosystem services supported by different habitat types.

There is uncertainty over the degree to which condition assessments can be related to climate vulnerability. Research is required to establish the specific condition-vulnerability relationships for different habitats and regions.

More precise valuation of adaptation benefits might be possible by developing a greater understanding of the relationship between condition and ecosystem service provision and how in turn this may be affected by future climate change. In other words, we make the implicit assumption that the relative proportions of ecosystem services provided by each habitat remain constant regardless of condition or climate change impacts. In reality we might expect the balance of services and hence benefits to vary with some declining whilst others improve.

There should also be further exploration of the links (in terms of biodiversity and ecosystem services) between different habitats at landscape and regional scales and their responses to climate and adaptation. This would help to determine optimal adaptation strategies.

The spreadsheet model assumes a counterfactual of no adaptation or management measures; but there is existing management in place for SSSIs. The Government's Biodiversity Strategy for 2020[41] requires that 50% of SSSI sites in England will be in favourable condition and 95% of sites will be in either favourable or recovering condition. Consequently, actions that will help to achieve adaptation should be taking place. Our model together with information on vulnerability can be of use in selecting habitat types, extent (the strategy refers to sites not area) and location that could be targeted to optimise the adaptation benefits whilst meeting the Biodiversity Strategy.

[41] https://www.gov.uk/government/publications/biodiversity-2020-a-strategy-for-england-s-wildlife-and-ecosystem-services

3 Adaptive Management Measures

3.1 Crop disease in a changing climate

3.1.1 Introduction

In general terms, the projected increases in temperature and elevated levels of CO_2 should provide more favourable conditions for crop growth and development (Knox et al., 2012). However, these potential productivity gains will only be achieved where the growing conditions are not constrained by other factors such as water and nitrogen availability, and the increased incidence of new pests and diseases.

In the UK, average wheat yields have shown little increase over the past decade, failing to increase in line with genetic improvements, suggesting that plant breeding benefits are being lost elsewhere in the production cycle (Knox et al., 2012). This yield plateau can be attributed to soil management issues (e.g. degradation, compaction, and fertility), inadequate crop nutrition, failure to control weeds, pests and diseases or, more likely, a combination of these factors.

For this study we have looked at two of the most important current diseases of winter wheat; Septoria (*Mycosphaerella graminicola* Syn*. Septoria tritici*), and brown rust (*Puccinia tritici*), and evaluated the potential changes in the distribution and severity of these diseases under climate projections for 2020, 2050 and 2080.

Septoria (*Mycosphaerella graminicola* Syn*. Septoria tritici*)

Septoria is the most important foliar disease on winter wheat in the UK. Losses of 50% have been reported in severely affected crops. This is largely because of the predominance of varieties which are susceptible to the disease. It is the principal target for foliar fungicides applied to wheat and the major target for resistance breeding for the UK market and in most of western Europe.

The regional severity of Septoria on wheat varies between seasons, but a map generated by surveys carried out between 1998 and 2007 (Figure 7) identifies areas where there is a higher risk of Septoria, primarily in the South-West and Welsh Borders. Early drilled crops are exposed to incoming ascospores of Septoria for longer periods and hence tend to have higher levels of disease through the winter and early spring period. Later drilled crops may carry lower levels of disease through the winter period but this has little effect on the final level of disease in the crop as inoculum is rarely limiting, the final level of disease being determined largely by weather conditions during stem extension. Consequently severity and distribution of disease can vary depending on agronomic practice and the weather.

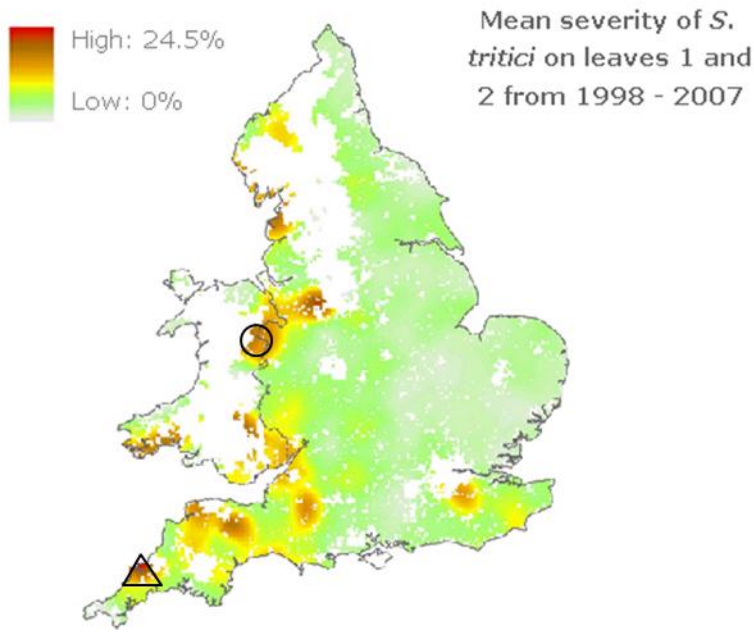


Figure 7: Severity of Septoria on wheat 1998 – 2007 (source Crop Monitor). ○ and Δ indicate 'hot spot' areas used as climate envelopes for Septoria.

Brown rust (*Puccinia tritici*)

Until recently brown rust was not considered to be a major problem despite early-sown crops generally carrying high levels of brown rust through the winter. However, the occurrence of new virulent strains overcoming varietal resistance in a few key wheat varieties has moved brown rust up the league table of importance. Severe attacks result in a significant loss of green leaf area and hence yield; infection of the ears of the plant? will also result in loss of grain quality.

Until recently the disease was rarely important in the spring as temperatures between 15°C and 22°C, accompanied by 100% relative humidity are needed for sporulation and spore germination. Consequently, brown rust epidemics have normally occurred during mid to late summer in the UK with dry windy days which disperse spores, and cool nights with dew, favouring the build-up of the disease. However, with mild winters, brown rust can often be found at high levels in the spring. With projected climate change, mild winters and warm springs are likely to lead to brown rust becoming a more common problem earlier in the season.

A map generated by surveys carried out between 1998 and 2007 (Figure 8) identifies areas where there is a higher risk of brown rust, the most severe cases of the disease being found in the South-East and in north-east Cambridgeshire.

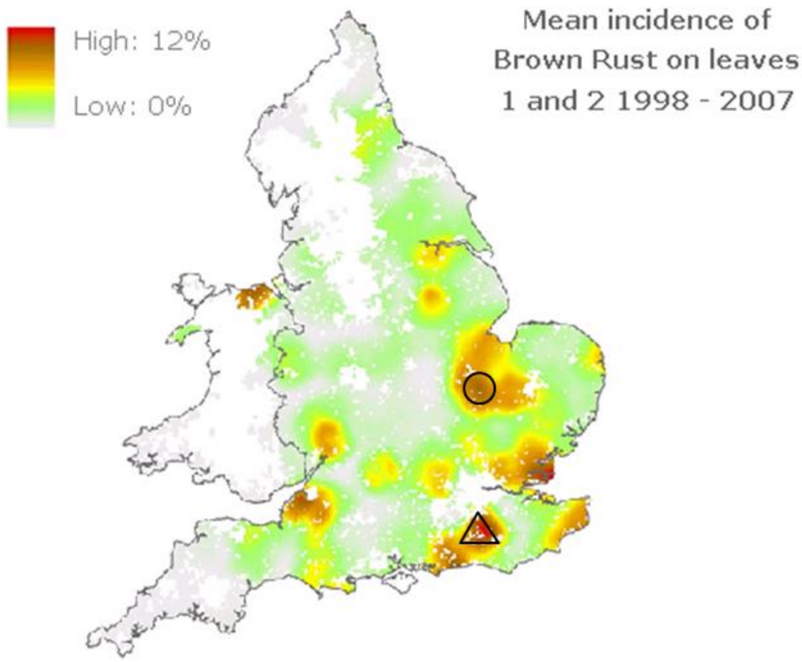


Figure 8: Mean incidence of Brown Rust on wheat 1998 - 2007 (source Crop Monitor) ○ and Δ indicate 'hot spot' areas used as climate envelopes for brown rust.

3.1.2 Key existing reports

There are a number of reports and websites which have detailed the potential impacts of climate change on crop disease, the current costs of disease outbreaks in the UK, and that review current disease surveillance strategies.

Burnett, F., Fox, N. J., Hutchings M. R., Moran D., Searle A., Stott A., Vosough Ahmadi B., Wall E., White P., and Wreford A. (2009). A Strategic Review of Recent Past and Current Research Programmes Relating to the Effects of Environmental Change on Animal, Plant and Human Health. (Project Number SCL/015/09). SAC. Scotland.

Clark (2011). EURO-wheat: A European collaboration on resistance characteristics of wheat cultivars, wheat pathogen virulence, disease management tools and fungicide efficacy. Home Grown Cereals Authority (HGCA) Project Report No. 462. December 2011.

Clarke, S., Sylvester-Bradley, R., Foulkes, J., Ginsburg, D., Gaju, O., Werner, P., Jack, P., Flatman, E. & Smith-Reeve, L. (2012). Adapting wheat to global warming or 'ERYCC' - Earliness and Resilience for Yield in a Changing Climate. HGCA Project Report No. 496. July 2012.

Crop Monitor. http://www.cropmonitor.co.uk/ The Home Grown Cereal Authority (HGCA) provides a service monitoring disease levels in winter wheat, winter oilseed rape, spring beans, winter barley and potatoes.

Foresight (2010). The Future of Farming and Food. Challenges and choices for global sustainability. pp211. Government of Science, London.

Foresight (2011). Land Use Futures: Making the most of land in the 21st century. Executive Summary. pp46. Government of Science, London.

Foresight International Dimensions of Climate Change (2011), Final Project Report, The Government Office for Science, London

Hermans, C.M.L., I.R. Geijzendorffer, F. Ewert, M.J. Metzger, P.H. Vereijken, G.B. Woltjer, A. Verhagen (2010). Exploring the future of European crop production in a liberalised market, with specific consideration of climate change and the regional competitiveness. Ecological Modelling doi:10.1016/j.ecolmodel.2010.03.021

Knox J.W., Hurford, A., Hargreaves, L. & Wall, E. (2012). Climate Change Risk Assessment for the Agriculture Sector. UK 2012 Climate Change Risk Assessment (CCRA) Defra January 2012.

Knox J, Morris J, Hess T, 2010, Identifying future risks to UK agriculture crop production: putting Climate Change in context, Outlook on Agriculture 39 (4), 249–256

Semenov, M. (2009). Impacts of climate change on wheat in England and Wales. Journal of the Royal Society Interface 6(33): 343–350.

3.1.3 Link to hotspot map (i.e. spatial dimension and timing) where relevant

Two 'hot spot' areas of disease were chosen to obtain two climatic envelopes (see Box for explanation of climate envelopes and climate mapping approach) for the climatic suitability of Septoria based on the historical severity map in Figure 7. These were the Welsh Borders area (○ in Figure 7; latitude 52.92, longitude -3.08), and the north of Cornwall (Δ in Figure 7; latitude 50.58, longitude -4.92).

Climate Mapping

Climatic mapping can be used to assess the potential distribution of disease based on the climate in a 'hot spot' of disease severity (Baker *et al*, 2000), through comparing 'hot spot' climatic parameters with other regions. CLIMEX (Ver. 3) was used in this study to assess potential distributions of disease through comparing climates of disease 'hot spots' using the match climates function within CLIMEX. The match climates function uses meteorological data of a 'home location' or in this case a disease 'hot spot' to create a 'climate envelope' for that disease, and compares this climate envelope with meteorological data from the rest of England. Similarity is based on seven indices; maximum temperature, minimum temperature, average temperature, rainfall pattern, total rainfall, relative humidity and soil moisture. A Composite Match Index combines all variables to provide an overall climate match, indicating the degree of overall climatic similarity with the climate envelope (Sutherst *et al*, 2007).

The climatic envelope maps for Septoria for the current climate and the projected climates for 2020, 2050 and 2080 are shown in Figure 9 (Welsh Borders) and Figure 10 (Cornwall).

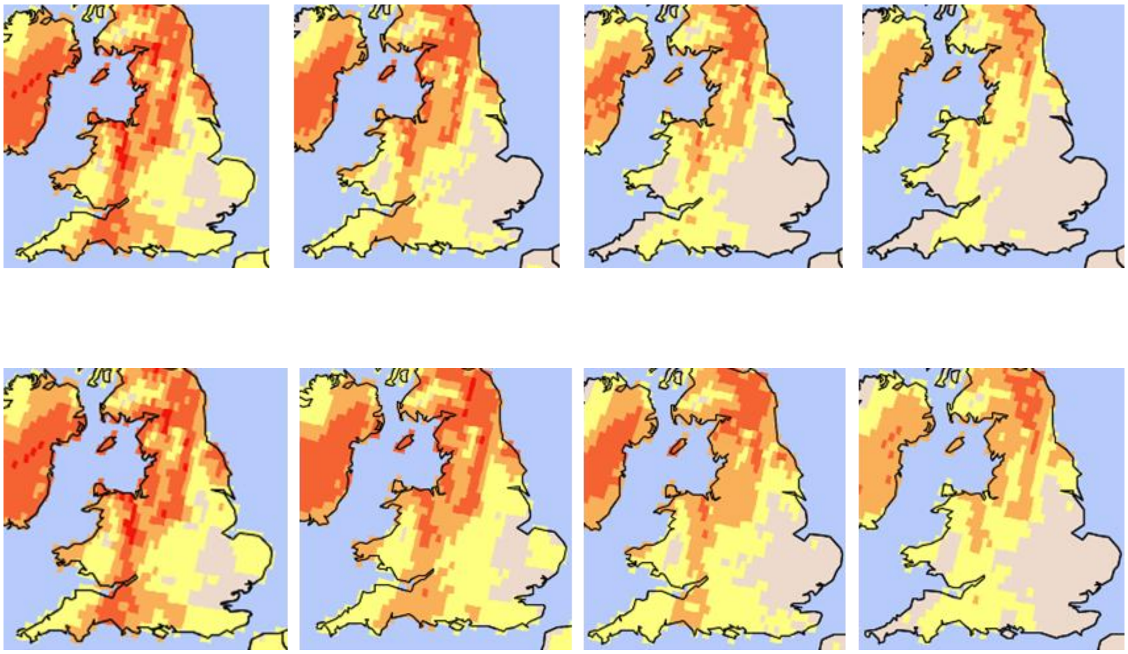
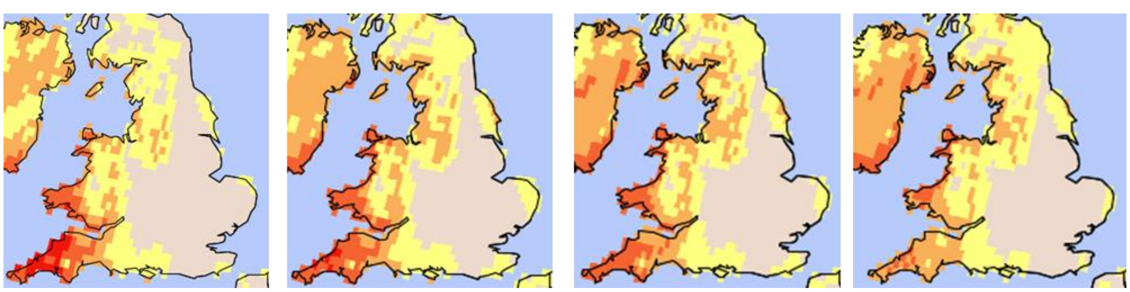


Figure 9: Areas that match the climatic envelope of the Welsh Borders as being suitable for Septoria: from left to right; current climate, 2020, 2050 and 2080. The darker the colour, the greater the match with the climatic envelope. Top; High emissions scenario 90% probability level (p90); Bottom; Low emissions scenario 10% probability level (p10).

Under the high emissions 90% probability level climate projections, when the Welsh Borders climate envelope is compared to the climate projections (Figure 9– Top), there is a reduction in the area that matches the climatic envelope currently suitable for Septoria severity.

Under the Low emissions 10% probability level climate projections, when the Welsh Borders climate envelope is compared to the climate projections (Figure 9– Bottom), there is a gradual decline in the area that matches the climatic envelope currently suitable for Septoria from the 2050s onwards.



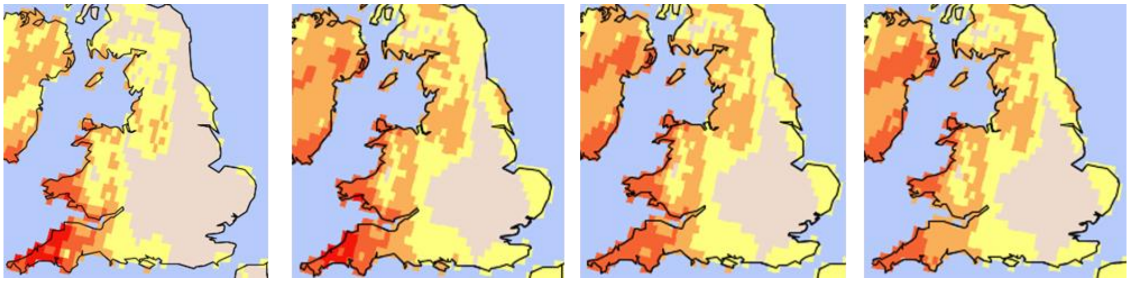


Figure 10: Areas that match the climatic envelope of north Cornwall as being suitable for Septoria: from left to right; current climate, 2020, 2050 and 2080. The darker the colour the greater the match with the climatic envelope. Top; High emissions scenario 90% probability level (p90); Bottom; Low emissions scenario 10% probability level (p10).

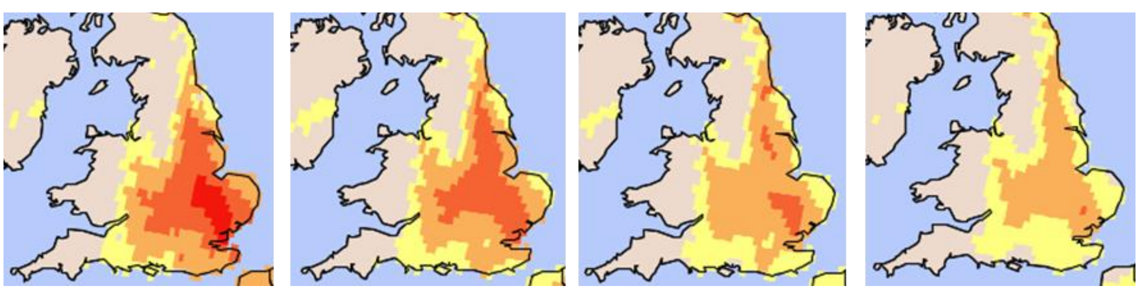
When the Septoria climatic envelope for north Cornwall is compared to the high emissions 90% probability level climate projections (Figure 10– Top) there is no significant change in areas with matching climates; Cornwall and south-west Wales remain as a suitable climate for Septoria, with the north-west becoming more suitable for Septoria.

Under the Low emissions 10% probability level climate projections, when the north Cornwall climatic envelope is compared to the climate projections (Figure 10– Bottom), there is an increase in the area that is suitable for Septoria from the 2020's, with no real change over the next 60 years.

In summary, Septoria is likely to remain as a significant disease under future climate projections, with the potential to spread into areas which are currently less climatically suitable. Adaptations to reduce the threat from Septoria are discussed below.

Two 'hot spot' areas of disease were chosen to obtain a climatic envelope for the climatic suitability of brown rust based on the severity map in Figure 8.

These were north-east Cambridgeshire (○ in Figure 8; latitude 52.42, longitude 0.42), and the south-east (Δ in Figure 8; latitude 51.08, longitude -0.08)



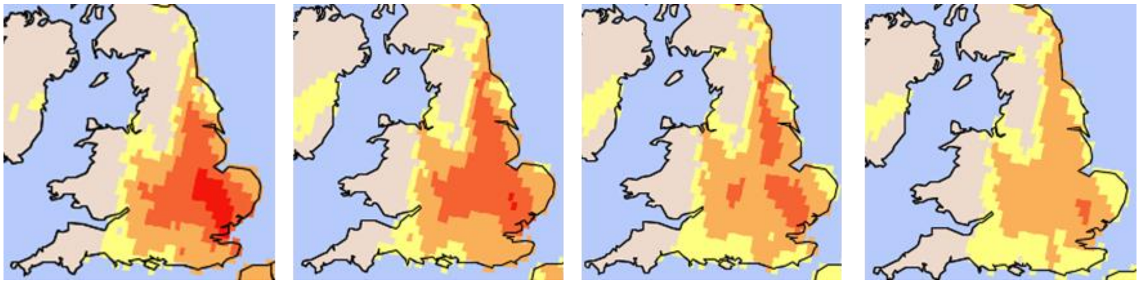


Figure 11: Areas that match the climatic envelope of north-east Cambridgeshire as being suitable for brown rust: from left to right; current climate, 2020, 2050 and 2080. The darker the colour the greater the match with the climatic envelope. Top; High emissions scenario 90% probability level (p90); Bottom; Low emissions scenario 10% probability level (p10).

When the brown rust climatic envelope for north-east Cambridgeshire is compared to the High emissions 90% probability level climate projections (Figure 11– Top) there is a decrease in the brown rust severity, although the area susceptible to brown rust remains relatively consistent.

Under the Low emissions 10% probability level climate projections, when the north-east Cambridgeshire climatic envelope is compared to the climate projections (Figure 11 – Bottom), there is a slight increase in the area that is suitable for brown rust from the 2020s, with no real change over the next 60 years. The area suitable for severe brown rust outbreaks declines.

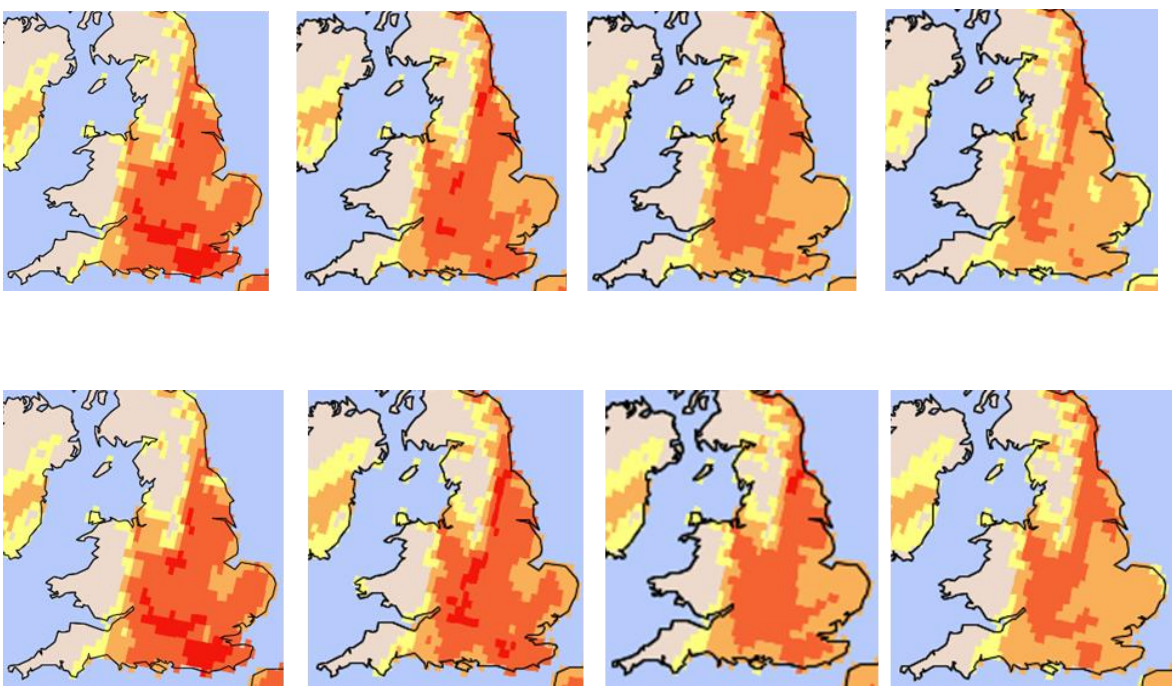


Figure 12: Areas that match the climatic envelope of the south-east as being suitable for brown rust: from left to right; current climate, 2020, 2050 and 2080. The darker the colour the greater the match with the climatic envelope. Top; High emissions scenario 90% probability level (p90); Bottom; Low emissions scenario 10% probability level (p10).

When the brown rust climatic envelope for the south-east is compared to the High emissions 90% probability level climate projections (Figure 12 – Top) there is a decrease in the brown rust severity, and the area susceptible to brown rust remains relatively consistent.

Under the Low emissions 10% probability level climate projections, when the south-east climatic envelope is compared to the climate projections (Figure 12 – Bottom), there is an increase in the area that is suitable for brown rust from the 2020s, with areas suitable for severe outbreaks spreading into the Midlands and into the north-east. The areas suitable for severe outbreaks decline by the 2050s and into the 2080s.

In summary, brown rust is likely to decline in severity and distribution under projected future climates, primarily due to less risk of achieving 100% relative humidity to achieve sporulation. However, extreme weather events such as storms in the spring could make brown rust outbreaks sporadically occur in some areas. Alternatively, any increased irrigation of crops to counter spring/summer droughts would increase the threat from brown rust by encouraging sporulation.

3.1.4 Rationale for specific adaptation intervention

Adaptations to reduce the threat from Septoria

Wheat growers have several options in the short-term that they can adopt to reduce the threat from Septoria, including :

- Increase level of crop surveillance (Crop Monitor)
- Changing sowing date
- Choice of fungicide
- Sowing a resistant variety
- Improvement in farm machinery, precision farming & new technologies
- Taking agronomic advice from external consultants
- Breeding of resistant cultivars
- Development of new fungicides

Changes to agronomic practice such as delaying sowing of the crop reduce the risk of Septoria spores getting into crop over the winter. However, as Septoria tends to be widespread and present on most crops, there tends to be an unlimited supply of inoculum available to infect crops, whether it be in the winter or early spring.

Widespread adoption of Septoria resistant varieties and rigorous and effective fungicide programmes (i.e. more expensive using new products) will reduce the levels of available inocolum, however, all growers in an area would need to adopt this approach, as any Septoria-infested wheat within an area can act as a reservoir of disease. Adopting Septoria resistant varieties and more intensive fungicide programmes brings with it a risk of increased pressure of Septoria breaking the crop resistance and/or becoming resistant to chemical fungicides. Consequently there is a need for continual improvements in breeding resistant wheat varieties to Septoria, and development of new fungicides to cope with the likely change in Septoria susceptibility.

Advances in Septoria management beyond those outlined above could include improved forecasting of the disease based on risk assessments linked to variety, weather, previous seasons' severity, and spore trapping for example. The development of this type of management relies on investment by levy boards, government and private companies to fund the research and validation necessary to convince growers that paying for this system provides an adequate return in terms of increased disease protection, yield and quality.

Adoption of new technologies and investment in precision farming can be considered both short and long-term approaches that can be adopted by growers that would aid in the management of Septoria, but are most likely to be undertaken as an investment in improving all aspects of crop production and not specifically for a single problem such as crop disease.

The wheat breeders will need to encompass a range of attributes in the development of new commercially suitable varieties of wheat, of which Septoria resistance is just one attribute. Drought tolerance, resistance to other diseases and pests, yield and quality are all attributes that need to be considered. It is unlikely that varieties that have all of the desired attributes will be available in the short-term, or in the long-term, and will often be dictated by the commercial requirements of the day; primarily yield and quality followed by other requirements.

Pesticide manufacturers are continually developing fungicides with novel modes of action, and this will be necessary to combat changes in disease resistance and sensitivity to the popular products of the day. Development of new fungicides is a challenging and expensive process (taking up to 10 years and costing of more than €300 million), and the cost is likely to increase with stricter environmental and regulatory frameworks being adopted by the EU.

Adaptations to reduce the threat from brown rust

Many of the adaptations outlined above for Septoria are also applicable to brown rust. Growers can improve management of the disease through choice of resistant cultivars, improved fungicide programmes and taking advantage of advice offered on weather-driven increases in brown rust risk. As brown rust is a relatively new problem in the UK, there are still many answers required on its biology such as is there a risk of seed borne infection for example? Currently the occurrence of warm springs with 100% humidity are relatively rare, however in the future warm springs will be the norm and growers may well increase the risk of brown rust through irrigation of crops to counteract the lack of rainfall. Unpredictable extreme weather events such as storms will also increase the risk of brown rust outbreaks beyond the immediate control of growers.

3.1.5 Costs

Crop surveillance is currently coordinated through a HGCA-funded project – Crop Monitor (see www.cropmonitor.co.uk). This involves regular monitoring of crops for the onset of disease, and the use of forecast models to predict the severity of disease, with growers able to access 'real-time' data on disease via smartphone apps as well as via the web site. The current annual budget for the monitoring of winter wheat for disease is £180,000, and it is expected that this budget will rise annually via inflation and the need for increased monitoring to cover areas of the country where growers may well start growing wheat due to more favourable growing conditions because of the changing climate.

Currently fungicide programmes used on wheat target several diseases rather than a single disease in isolation, so it is difficult to tease out the specific cost involved in protecting wheat from Septoria. However, fungicide trials specifically targeting Septoria have indicated that yield increases of up to 2 t/ha can be achieved using the most modern (and expensive) fungicides currently available. This translates into an increase of up to £400/ha assuming a market price of £200/t for wheat. Currently a robust fungicide programme on wheat costs around £100-120/ha (Craig & Logan, 2012). In the short-term growers should focus on using wheat cultivars with good Septoria resistance and a solid fungicide programme (i.e. best practice) to maintain a 1-2t/ha benefit. In seasons such as 2011/2012 where Septoria was an increasing problem due to the wet spring/summer, the disease pressure (including other diseases) reduced yields despite robust fungicide programmes, so there is always the risk of extreme weather events having a negative impact on yields and ultimately increasing costs through the need to apply more fungicide.

Use of precision farming techniques and adapting machinery will involve an investment by the grower, which would cover all aspects of crop production and not specifically targeted at Septoria or wheat crops alone. A cost/benefit analysis of precision farming techniques for cereals and oilseeds (Knight *et al.,* 2009) indicated that adopting precision farming technology and machinery would cost £14.25/ha for a 300 ha farm, £26.50/ha for a 500 ha farm, and £36/ha for a 750 ha farm, and the benefits were estimated to be £20/ha (28.8%), £36.25/ha (26.9%) and £55/ha (34.5%) respectively. However, Knight *et al* (2009) concluded that there is little to be gained from attempting to apply variable rate fungicides to crops given our current capabilities and understanding.

Growers can benefit by paying for advice from specialist crop consultants who can advise on fungicide programmes, variety choice, and other agronomic inputs. Typically costs range from £8-£10/ha but this encompasses a range of advice and is not specific to disease management. However, taking expert advice, particularly on choice of fungicide programmes may well increase yields up to 20%.

Many costs of adaptation and mitigation are outside of the control of growers. Wheat breeders need to invest in developing new wheat cultivars that encompass a range of traits, and not just disease resistance. Using costs provided by Brennan & Martin (2007) they state a value equivalent to £37.85/ha for breeding a cultivar under 'old' technology, and £42.27/ha using 'new' technology such as molecular markers for specific traits.

Development of new fungicides is essential to replace fungicides that lose their efficacy through a combination of disease resistance and insensitivity. Pesticide manufacturers will also withdraw products due to a declining market as newer more effective products become available. The cost for the development of a new pesticide from discovery to market has been estimated to exceed €300m (£250m) (Bayer Crop science, pers. comm.), and these high development costs are likely to remain or inflate over the next 50 years or so as the costs for obtaining environmental data for approval by the regulatory authorities increase. Consequently the costs for development will need to be recouped from fungicide sales to growers, so the price of fungicides will increase.

3.1.6 Benefits

Total hectares of crops affected using the current estimated hectarage of wheat in England from HGCA figures = 1,875,000 ha. If we assume hectarage remains constant at this level, then the area currently moderately-severely affected by disease (Septoria and brown rust combined (Figs. 1 & 2) is ~70% = 1,875,000 x 0.7 = 1,312,500 ha. Under the low (p10) climate change scenario, by 2020, the area affected by moderate-severe disease from climate mapping was estimated to be 60% = 1,125,000 ha; by 2050 (40%) = 750,000 ha, by 2080 (20%) = 375,000 ha. Under high (p90) climate change scenario, by 2020, area affected by moderate-severe disease from climate mapping estimated to be 50% = 937,500 ha, by 2050 (20%) = 375,000 ha, by 2080 (10%) = 187500 ha. All of these estimates assume that there are no shifts in disease virulence.

Options and benefits under the control of the grower

Crop surveillance as under the current Crop Monitor programme funded by the HGCA has a budget for winter wheat crop surveillance for 2013 of £180,000. The benefit of surveillance (Crop Monitor or equivalent) is an increase in yield of up to 2 tonnes/ha based on SAC/SRUC experience of crop surveillance to inform growers of fungicide inputs. If we assume the wheat price at £200/t, this would lead to a £400/ha benefit from the use of crop surveillance to inform fungicide decisions and timing of application.

A change in sowing date would have no cost to the grower but yield benefits in terms of reduced disease inoculum on crop over the winter. This would reduce the risk of disease in the spring/summer and potentially yield up to an extra 1 tonne/ha (up to a £200/t benefit).

If a grower was to change their fungicide programme to a more robust programme to combat increased threat from disease, the extra cost above a £119/ha basic fungicide programme (seed treatments and fungicide sprays) would be estimated to be an extra 10% above the basic programme. SRUC/SAC fungicide trials indicate a potential 2 tonnes/ha yield benefit = £400/ha benefit at current wheat price of £200/t.

If a grower was to specifically grow disease resistant cultivars – the current seed cost is approximately ~ £400/t. Resistant cultivars will be more expensive ~ £420/t. A yield benefit of 1 t/ha would lead to a benefit to choosing resistant cultivars of around £200/ha.

Improvement in farm machinery, precision farming & new technologies and their adoption by a grower could provide the following benefits based on figures from Knight et al (2009). The estimated costs of adaptation of £14.25/ha for a 300 ha farm, £26.50/ha for a 500 ha farm, and £36/ha for a 750 ha farm, would lead to benefits of £20/ha, £36.25/ha and £55/ha respectively. Note this is whole farm adaptation not specifically for disease control. If we were to take the middle values of £26.50/ha cost and £36.25/ha benefit for this example it would lead to a benefit of 29.5% per annum.

Taking paid advice from agricultural consultants in the form of crop walking, meetings and guidance on fungicide programmes currently costs around £10/ha. The potential benefit based on using advice from consultants to have better timing and choice of fungicide programme could give up to an additional 2 t/ha yield = £400/ha.

Options outside of the grower control

Breeding and development of disease resistant cultivars is dependent on the plant breeding companies investing in this area. Costs borne by the plant breeder include development of all new cultivars and traits such as disease resistance, drought tolerance yield and quality, and not breeding specifically for Septoria or brown rust resistance. Using costs provided by Brennan & Martin (2007) they state a value equivalent to £37.85/ha for breeding a cultivar under 'old' technology, and £42.27/ha using 'new' technology. Adoption of new varieties by growers would expect yields to improve up to 2 t/ha = £400/ha.

Development of new fungicides is essential to maintain and potentially increase yields. New fungicide products are likely to be launched on a regular basis and old products phased out. Currently fungicides provide a benefit of ~ 2t/ha in yield = £400. Cost for new fungicide development are ~ £250m per product over a 10 year development phase. This includes safety testing, environmental impact, formulation, registration costs, marketing etc.

A typical scenario for a grower would be as follows:

Grower is in a high-risk area for disease based on historical prevalence and severity (from Crop Surveillance). The grower would consequently choose a disease resistant cultivar (at extra seed cost of ~ £20/tonne).

Grower would pay consultants for crop walking and advice so that they could inform him/her when disease starts to appear in the crop and advise on a fungicide programme.

Grower may have invested in precision farming technology for their sprayers so that targeted applications of fungicides may be possible.

Adopting one, two, or all of the above may give a potential yield increase of up to 2 t/ha.

In some cases just using one of the adaptations (e.g. more expensive fungicide programme) would provide a 2 t/ha yield.

Benefits of adaptations are not additive.

3.1.7 Uncertainties

For many sub-sectors within agriculture, there remains much uncertainty in the direct impacts, but also uncertainty in the indirect effects, including the future sustainability of rural communities, the viability of particular production sectors and the increasing pressure on the natural resources (land, water, energy) on which agriculture is heavily dependent (Knox et al., 2012). There are significant gaps in the scientific literature on the projected impacts of climate change, including climate uncertainty and adaptation responses. This includes impacts on disease as well as other factors affecting crops. The development and application of the risk metrics for wheat disease include a number of assumptions, particularly regarding future impacts on crop production which need to be recognised. In reality, crop yield is a function of a large inter-related number of climate, soil and crop management factors.

3.1.8 Cost Benefit Analysis

Figure 13 illustrates the reduction in wheat crop area affected by moderate-severe levels of disease as climate changes from 2013 to 2100. This decline is based on estimates on disease severity from the climate envelopes shown previously.

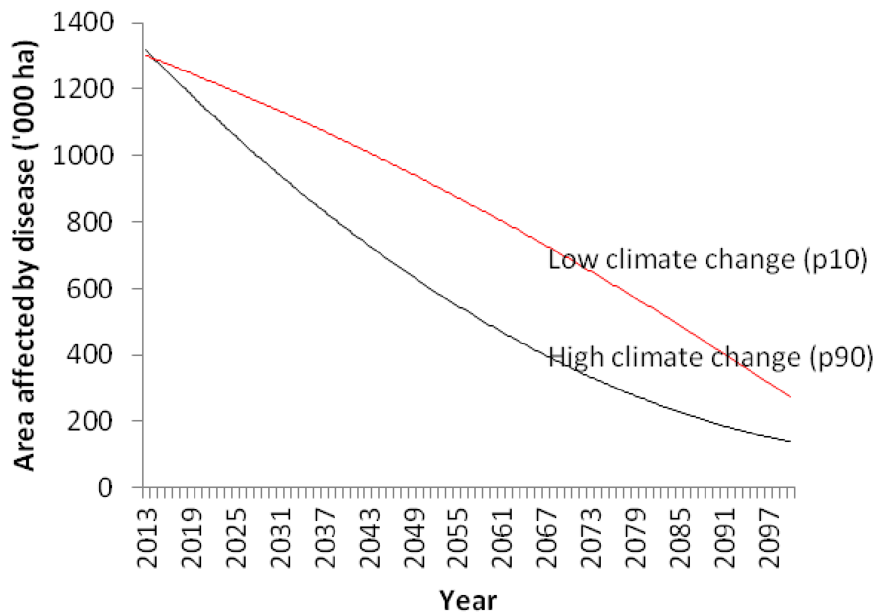


Figure 13: Area of wheat crop predicted to be affected by moderate-severe Septoria and brown rust disease from 2013-2100 under the low (p10) climate change scenario and the high (p90) climate change scenario..

The NPVs for all the adaptations discussed above are presented in Table 9, for both the low and the high emissions scenario. Because the area suitable for these diseases declines under higher climate change, the NPVs for the high climate scenario are lower than the low climate scenario.

Table 9: NPVs for different adaptation options under two climate scenarios

Adaptation	Low climate change	High climate change
Increase surveillance	11.5	9.2
Change sowing date	6.2	5.0
Choice of fungicide programme	12.3	10.0
Disease resistant seed	12.3	10.0

Precision farming	1.1	8.3
Expert advice	12.3	10.0
Breeding resistant cultivars	12.3	10.0
New fungicides	12.3	10.0

These results illustrate that all of the adaptation options have high NPVs regardless of which climate scenario eventuates. Some of these adaptations can be undertaken at reasonably short notice (e.g. changing sowing date, precision farming) while others will require significant planning and investment (developing disease resistant cultivars, and developing new fungicides). It is likely that individual farmers will implement a mixture of the adaptations above, while the industry as a whole should be planning for the longer term adaptations.

3.1.9 Caveats /further research

As with most climate change research and predications based on climate change and financial models there is uncertainty in the value of key parameters. The results of the CBA indicate that there is potential gain up to around 2080 in terms of adopting adaptation strategies for disease (Septoria and brown rust) management; however after this point the area likely to be damaged by these diseases is significantly reduced due to unsuitability of the climate for disease to be moderate-severe.

Caveats related to these conclusions are that the areas where wheat are to be grown remain relatively constant, that the diseases do not adapt to climate chance and increase their virulence, and that improvement in wheat varieties follow the trend over recent years of increasing yields by around 2 tonnes/ha. Financial calculations carried out in this CBA assume a wheat price of £200/tonne, which is perhaps unrealistic as wheat prices will vary significantly over the next century and will of course be subject to inflation. However the trends will be the same in that the NPV for adaptation strategies will decline in parallel with the lowering risk of disease in wheat.

The development and validation of models to predict yields, disease risks requires on-going research.

3.1.10 Conclusions

In the long-term the development and exploitation of new technologies for the management of cereal diseases will provide options for growers in addition to fungicides and resistant varieties. However, as disease threats (in this case brown rust and Septoria) diminish due to climate change, the gain from investment in these adaptation strategies declines. There will be new disease and pest problems likely to arise over the next century which will require similar adaptation strategies to develop cost-effective management. Disease and pest management in wheat (and other crops) will be a continually evolving process, with some problems diminishing (as in the case of Septoria and brown rust in this study) and others arising.

3.2 The importance of improved livestock disease surveillance in a changing climate

3.2.1 Introduction

Environmental change has already been implicated as a driving force for changing patterns of livestock disease outbreaks in the UK, and further increases in disease risk are predicted under future climate change (Burnett et al., 2009). A number of climatic factors directly influence pathogen survival and development, including moisture, temperature and UV levels. Due to the large proportions of their lifecycle spent outside their definitive hosts, where development and survival is governed by abiotic conditions, climate change is having a direct impact on macro-parasites of livestock such as liver fluke (Fox et al., 2011) and blowfly strike (Broughan & Wall, 2007).

Vector-borne parasites are also especially sensitive to climate change. Most elements of a vector's lifecycle and vectorial capacity are influenced by abiotic conditions, and being habitat generalists with high dispersal abilities and reproductive rates, vectors can track their climate envelopes and colonise new areas quickly. Bluetongue Virus (BTV) is transmitted by culicoides midges and a changing climate was identified as a driver of BTV spread across Europe (Purse et al., 2005; Wilson & Mellor, 2008), with the spatio-temporal distribution of the disease echoing the changing distribution of its vectors. Changes in temperature and rainfall will continue to impact on disease transmission through impacting on vector survival, development and vectorial capacity. Extreme weather events, such as high winds, will also aid the passive dispersal of volant vectors into newly viable habitats.

As BTV expansion has demonstrated, viruses that evolve rapidly, lead to subclinical infection of a wide range of hosts and are spread by a plethora of generalist vector species, are likely to be greatly influenced by environmental changes. Expansion of BTV's range warns that other culicoides transmitted arboviruses could also spread with climate change. Primary examples include epizootic haemorrhagic disease which can cause mortality in wild deer and cattle and is currently found in the western Mediterranean, Israel, Algeria and Morocco, and African Horse Sickness currently circulating northwest Africa and resulting in a horse mortality rate approaching 95% (Wilson & Mellor, 2008). The potential impact of new and emerging arthropod borne viruses, whose prevalence and distribution are influenced by climate, is further exemplified by Schmallenberg Virus (SBV). First identified in 2011, SBV is now widespread across Northern Europe (Lievaart-Peterson *et al*, 2012), with multiple outbreaks recorded in the UK in both sheep and cattle (Garigliany *et al*., 2012; Tarlinton *et al.*, 2012). In addition to its impact on livestock, SBV is also circulating in wild deer populations (http://www.bbc.co.uk/news/science-environment-21541997 Access date 22/02/13). Due to the virus's widespread distribution at the point of initial detection, and spread to wildlife populations, this pathogen could prove very difficult to manage and control. In addition to direct effects on pathogens and their vectors, changing environmental conditions and associated changes in livestock husbandry will also influence host susceptibility.

The potential annual average cost of animal disease outbreaks in the UK in 2010 was estimated to be £98 million, with £63 million of that from outbreaks of current unknown or unexpected diseases (DEFRA, 2010). An increase in the prevalence and distribution of animal disease under climate change could therefore have substantial economic implications, in addition to the detrimental impacts on animal welfare. An increase in the prevalence and distribution of animal disease under climate change could therefore have substantial economic implications, in addition to the detrimental impacts on animal welfare. Although the exact nature of the changing risk is unknown, an increase in disease surveillance can mitigate this potential increased risk: through identifying disease incursions early on, silent spread (where there are no clinical signs of disease) and undetected spread can be prevented and control costs lowered.

3.2.2 Key existing reports

There are a number of reports which have detailed the potential impacts of climate change on livestock disease, the current costs of disease outbreaks in the UK, and that review current veterinary surveillance strategies.

Key reports on the impacts of climate change on livestock health:

Burnett, F., Fox, N. J., Hutchings M. R., Moran D., Searle A., Stott A., Vosough Ahmadi B., Wall E., White P., and Wreford A. (2009). A Strategic Review of Recent Past and Current Research Programmes Relating to the Effects of Environmental Change on Animal, Plant and Human Health. (Project Number SCL/015/09). SAC. Scotland.

Haskell, M, Kettlewell, P., McCloskey, E., Wall, E., Hutchings M R., and Mitchell, M. (2011). Animal Welfare and Climate Change: Impacts, Adaptations, Mitigation and Risks (AW0513). SAC. Scotland.

Key report detailing costs of livestock disease outbreaks in the UK

Defra (2010). Draft Animal Health Bill. ISBN: 9780101778428

Key reports on current veterinary surveillance strategies

DEFRA, (2011). A review of the implementation of the Veterinary Surveillance Strategy (VSS).

The Scottish Government, (2011). The review of veterinary surveillance, final report. How information on animal disease is gathered, analysed and disseminated in Scotland. ISBN: 978-1-78045-488-7

The World Organisation for Animal Health (OIE), (2007). Prevention and control of animal diseases worldwide. Economic analysis – Prevention versus outbreak costs. Final report – Part 1.

The findings of this section are not spatially dependent (although spatio-temporal variation in changes in disease risk is expected under climate change).

3.2.3 Rationale for specific adaptation intervention

Effective disease control is underpinned by effective surveillance: planning, implementation, and evaluation of control and management strategies are critically dependent on the systematic collection and collation of disease data, coupled with timely analysis and dissemination of data on animal health.

When comparing the costs of disease preventions versus outbreaks, a review by the OIE (2007) indicated that in the large majority of cases the accrued benefits of disease prevention and control measures outweigh the costs of investment (OIE, 2007).

In the absence of effective surveillance, silent and undetected spread of novel or exotic pathogens can have extensive economic consequences. This was demonstrated by the foot and mouth disease (FMD) outbreak in the UK in 2001, with estimated costs between £3.1 billion (Thompson et al., 2002) and £6.3 billion (OIE, 2007) (estimates vary depending on the assumptions made for the overspill impact). In addition to other factors, the extensive impact and spread of FMD in the UK was attributed to delayed detection of disease (Carpenter et al, 2011; Morris et al, 2001), as by the time the outbreak was diagnosed it was already well established and disseminated, with extensive movement of infected livestock driving an explosive epidemic (Morris et al., 2001). Equally the current SBV outbreak will prove difficult to control as it was already widely spread across multiple countries (and several English farms) before the pathogen was first detected. Through detecting SBV earlier, farmers could have been better informed of the risks and thus better prepared to implement prevention/control strategies.

As environmental conditions in the UK become favourable for the survival and transmission of a changing diversity of pathogens, future control of endemic, exotic, and emerging animal diseases will be critically dependent on their early detection (Souza Monteiro et al., 2012). Improved surveillance would facilitate the rapid detection of disease incursions and reduce the window of opportunity for silent spread; the sooner disease is detected within a population the faster intervention strategies can be implemented, minimising both economic and welfare costs.

Table 10 shows the numbers of samples currently submitted for scanning surveillance in England and Wales, and the total numbers of livestock. This is a voluntary surveillance scheme and does not include the numbers of livestock tested for statutory diseases (e.g. TB, TSEs), monitoring of endemic diseases, health schemes etc. However, scanning surveillance offers the best platform for the detection of unexpected incursions of exotic pathogens under climate change, and this table highlights the limited extent of this surveillance approach. The proportion of wildlife sampled is even smaller with only around 250 samples submitted each year to the GB wildlife disease surveillance partnership (http://www.defra.gov.uk/ahvla-en/publication/wildlife-survreports/). These figures highlight the scope for an increase in scanning surveillance effort.

Table 10: Number of livestock with samples submitted to the VLA, in England and Wales in 2009

	Surveillance submissions to VLA*	Livestock numbers**	% of livestock with samples submitted for scanning surveillance
Cattle	42,122	6,614,051	0.6369
Sheep	7,013	23,221,576	0.0302
Pigs	1,212	3,894,716	0.0311

Poultry	5,453	129,105,974	0.0042

* Surveillance data for England and Wales from: The Scottish Government (2011). The review of veterinary surveillance. Final report. How information on animal disease is gathered, analysed and disseminated in Scotland (pp. 1-60).

** English livestock numbers from:
http://www.defra.gov.uk/statistics/foodfarm/landuselivestock/junesurvey/junesurveyresults/

Welsh livestock numbers from:
http://wales.gov.uk/topics/statistics/publications/welshagriculturalstatistics2010/?lang=en

An outbreak of an unknown major disease was estimated to represent the greatest proportion of animal disease costs in the UK, accounting for 64% of total expected annual costs (DEFRA, 2010). Incursion pressure from novel pathogens into the UK's naïve host population is predicted to rise under climate change (Burnett *et al*., 2009; Haskell *et al*., 2011): strategically targeted surveillance could mitigate this increased risk. One of the ways to pick up new and emerging diseases is scanning surveillance, in which animal populations are monitored for new, unexpected changes in disease patterns. This is currently done passively through analysis of unusual laboratory submissions, notifications from farmers or PVS, and actively through sentinel networks (DEFRA, 2011). Improvements in early warning surveillance strategies will be necessary to prevent both undetected and silent spread of novel pathogens whose ranges are shifting under climate change.

3.2.4 Costs

In 2009/2010 laboratory-based veterinary surveillance had a total program budget of £33.1 million (DEFRA, 2011).

There is a marked difference in spend between different areas of surveillance; the current spend on scanning surveillance is around a third of that of surveillance for specific known diseases (£8.2 million, versus £23.5 million) (DEFRA, 2011). This spend on scanning surveillance is unevenly distributed across host populations, with £3.1 million spent on cattle scanning surveillance in 2009/10, and £0.2 million spent on wildlife scanning surveillance in the same period (DEFRA, 2011). Some case studies suggest that this investment in scanning surveillance currently delivers annual monetised benefits of over £200 million (AHVLA, 2011).

In addition to direct costs of sample analysis, there are indirect costs which are included within the total surveillance program budget. For example, £1.4 million is currently spent per year on the systematic profiling of diseases, and surveillance information management (through RADAR), to inform the prioritisation of surveillance and control activities (DEFRA, 2011).

In the cost-benefit analysis used here, a 100% increase in scanning surveillance costs above baseline levels was used to calculate the increased costs of improved surveillance. Increases in import testing, targeted surveillance for specific exotic pathogens, and infrastructure costs were also incorporated as these services would improve detection of invading pathogens under climate change. Consequently, a 50% increase in the total cost of veterinary surveillance, compared to current base-line levels, was used in the analysis to represent the increment cost of this adaptation.

Although not incorporated in our analysis, there is scope for a step change in the effectiveness of surveillance programmes without increasing costs, through utilising novel technologies. The application of recently developed multiplex technology would enable high through-put screening of animal samples, enabling the rapid detection and identification of a large range of livestock and wildlife diseases (www.wildtechproject.com). This technology currently provides the tools for one test to detect and identify multiple pathogens concurrently (up to 45 pathogens per test in recent studies) (www.wildtechproject.com), for the same price as a single pathogen test using the techniques currently employed by the AHVLA (www.defra.gov.uk/ahvla-en/tests-and-services/lab-services/disease-surveillance-price-list/) . Through utilising such novel technologies, the benefits of improved surveillance could be realised without an increase in costs.

3.2.5 Benefits

Outbreaks of unknown major diseases were estimated to cost the UK an average of £63 million per year (DEFRA, 2010); this number is expected to increase under climate change (Burnett et al., 2009). The most direct benefit of improved surveillance will be through the reduction in the costs of disease outbreaks. Figure 14 illustrates how the costs associated with disease outbreaks can be minimised through their early detection (Carpenter et al., 2011). In addition to decreasing costs of disease outbreaks, increased surveillance will also facilitate the control and management of endemic diseases.

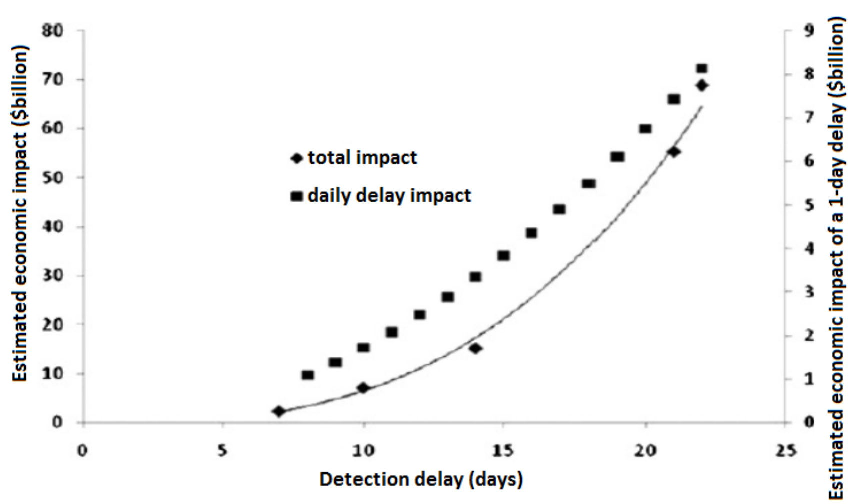


Figure 14 Estimated total and increment daily economic losses associated with a diagnostic delay of a simulated foot-and-mouth disease in Californian dairy herds. From Carpenter *et al.*, (2011).

Modelling the potential impacts of an endemic pathogen being introduced into a naïve host population (parameterised for FMD in California), Carpenter et al., (2011) showed that agricultural losses could escalate from \$2.3 billion if the disease was detected at day 7 post introduction, to \$69 billion if detection was delayed to 22 days. Following detection, the speed of implementation of appropriate control strategies is also important. Traulsen et al, (2011) modelled the impacts of delaying the establishment of control strategies in a livestock disease outbreak; for a simulated outbreak of foot and mouth disease they showed that delaying control by 3 days could lead to over twice as many farms being infected, compared to delaying implementation of control strategies by 1 day. Although these studies indicate that even small improvements in detection time can lead to substantial reductions in outbreak costs, the scope for improvement depends on the disease and risk pathways. This approach has not been applied to a diverse range of host-pathogen systems and there is a lack of studies quantifying the improvement in disease detection time for a given increase in surveillance. We do know the direction of the trend; an increase in surveillance will lead to more rapid disease detection, however the magnitude of the improvement in detection time will vary with both disease transmission characteristics, the vigilance of the owner, the willingness to report and the sensitivity and specificity of available tests. The uncertainties in parameter values are discussed in more detail below, and the analysis explores a full range of potential values to account for this lack of quantitative information.

In addition to decreasing the subsequent economic costs of disease control, improved surveillance would have a number of ancillary benefits. If disease incursions were detected and control measures implemented sooner, the magnitude of outbreaks would be reduced. This would have positive impacts on the total length of time from initial disease incursion to the lifting of trade restrictions. This would minimise potential welfare issues (OIE, 2007) and slaughter measures (OIE, 2007; Thompson et al., 2002) associated with movement restrictions. . Even if slaughter is not required, there are monetary costs associated with movement restrictions, including losses from extra feed requirements and stock being kept beyond the optimum marketing date (Thompson et al., 2002). Thompson et al., (2002) suggested that a 6 month delay in the recovery of livestock export markets following a disease outbreak could cost producers an extra £170 million.

An additional benefit of increased surveillance is the improved availability of epidemiological data. There is currently a lack of quantitative predictions of future disease risk under climate change, due the paucity of active surveillance data required for the parameterisation and subsequent validation of predictive models (Fox et al., 2012). Outputs generated from active disease surveillance could inform the development and parameterisation of predictive models, leading to a better understanding of disease risk under climate change. Such predictive models could also inform future risk-based surveillance and aid the development of improved control strategies.

A proactive approach to detecting and managing future disease threats could also have broader environmental benefits. Both clinical and subclinical infections have deleterious consequences for livestock growth and production. Any measures which improve production efficiency will influence the carbon footprint, hence improved disease management would decrease green house gas emissions per unit product.

Aside from the economic and environmental benefits of decreasing disease levels, reductions in levels of disease will also improve animal welfare. Additionally, many emerging animal diseases are zoonoses and could threaten human health. Through controlling the spread of exotic diseases through targeting livestock and wildlife reservoirs, future threats to public health could be minimised.

3.2.6 Uncertainties

Although the roles of abiotic drivers in transmission dynamics are relatively well understood, quantitative predictions of how livestock disease risk will change under climate change have so far been limited to macro-parasites. Despite this dearth of quantitative predictions, qualitative predictions of changes in disease risk under climate change have been made. Also, the types of diseases most likely to be affected by climate change have been characterised, with those most susceptible to changing environmental conditions being macro-parasites which spend large proportions of their lifecycles outside their definitive host, and micro-parasites which evolve rapidly. These diseases can lead to subclinical infection of a wide range of hosts and are spread by a plethora of generalist vector species.

Climate change has already played a role in the northward spread of vector borne pathogens from mainland Europe to the UK (e.g. BTV and SBV). The risk of disease epidemics in the UK will therefore also be influenced by the ability of the rest of Europe to control disease. If the prevalence and intensity of diseases increases in mainland Europe, the subsequent rise in propagule pressure will increase the risk of outbreaks in the UK.

Uncertainties surrounding the effects of climate change on livestock disease have been incorporated in the analysis through the exploration of a range of potential parameter values (with climate change leading to a 0-25% increase in disease risk per decade). The sensitivity analysis does include values for no increase (where the decline in some pathogens from changes in husbandry etc. cancels out the increased risk in other pathogens due to shifting climate envelopes). However, as we are mainly focussing on incursions of exotic diseases, it is likely that risk from these will increase overall under climate change.

The benefits of improved surveillance strategies varies with the risk of disease incursions (Häsler *et al*, 2012), and there are uncertainties regarding the changes in detection time and potential decreases in outbreak costs as a consequence of increased surveillance effort. We do however know the direction of the trend; finding a disease earlier can substantially reduce economic and welfare costs, and the benefits of surveillance and control strategies have previously been quantified for specific disease outbreaks (e.g Fofana et al, 2009; Häsler et al., 2012).   The probability of disease detection for a given level of surveillance effort varies with a multitude of factors including disease prevalence, and test sensitivity/specificity, however even small improvements in pathogen detection and identification time can lead to substantial reductions in disease costs (see Figure 14) (Carpenter et al., 2011). Therefore the 0-50% reduction in outbreak costs explored in the sensitivity analysis, as a consequence of a 100% increase in scanning surveillance, will provide a conservative estimation of potential benefit/cost.

3.2.7 Cost benefit analysis

Figure 15 shows the overall benefit/cost of improved disease surveillance under climate change from the years 2013 to 2100, based on the Net Present Value (NPV). Here, potential costs of livestock diseases increase by a set % per decade (indicative of increasing disease risk in a changing climate), and the incremented increase in surveillance leads to a percentage reduction in total disease outbreak costs (compared to costs under baseline surveillance conditions). Due to the lacuna in research quantifying both the changes in overall disease risk under climate change, and the reduction in disease costs for a given increase in surveillance effort, a range of potential parameter values are explored. The incremented cost of improved surveillance is calculated as an additional 50% of the costs of current veterinary surveillance programmes, with all cost/benefit calculations for future values incorporating discount rates to provide an NPV (HM Treasury, 2003).

Figure 15 shows that for a majority of the parameter space, the benefits of improved surveillance outweigh the costs. The magnitude of the potential in gain is also far greater than that of the potential loss.

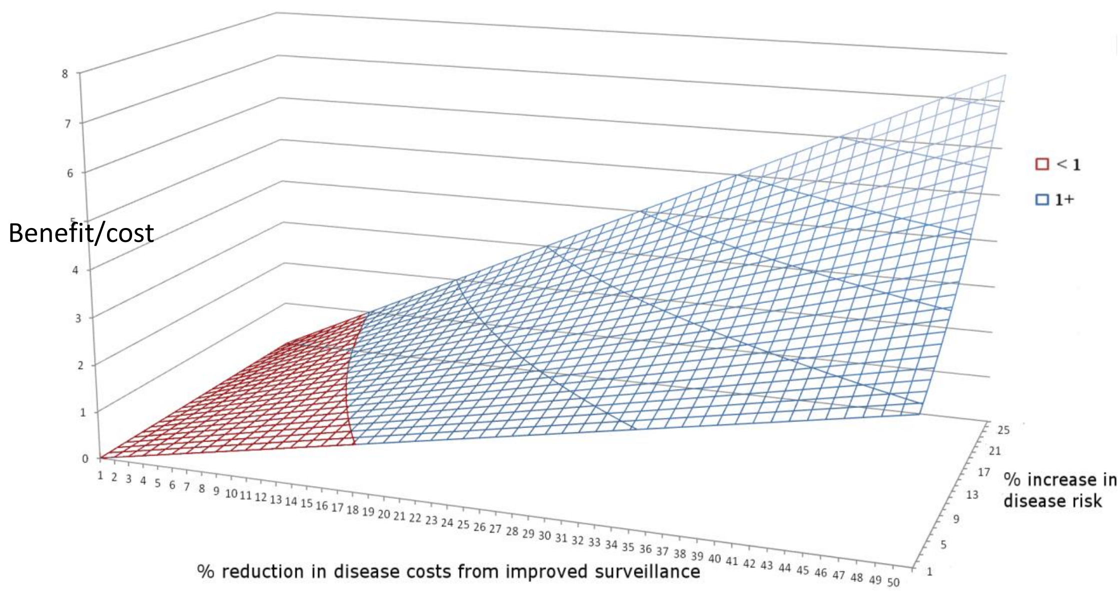


Figure 15: Overall benefit/cost of improved surveillance (based on NPV), for varying degrees of increased risk of disease outbreaks under climate change, and varying levels of reduction in disease costs for a 50% increase in surveillance investment.

Figure 16 breaks the potential benefit/gain down by decade, again using the NPV. As **Figure 15** and **Figure 16** illustrate, the potential benefit varies with the percentage increase in risk of disease outbreaks, especially in latter decades (see **Figure 16**). The different climate change scenarios are incorporated implicitly by varying this parameter with a greater percentage increase in disease risk expected under higher emissions scenarios. Changes in future risk will also be affected by myriad other factors, including changes in livestock management and the disease levels in other countries.

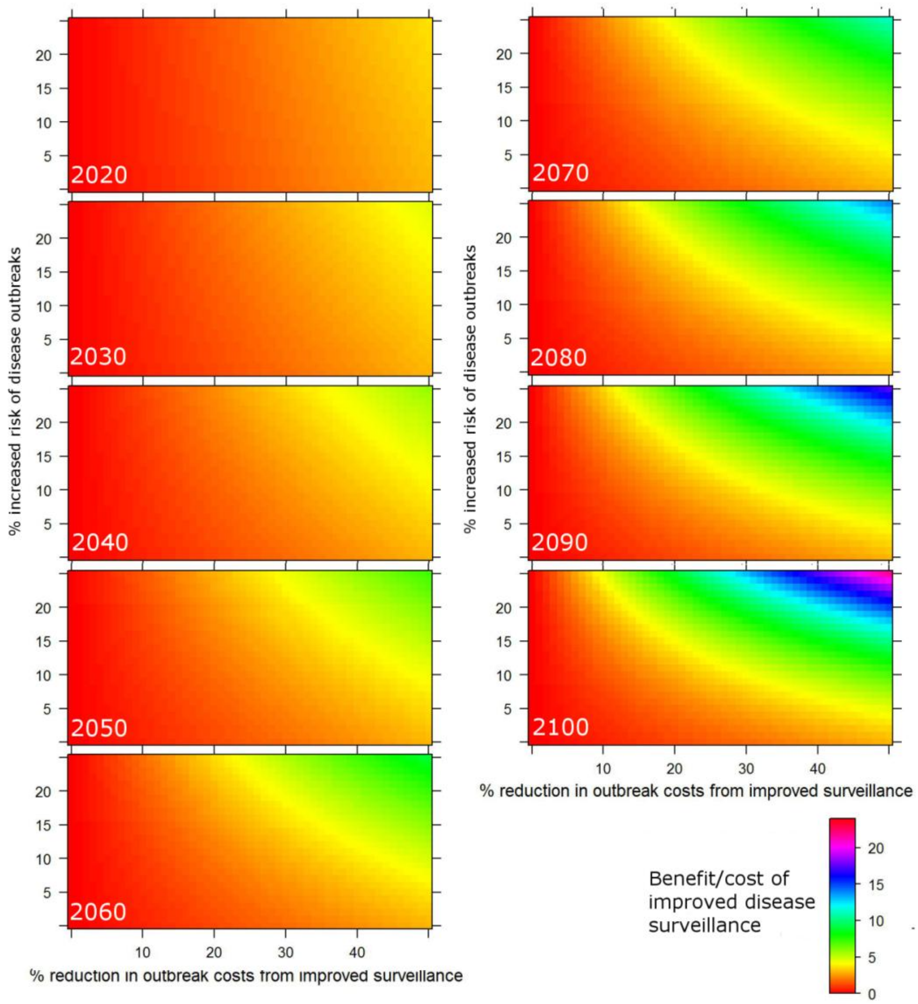


Figure 16: Benefit/cost of improved disease surveillance for each decade, for varying (0-50%) levels of reduction in disease costs from a 50% increase in surveillance investment, and varying (0-25%/decade) increased risk of disease outbreaks under climate change.

Variations in the percentage reduction in outbreak costs from improved surveillance also influence the outcomes of the CBA. As the decrease in disease costs increases (for a given level of surveillance effort), the magnitude of the potential benefit increases. The value of this parameter is dependent on a number of factors, including the extent to which detection is followed up with efficient and timely control strategies, and the sensitivity/specificity of the test technology used (the better the surveillance test and subsequent implementation of control strategies, the higher the percentage reduction in disease costs).

The results indicate that there is potential for economic benefit for the majority of possible parameter values. The sensitivity analysis shows that the benefits of this adaptation are primarily dependent on the efficacy of increased surveillance in leading to a decrease in outbreak costs, and (in the longer term) the extent to which disease risk increases under climate change. Modelling studies based on past outbreaks indicate that disease outbreak costs can be reduced substantially through early detection (and early implementation of control strategies); this indicates that the actual net benefit would be in the upper part of Figure 15.

3.2.8 Caveats /further research

As is detailed above, there is uncertainty in the value of key parameters. Although the results of the CBA indicate that the potential for gain far outweighs the potential for loss across the parameter space, a more accurate estimate of the value of this adaptation would require refined quantitative predictions of these parameter values (e.g. data are required on the % increase in disease detection time for a given increase in surveillance). The development and validation of models to predict these values is an area of on-going research. The assumptions made in the CBA presented here can be considered conservative. Advances in pathogen detection technology have been made which have yet to be utilised at the national scale (e.g. multiplex diagnostics); the implementation of such cutting-edge technology could lead to a step change in the cost and benefits of surveillance.

3.2.9 Conclusion

Climate change is already changing the patterns of disease outbreaks, and will continue to affect the spread of established, new, and exotic pathogens. An improvement in the level and targeting of disease surveillance will allow emerging pathogens to be identified sooner, leading to a substantial decrease in control costs. In addition to the economic and welfare benefits of reduced disease prevalence, there are environmental benefits. Production efficiency is decreased by clinical and subclinical infection, so GHG emissions per unit product can be reduced through improved disease management.

In addition to preventing the spread of emerging pathogens, improvements in the collection of active surveillance data would also improve our understanding of the spatio-temporal shifts in disease risk. The current paucity of data is impeding our understanding of the influence of abiotic drivers, and is hindering the parameterisation and validation of predictive models, making it difficult to quantify future disease risk and identify potential outbreak hotspots. An improvement in disease surveillance will help address these issues, as long as there are frameworks in place to deal with the increase in information.

In this report we focus on scanning surveillance, and our calculations also incorporate increases in import testing, targeted surveillance for specific exotic pathogens, and infrastructure costs. These aspects of surveillance only represent a small percentage of current total surveillance costs. We have chosen to focus on increased scanning surveillance as a worked example as it is most relevant to detecting incursions of exotic pathogens driven by climate change. Ultimately, the more tests that are carried out the more likely a disease will be detected earlier, and the most efficient way to distribute increased surveillance effort remains up for discussion.

Increasing surveillance will only be useful if disease detection is followed up by disease control; although improved surveillance will decrease intervention costs, the infrastructure for the timely implementation of control strategies following pathogen detection is an integral element of mitigation. Ultimately a co-ordinated disease surveillance and management strategy is required, which couples improved sampling with new technologies and risk analysis to identify, characterise, and control disease threats in a changing climate.

3.3 Intensive livestock systems: transportation of intensively produced species – poultry

3.3.1 Introduction

Whilst all livestock production systems may be considered to be sensitive to the threats posed by the projected climate change scenarios it may be proposed that intensive animal production, specifically meat poultry and pig systems, constitute an important area of concern. These systems present some complex challenges in terms of prioritisation of adaptations and assessment of such strategies in terms of true cost-benefit. Indoor intensive systems require various degrees of environmental control and are thus deemed less sensitive to changes in external environments or meteorological conditions, however, current systems may not have the capacity for effective control in the face of large changes in thermal challenges or during an increased incidence of extreme events. In addition the adaptations required under such conditions e.g. improved house design and structures, ventilation systems and insulation, water provision and husbandry practices and procedures have economic costs, energy costs, welfare costs and consequences for the carbon footprints of the systems. It is therefore considered important to model these aspects of the adaptations required by the UK poultry and pig intensive production sectors both in relation to the production or housing requirements and transportation of animals by road to slaughter. The latter may be considered to be extremely vulnerable to changes in average and maximum temperatures and to any change in the frequency and/or severity of extreme events. Defra (2012) has indicated that in relation to the effects of climate change upon agriculture in the UK pigs and poultry may be particularly vulnerable to heat stress and resulting increased mortality. In particular, transportation of animals in heat waves presents major risks to the health and welfare of these species.

The UK broiler industry currently produces and slaughters around 873 million birds per annum. As 919 million chicks are placed this represents mortality on farm of around 5%. The total worth of broiler production to the economy exceeds £1.5 billion. The UK is 91% self sufficient in poultry meat (Anon 2011). There are 5 main integrated companies accounting for >85% of production. These companies have a mixture of contract farms and company farms. The main producer / processors manage the production, catching, transport and slaughter of all their birds. There are approximately 3000 broiler farms in the UK. Each farm will produce between 5-7.5 times their stated capacities of birds i.e. 5-7.5 flocks per annum. Each flock will be grown for approximately 6 weeks with slaughter ages range from 35-42 days and an approximate slaughter body weight of 2.1kg and a 6-10 break between flocks. At any given time approximately 120 million broiler chickens will be on the ground with 95% being brown in intensive shed systems (at a stocking density of 35-35 kg per m^2) and only 5% being described as free range.

Around 21% of the production costs for a broiler are attributable to the purchase of chicks, 58% to feed costs, 7.3% to building costs, 3.5% to labour and 3.3% to electricity, gas, oil and water with a target margin of 3%. The farm total gross output for a broiler is around £1.34- £1.37 with total costs of £1.01 and therefore a margin of around £0.31 per bird. The wholesale to retail value is approximately £1.45 per kg or £2.90 per bird. The current annual increase in demand for poultry meat in the UK is 3.6%.

80% of UK broiler production is undertaken in England and Wales. Historic data (Sheppard 2004) indicate that English producers constitute over half the UK broiler farm sites (approximately 1600) and 98% of the birds are reared in over 700 flocks of more than 20,000 birds. Broiler production is concentrated in England with more intensive output in areas in East Anglia, the South East, the Midlands and Welsh Borders, the South West, Lincolnshire and Humberside and Yorkshire. There are approximately 80 slaughterhouses killing and processing poultry in England reflecting the regional production distributions. The key slaughterhouses associated with the 5 main producers have the largest throughputs and the most extensive catchment areas. In terms of transportation of broilers to slaughter in these main plants the actual times in the UK have been reported as 2.7 hours with the total legal journey time being 3.6 hours (including loading and unloading) despite an average distance from farm to processing plant of only 33.5 kms (Warriss et al. 1990). The maximum journey times in that study exceeded 12 hours. In 46% of journeys birds were unloaded within 3 hours of loading, 78% within 4 hours and 94% within 7 hours of commencement of loading.

Thus, many broiler chickens in England (UK) will be in transit for periods in excess of 2 hours and be held in transport containers or crates on the vehicles and in lairage for periods of 3-7 hours. It has been demonstrated (Mitchell and Kettlewell 1998; 2008) that under such transport conditions thermal loads will develop in the containers which will impose moderate to severe heat stress and an increase in mortality when external temperatures are relatively low. Warriss et al. (2005) have established a very clear relationship between maximum external temperature and broiler mortality in transit (or dead on arrival – DOAs) in England. From a baseline DOA of 0.12% an increase was observed (+30%) when external temperature was between 17-19°C, between 20-23°C it increased 2.6 fold and above 23°C by 6.6 fold. That study identified the period of May to September as the critical time for temperature associated mortality in UK broiler production. It is proposed that the critical maximum daily temperature at which broiler DOA will increase rapidly in the absence of remedial measures is 17°C. It may be postulated that the effect will be exacerbated by extended exposure to hostile thermal micro-environments on-board the transport vehicles on long journeys. It should be noted that recent studies on laying hens (Richards et al. 2012; Weeks et al. 2012) which have poor feather cover and are transported at lower stocking density than broilers, demonstrated that journey time and temperature were the best predictors of DOA in these birds but that low temperatures on extended journeys were the main causes of mortality. Many other studies have demonstrated the relationships between external thermal conditions, journey time and DOA (Ritz et al. 2005, Verecek et al. 2006; Voslarova et al. 2007a and b; Chauvin et al. 2010. Of these studies, those conducted outside the UK report baseline DOAs greatly in excess of those currently found in the UK (e.g. Petracci et al. 2006). It may be suggested that the risk of increases in average DOA in the UK will be elevated under various climate change predictions involving higher average and maximum temperatures more similar to those currently observed in mainland Europe, the Mediterranean countries and the USA.

An additional factor that impacts upon the efficiency of broiler production is the recognised influence of stress in transit upon muscle and meat quality in slaughter birds (Nijdam et al. 2004, 2005; Delezie et al. 2007; Petracci et al. 2010). Thermal stress is a primary cause of poor meat quality including an increased incidence of PSE and DFD[42] like meat. Under semi-tropical conditions it has been reported that cooling birds by pre journey showering can reduce the incidence of these meat quality problems from > 50% to around 17% (Oliveira de Sousa Langer 2010). It may be proposed that any environmental control or other strategies to reduce thermal stress in transit may have significant economic effects not only through reducing mortality or DOA but also through avoiding large losses through reduced meat quality and downgrading.

3.3.2 Key existing reports

There are few reports which have detailed the potential impacts of climate change on livestock health and welfare and which identify possible adaptations or response strategies.

Key reports on the impacts of climate change on livestock health and welfare:

Moran, D., Topp, K., Wall, E., Wreford, A (and Mitchell, M.) 2009. Climate Change impacts on the livestock sector. Defra project Report AC0307 www.defra.gov.uk/

Haskell, M, Kettlewell, P., McCloskey, E., Wall, E., Hutchings M R., and Mitchell, M. (2011). Animal Welfare and Climate Change: Impacts, Adaptations, Mitigation and Risks (AW0513). SAC. Scotland.

3.3.3 Link to hotspot map (i.e. spatial dimension and timing) where relevant

There is a wide distribution of broiler chicken (poultry) production across England and Wales but the distribution of the associated slaughterhouses and processing plants and movement of birds from one production area to another precludes correlation of the effects of climate change on birds in transit to spatial hot spots.

3.3.4 Rationale for specific adaptation intervention

There are a number of potential strategies or adaptations that might be implemented to improve the welfare of birds in transit and to reduce losses and poor meat quality in the phase of the increased risk of heat stress. Long term genetic strategies might involve the selection and introduction of slower growing lines of birds with lower metabolic rates. Current trends and market demands suggest that this is unlikely to be acceptable in the expanding intensive broiler production industry. It may be proposed that the importation of product from outside the UK might be required although the country's high self sufficiency in poultry production is likely to continue to be a key industry objective in the phase of economic pressures. Reducing stocking density in transit (fewer birds are currently employed in response to predicted high temperatures but has a high economic penalty. Improving the passive ventilation of broiler transport vehicles is an option with low cost but severe limitations particularly in the face of sustained high average or maximum temperatures. Implementing cooling/showering of birds prior to and after transportation is currently employed in some tropical and sub-tropical producer areas but has limited efficacy particularly when humidity is elevated. The most effective option may be the use of mechanically ventilated transport vehicles as is the current practice in some produced areas and for

[42] Dark firm dry (DFD) and normal and pale soft exudative (PSE).

other livestock species (in the EU it is mandatory for journeys of over 8 hours for livestock other than poultry)

All of the above options clearly have different time frames, costs and effects upon production. The genetic strategies are outside the remit of the current exercise. Reducing stocking density in transit will require carrying around 10-15% less birds per journey to avoid thermal (heat) stress in the thermal core of the vehicle (Mitchell and Kettlewell 1998). Thus, for a typical UK vehicle carrying 6500 birds a reduction in load of 975 would require an additional truck every 6-7 journeys to clear the same numbers of birds. For a farm of 20,000 to 40,000 birds (relatively small) this would result in a 3 -6 vehicle flock clearance requiring 4-8 vehicles and all the additional costs in terms of diesel, vehicle running costs, labour and GHG and other emissions. Thus, at typical fuel consumptions of 30-35 litres per 100km driven loaded and an average farm distance of 50 km then a return journey would require 60 litres additional fuel at 1.89p per litre or around £115 -£330 additional costs per small flock clearance. To consider the other options involving vehicle ventilation it is pertinent to introduce the possible thermal loads and risks that might occur under various climate change predictions. Firstly it is possible to use the existing published data to calculate the potential effects of different temperatures scenarios (mean and maximum) on losses in transit, with the primary focus being on DOA and then with some consideration for product quality losses which might be estimated from current knowledge. If the operation and costs of current vehicle types in typical UK/English systems are examined it is possible to estimate the impacts of the climate change predictions and to evaluate the costs of the adaptations that might be implemented.

A typical trailer used to transport 7000 broilers in the UK will cost £30,000 (the tractor unit would be costed separately). Manufacturers claim that a mechanically ventilated trailer to currently proposed specifications would cost 25-30% more (£37,500-39,000 capital outlay). Typically the replacement of a fleet of trucks would have at least a five year cycle time. A typical large producer might have 3-4 centralised processing plants with a fleet of 30-50 trucks. One such producer processes 3 million birds per week form 4 sites ranging in capacity from 240,000 to 1.1 million per week. These would be transported on trailers carrying 6000-7000 birds.

Priorities identified by a producer (personal communication) include:-

(1) Current losses due to shrinkage (probably water loss) – 1% “shrinkage” per truck costs £75,000 to the business per year

(2) “Down-stocking” in warm / hot weather is already an issue and the losses are significant in terms of reduced load size - no figures were presented but could be estimated from the data above

(3) The industry already recognise that mechanically ventilated vehicles could operate at maximum stocking density all year with benefits in fuel use, labour and other costs

(4) On one processing plant alone a producer estimates a saving of 1 mile per gallon on the fleet equate to £1.0 million in fuel costs

3.3.5 Costs

Thus, it can be safely assumed that a major cause of losses in broiler transportation for all current climate change predicted scenarios is an increased transport mortality resulting from increased risk of heat stress as a consequence of increased average and maximum temperature. This will be accompanied by increased losses due to heat stress induced meat quality problems. Current models of the effects of average and maximum temperatures upon mortality have been employed to estimate the potential increases in transport mortality and losses. The most significant adaptation to minimise the consequences is the use of mechanically ventilated vehicles. The introduction of these vehicles (as is already taking place) is no regrets. The costs of the losses and the adaptations are based upon current values and assume that parallel relative increases in costs of losses and benefits of adaptations over the time frame employed will offset one another.

A preliminary impact analysis based on dead on arrival or DOA, has employed a threshold temperature of 17°C, an upper danger limit of 23°C, average journey duration of 3 hours (based on existing literature) and a single climate change prediction scenario. The DOA increases have been projected and the financial losses estimated. This has been supplemented by estimation of losses resulting from product quality effects. Although not included in the current model future analyses should also address the effects upon animal welfare and the appropriate costs should be estimated (quality assurance requirements, legislative requirements).

3.3.6 The costs / benefits of introducing mechanically ventilated vehicles

The model:-

Assumptions and inputs

- The adaptation examined is the design, provision and use of mechanically ventilated poultry transport vehicles;
- Climate change scenarios employed assumes medium emissions over period in question (until 2100);
- Average maximum temperature for the summer months has been employed to calculate predicted rise in transport mortality;
- This is expressed as DOA or dead on arrival - the current baseline transport mortality value is 0.1%;
- The increase in mortality has been estimated in relation to threshold temperatures taken from models in existing literature;

- The maximum temperatures in June, July and August will have the greatest impact;
- The effect has been estimated, however, over typical 12 month periods;
- The data relate to the UK but the England only scenario (85% of broiler production) will parallel the model or may be worse in terms of impacts as some high production regions may be more vulnerable to temperature increases;
- The financial losses in terms of DOA are estimated on today's prices - all costs and losses are per annum;
- The increases in broiler demand and production are estimated from current trends;
- The cost of new mechanically ventilated vehicles have been estimated on today's values
- The replacement cycle rates for vehicle fleets has been estimated but may over estimate the true costs of this adaptation
- In addition to the effects of increased temperatures on DOA and the benefits of the adaptation a product quality term has been introduced
- Reduced product quality resulting from heat stress is a major issue - This is taken as 1% value loss – future models will incorporate higher values based on information obtained from the industry – Current limited scientific data indicate a maximal loss approaching 30%
- Similarly the benefit of the adaptation in terms of product quality only assumes a 50% improvement
- The benefits of the adaptation have been calculated for reduced DOA and improved product quality
- The average impacts have been calculated over each of the periods identified (used for climate change scenarios) and then averaged over the appropriate number of years
- All costs and benefits have been calculated per annum in each time period considered

These mean values have been employed in any further calculations. Based on these assumptions and inputs the models have been developed and applied and the potential costs and benefits analysed. Thus, the requirement for broiler production is predicted to increase from a present number of 873 million per annum to 1.26 billion in 2025 and 1.65 billion by 2100. The corresponding DOA figures, calculated from the predicted increases in mortality due to increased average and maximum temperatures, are 1.95 million birds in 2050 and 2.72 million in 2100. The value of these losses will be £2.64 million and £5.78 million (calculated on today's values and assuming proportional increases in all cost values over the model period).

Losses in these same periods due to meat quality decrements will be £1.7 million and £2.2 million per annum for 2050 and 2080 respectively. It is important to stress that these values are based on only a 1% quality loss. The estimated magnitude of this effect in published literature ranges from 1% to 30% and thus a highest estimate of the potential value of quality losses may be as high as £51 million per annum in 2050 and £66 million in 2100. The costs of the vehicle design, construction and purchase at present values and assuming a vehicle fleet replacement cycle consistent with current practice yields an adaptation cost of £0.38 million in 2050 and £0.49 million in 2100 (averaged over replacement cycle).The annual benefits of this adaptation would thus be £0.84 million per annum in terms of reduced DOA in 2050 and £1.83 million in 2100 with a corresponding net benefits of £0.46 million and £1.34

million. If meat quality effects are included then the net benefits will increase to £1.31 million in 2050 and £2.46 million in 2100. Again it should be noted that much greater benefits in terms of meat quality (up to 30 fold) may be estimated as described above).

3.3.7 Uncertainties

The model employs estimates of the predicted growth of the poultry meat market over a very long period and is based on the cost of the adaptation(s) calculated on the basis of current cost of existing technology. Economic drivers may result in changes in trade on poultry meat and products and global adaptations may change the distributions of poultry production and import/export requirements. UK poultry meat self sufficiency may cease to be attainable and imports may have a profound effect upon production requirements. Advances in technology may render current vehicle ventilation systems obsolete and cost of more efficient systems may decrease in relation to the costs of the potential losses. Thus, some uncertainty in relation to the models must be accepted.

3.3.8 Caveats /further research

Future proposed work will focus upon refinement of this model and its application / extension to other livestock transport and ALL intensive production systems. Further development will require the integration of the other factors e.g. energy, water use and GHG emissions in to the final holistic models

3.3.9 Conclusion

The poultry industry along with other intensive systems is vulnerable to climate change challenges. On the basis of current technologies, the controlled indoor environments will face ever increasing costs of control and will experience associated increases in GHG emissions, pollution and water and energy usage. The transport of an animal to slaughter is particularly exposed to increased risk of heat stress. The industry recognises these risks and some adaptations are already in place. A major concern is the effect of thermal stress in transit upon transport mortality and product quality in meat animals. This latter concern will have major impacts upon profitability and production efficiency and the appropriate adaptations, including improved vehicle ventilation, will have to be addressed in the immediate to very short term. The models reported here should be refined to facilitate accurate estimates of the costs and benefits.

3.4 Livestock System Losses - dairy cattle and heat stress

3.4.1 Introduction

Climate change and fluctuations in temperature could impact negatively on animal welfare. Livestock will be directly exposed to increasing thermal challenges with negative impacts on productivity, health, fertility and welfare (St-Pierre et al., 2003[43]). Animal performance may also be affected indirectly through altered water availability and land use changes (shifting of farming practices) that change feed availability and potentially change disease exposure.

This analysis focuses on anticipated heat stress impacts to housed animals and considers relevant adaptation to management systems to offset potential losses. Addressing the welfare of animals through appropriate adaptation measures can deliver a double-dividend in terms of avoided productivity loss.

3.4.2 Methodology

The impact on key performance parameters for livestock under alternative THI conditions is well studied in some livestock species. A summary of methods for calculating these impacts in a range of livestock categories is shown in St-Pierre et al. (2003), and is used on the basis of modelling the climate impacts and impact valuation.

A modelling approach previously employed by Wall et al. (2010) to calculate impacts of heat stress on dairy cows (and other livestock species) with UKCP02 data is used in this study. This study used UKCP09 taking future absolute temperatures and relative humidity. Two scenarios were used: the low emissions scenario at the 10% probability level and the high emissions scenario at the 90% probability level. Note that the low emissions scenario at the 10th%will likely lead to no significant change in heat stress due to climate change (excluding extreme weather events such as heat waves), and therefore the results focus on the high emissions scenario 90th%To provide a lower limit the results present a low emissions scenario 50% probability level to present a range of values.

Data on animal populations were taken from FAPRI dairy cow population statistics for England (scaled for NUTS1 region by Defra statistics). These were used to convert the results to actual numbers assuming that the future population would remain unchanged. Results were generated for the following:

- Duration of heat stress – expressed in hours per year when heat stress is experienced.
- Impacts of heat stress on milk production – expressed in kilograms per day per animal.
- Impacts of heat stress on days open (i.e. without calf) – expressed as increase in the number of days open.

[43] St-Pierre, N. R., B. Cobanov, and G. Schnitkey. "Economic losses from heat stress by US livestock industries." Journal of Dairy Science 86 (2003): E52-E77.

• Deaths due to heat stress – expressed as number of deaths in 1000 animals.

Statistics on the proportion of cows, and the time they spend indoors during warmer months (April – September) are unavailable except for some limited questionnaire/expert opinion. To account for limited information, this analysis assumed a range of population proportions for the numbers of cows housed of 5, 10 and 20% of cows in a given region. The majority of dairy cows in England (~90%) are currently grazed during these months, at least for part of the day and therefore are unlikely to experience prolonged periods of heat stress and were therefore omitted from the analysis of heat stress.

3.4.3 Results

Duration of heat stress in dairy cows

The projected duration of heat stress for a dairy cow (housed) in hours per annum, a function of thermal humidity index (THI) load, is shown in Figure 17. Note that for the 10th percentile under the low emissions scenario dairy cows are predicted not to undergo heat stress and no adverse effects are predicted. Figure 17 shows that UK dairy cows are unlikely to experience routine heat stress due to climate change until 2050 under all scenarios studied. Under the high emissions scenario (p90), housed dairy cows are projected to spend 20% of the year experiencing heat stress and associated adverse effects. This negative experience of heat stress, above and beyond the impacts it has in productivity and fitness losses, may be seen as an ancillary cost as it would be an indicator of dairy cow welfare as a result of climate change.

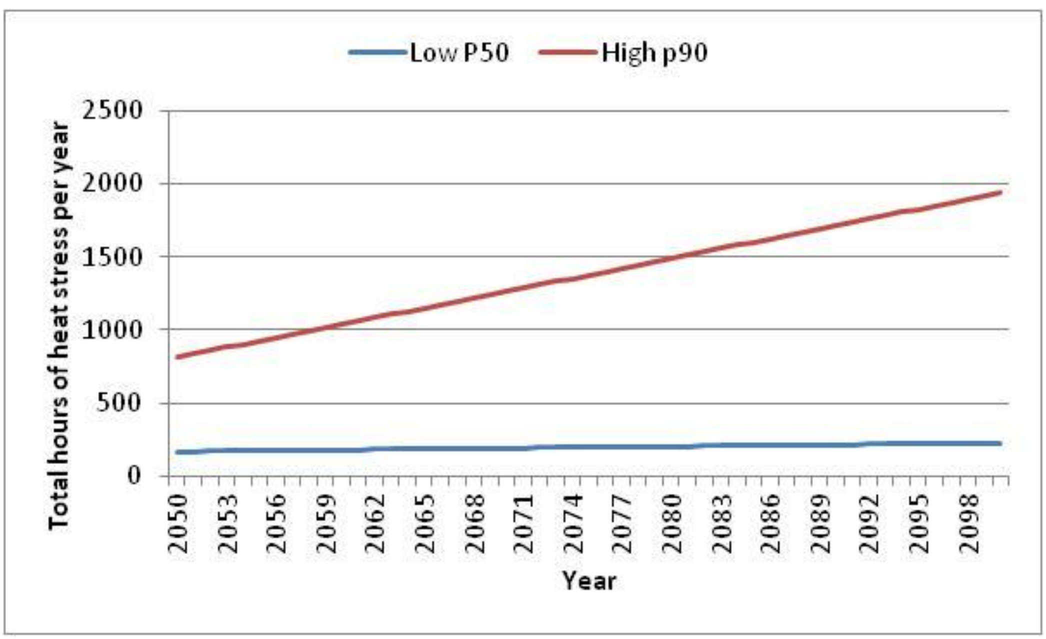


Figure 17: Total hours of heat stress a cow per annum under the low emissions scenario 50th percentile and the high emissions scenario 90th percentile.

Assumptions on Climate Impacts

- Heat stress reduces milk output (poorer productivity), increases fertility problems and risk of death.
- The climate scenarios are UKCP09 low emissions trajectory 50th percentile, and the UKCP09 high emissions trajectory 90th percentile. There was no evidence of heat stress to the end of the century for the UKCP09 low emissions trajectory 10th percentile (the bottom scenario requested in this study).
- Heat stress effects are for housed cows only. Using recent surveys[44] three values were used for the proportion of animals housed year round, 5%, 10% and 20%. It is difficult to project the proportion of cows housed year round in the future, and these three proportions are projected to the end of the century.
- The spatial distribution of cows across the different NUTS1 regions of England was taken from Defra June survey 2008[45].
- The total number of cows and milk yield where taken from the FAPRI projections[46] where available, and flat lined to the end of the century.
- The proportion of dairy cows within a region was assumed to be constant over time from the current distribution.
- The proportion of cows housed within a region was distributed evenly across region.
- Impact values are based on current prices available from literature and industry statistics, as listed in the spreadsheet.
- The ancillary welfare costs of the duration of heat stress do not have a monetary value so are not included in this analysis. Future work could estimate a societal ancillary cost of the impact of climate change on livestock well being.

3.4.4 Valuation of losses due to heat stress

Table 11 shows the cumulative present value of potential losses (cumulated across years) due to heat stress. The costs cumulated to 2100 in England £2.9 million for the low emissions scenario (p50) with 5% of cows housed (£11.7 million for 20% housed) rising to £0.84 billion (£3.34 billion for 20% housed) for the high emissions scenario (p90).

[44] March, M D, M J Haskell, F M Langford, D J Roberts, M G G Chagunda 2013 The effect of breed and herd size on the housing system in UK dairy farms. Annual Proceedings of the British Society of Animal Science Abstract No 140

[45] http://archive.defra.gov.uk/evidence/statistics/foodfarm/landuselivestock/junesurvey/documents/dairy_2008.xls

[46] http://archive.defra.gov.uk/evidence/economics/foodfarm/reports/fapri/

Year		2050			2075			2100	
% cows housed	5	10	20	5	10	20	5	10	20
East Midlands	£3,381	£6,763	£13,525	£99,546	£199,092	£398,185	£205,850	£411,701	£823,402
East of England	£7,765	£15,531	£31,062	£173,738	£347,476	£694,951	£312,183	£624,367	£1,248,733
North East	£0	£0	£0	£4	£8	£16	£12	£24	£48
North West	£0	£0	£0	£75	£150	£299	£219	£438	£875
South East	£30,918	£61,836	£123,673	£682,163	£1,364,327	£2,728,653	£1,214,942	£2,429,884	£4,859,767
South West	£10,709	£21,419	£42,837	£387,702	£775,404	£1,550,807	£863,869	£1,727,737	£3,455,475
West Midlands	£4,161	£8,323	£16,645	£147,699	£295,397	£590,794	£327,040	£654,081	£1,308,162
Yorks&Humb	£0	£0	£0	£27	£55	£110	£80	£161	£322
TOTAL	£56,936	£113,871	£227,742	£1,490,954	£2,981,908	£5,963,817	£2,924,196	£5,848,392	£11,696,784
East Midlands	£545,050	£1,090,101	£2,180,201	£24,678,415	£49,356,830	£98,713,660	£58,439,475	£116,878,950	£233,757,900
East of England	£243,625	£487,249	£974,498	£9,574,809	£19,149,619	£38,299,238	£21,861,254	£43,722,508	£87,445,015
North East	£2,321	£4,641	£9,283	£639,236	£1,278,471	£2,556,942	£1,811,765	£3,623,530	£7,247,059

North West	£154,983	£309,965	£619,930	£19,503,751	£39,007,503	£78,015,006	£53,152,404	£106,304,809	£212,609,618
South East	£1,138,773	£2,277,546	£4,555,092	£44,646,465	£89,292,929	£178,585,858	£101,866,957	£203,733,913	£407,467,827
South West	£3,764,247	£7,528,493	£15,056,986	£179,700,436	£359,400,872	£718,801,743	£430,707,393	£861,414,786	£1,722,829,571
West Midlands	£1,240,440	£2,480,880	£4,961,761	£57,830,405	£115,660,811	£231,321,621	£137,874,581	£275,749,163	£551,498,325
Yorks&Humb	£174,325	£348,650	£697,300	£11,681,973	£23,363,945	£46,727,890	£29,777,412	£59,554,823	£119,109,646
TOTAL	£7,263,763	£14,527,526	£29,055,052	£348,255,490	£696,510,979	£1,393,021,958	£835,491,241	£1,670,982,481	£3,341,964,962

Table 11. Cumulated costs due to heat stress in dairy including lost production, poorer fertility and livestock deaths at net present value (cumulated over the time trajectory out to 2100). Top set = low emissions 50% percentile, bottom set = high emissions 90% percentile.

3.4.5 Costs of adapting to heat stress

As previously noted the majority of cows in the UK are not housed year round. The proportion is rising, although no projections have been made to date. The competition for land and ability of producers to grow grass in different regions may well limit the area of land available to dairy cows in the UK into the future.

Some of the adaptations to deal with heat stress for housed animals include:

- Giving cows access to outdoor loafing areas/grazing during potential periods of heat stress. Costs associated with this are simply labour for increased animal management.
- Providing cows with cooling water spray on exit of sheds. Costs are related to water and potentially installation costs for all farms moving cows outdoors during periods of heat wave. (not included)
- Adapting housing for mechanical ventilation. Costs are high as major building modifications are required. This is not considered in this study as it is likely to entail high capital investment costs that would not be outweighed by avoided losses and at this stage would not meet the low-regrets criteria, nor do they require long lead times.

Assumptions on Climate Adaptations

Widespread building modifications are unlikely to be low cost or would not be installed simply as a result of climate change. It is likely that building modifications/replacement would be part of the normal capital reinvestment in the farming enterprise and climatic/technical specifications at the time of replacement would be taken into consideration. Such capital replacement would not be solely climate driven and therefore is not an appropriate no/low regrets adaptation option.

As a no/low regret option we have chosen to focus on increased labour during the days where heat stress may occur. This labour will include the time spent moving animals to outdoor areas so that they can thermally cool, time spent cleaning sheds, collecting yards etc after moving as well as increased health and fertility management to compensate for potential disease and fertility losses not offset by adaptation action. The main assumptions for adaptation were:

- Labour input would increase during the periods of potential heat stress to move cows to outdoor areas to allow for more natural behaviours of cooling not possible in the confines of housing. This labour includes the moving of animals to fields/loafing areas, cleaning farm areas before/after moving and additional health and fertility checking to offset any losses there. The total minutes per day per cow for each of these tasks were taken from the DairyCo labour survey.[47]
- This additional management for housed cows during period of heat stress was then allocated for each of the housing level (5%, 10% and 20%) by NUTS1 region out to the end of the century.

[47] http://www.dairyco.org.uk/media/394099/labour%20efficiency%20report%20oct10%20no%20details.pdf

- To estimate the total number of extra labour days by year and region the total annual hours of heat stress were used as a proxy for the total number of days that would require the extra labour input (assuming that on average there would only be 8 hours of heat stress per day).
- The current hourly wage for a Grade 2 agricultural worker[48] (a worker doing basic livestock management) was multiplied by the total number of labour hours required to manage the cows for the days they could experience heat stress by region and year.
- These additional labour hours were then offset (after discounting) against the costs of the losses due heat stress described above to give a net present value of the adaptation.

3.4.6 Net present value of adaptation

The cumulative net present value of costs of the adaptation for heat stress ranges from £60,099 in 2050 with 5% of cows housed under a low emissions scenario (50^{th} percentile) up to £62.2 million in 2100 with 20% cows housed under a high emissions scenario (90th percentile) (Table 12).

Under the majority of regions and time points the low regrets adaptation is favourable such that costs of adaptation are offset by the avoided damage costs (resulting from moving animals outside). This does not hold however for 2050 under a low emissions scenario for all housing levels where the net present value is negative. This indicates that the costs to the dairy industry of increasing labour intervention to help cows "cope" with heat stress is larger than the losses due to climate change. Under the low emissions scenario certain regions of England (i.e., East and West Midlands, South West) have a negative net present value for the adaptation out to the end of the century for all housing levels.

Under the low emissions scenario (50th percentile) it is projected that the net present value of adaptation is positive under all housing levels by 2075 with a value of £0.25 million for 5% housed and £1 million for 20%. This rises to £0.82 million and £3.2 million by 2100 respectively (Table 13).

Due the significant increase in losses to heat stress under the high emissions scenarios, the present value of the adaptations is positive from 2050 being £6.9 million for 5% housed cows and £27.7 million for 20% cows housed. This rises significantly to £0.82 billion and £3.28 billion by 2100 respectively.

[48] https://www.gov.uk/agricultural-workers-rights/pay-and-overtime

Year		2050			2075			2100	
% cows housed	5	10	20	5	10	20	5	10	20
East Midlands	£7,843	£15,685	£31,371	£155,661	£311,322	£622,643	£257,340	£514,680	£1,029,360
East of England	£3,242	£6,485	£12,969	£61,849	£123,698	£247,396	£99,061	£198,123	£396,245
North East	£0	£0	£0	£0	£0	£0	£0	£0	£0
North West	£0	£0	£0	£0	£0	£0	£0	£0	£0
South East	£9,212	£18,424	£36,847	£175,526	£351,051	£702,102	£280,875	£561,749	£1,123,498
South West	£29,066	£58,132	£116,265	£616,532	£1,233,064	£2,466,128	£1,069,690	£2,139,380	£4,278,760
West Midlands	£10,736	£21,472	£42,943	£227,721	£455,442	£910,883	£395,100	£790,200	£1,580,400
Yorks&Humb	£0	£0	£0	£0	£0	£0	£0	£0	£0
TOTAL	£60,099	£120,198	£240,395	£1,237,288	£2,474,577	£4,949,153	£2,102,066	£4,204,132	£8,408,264
East Midlands	£32,077	£64,154	£128,308	£720,632	£1,441,264	£720,632	£1,298,228	£2,596,456	£5,192,911
East of England	£10,233	£20,466	£40,932	£227,264	£454,528	£227,264	£406,464	£454,528	£1,625,857
North East	£2,164	£4,329	£8,657	£73,103	£146,206	£73,103	£159,224	£146,206	£636,897
North West	£41,731	£83,461	£166,922	£1,267,840	£2,535,681	£1,267,840	£2,655,477	£2,535,681	£10,621,909
South East	£30,051	£60,102	£120,205	£670,621	£1,341,243	£670,621	£1,203,073	£1,341,243	£4,812,290
South West	£153,530	£307,061	£614,122	£3,512,317	£7,024,635	£3,512,317	£6,398,483	£7,024,635	£25,593,931

West Midlands	£53,443	£106,886	£213,773	£1,242,542	£2,485,084	£1,242,542	£2,285,570	£2,485,084	£9,142,279
Yorks&Humb	£22,228	£44,456	£88,911	£590,460	£1,180,921	£590,460	£1,166,156	£1,180,921	£4,664,625
TOTAL	£345,457	£690,915	£1,381,830	£8,304,780	£16,609,560	£8,304,780	£15,572,675	£17,764,752	£62,290,699

Table 12. Cumulated costs of heat stress adaptation by region based on increased labour input to manage animals to help them cool at net present value (cumulated over the time trajectory out to 2100). Top set = low emissions 50% percentile, bottom set = high emissions 90% percentile.

Year		2050			2075			2100	
% cows housed	5	10	20	5	10	20	5	10	20
East Midlands	-£4,461	-£8,923	-£17,845	-£56,115	-£112,229	-£224,459	-£51,490	-£102,979	-£205,958
East of England	£4,523	£9,046	£18,092	£111,889	£223,778	£447,556	£213,122	£426,244	£852,488
North East	£0	£0	£0	£4	£8	£16	£12	£24	£48
North West	£0	£0	£0	£75	£150	£299	£219	£438	£875
South East	£21,706	£43,413	£86,825	£506,638	£1,013,275	£2,026,551	£934,067	£1,868,134	£3,736,269
South West	-£18,357	-£36,714	-£73,427	-£228,830	-£457,660	-£915,321	-£205,821	-£411,643	-£823,286
West Midlands	-£6,574	-£13,149	-£26,298	-£80,022	-£160,044	-£320,089	-£68,060	-£136,119	-£272,238
Yorks&Humb	£0	£0	£0	£27	£55	£110	£80	£161	£322
TOTAL	-£3,163	-£6,326	-£12,653	£253,666	£507,332	£1,014,663	£822,130	£1,644,260	£3,288,520
	£0	£0	£0	£0	£0	£0	£0	£0	£0
East Midlands	£512,973	£1,025,947	£2,051,894	£23,957,783	£47,915,567	£97,993,029	£57,141,247	£114,282,495	£228,564,989
East of England	£233,392	£466,783	£933,566	£9,347,545	£18,695,091	£38,071,974	£21,454,790	£43,267,980	£85,819,158

North East	£156	£313	£626	£566,132	£1,132,265	£2,483,839	£1,652,541	£3,477,323	£6,610,162
North West	£113,252	£226,504	£453,008	£18,235,911	£36,471,822	£76,747,165	£50,496,927	£103,769,128	£201,987,709
South East	£1,108,722	£2,217,444	£4,434,888	£43,975,843	£87,951,686	£177,915,237	£100,663,884	£202,392,671	£402,655,536
South West	£3,610,716	£7,221,432	£14,442,865	£176,188,118	£352,376,237	£715,289,426	£424,308,910	£854,390,151	£1,697,235,640
West Midlands	£1,186,997	£2,373,994	£4,747,988	£56,587,863	£113,175,727	£230,079,079	£135,589,012	£273,264,079	£542,356,046
Yorks&Humb	£152,097	£304,194	£608,389	£11,091,512	£22,183,024	£46,137,430	£28,611,255	£58,373,902	£114,445,021
TOTAL	£6,918,306	£13,836,611	£27,673,223	£339,950,709	£679,901,419	£1,384,717,178	£819,918,566	£1,653,217,729	£3,279,674,263

Table 13. Cost/benefit of low regrets adaptation based on avoiding heat stress losses with increase labour input during danger period at net present value (cumulated over the time trajectory out to 2100). Top set = low emissions 50% percentile, bottom set = high emissions 90% percentile.

3.4.7 Uncertainties

There are a number of assumptions that were made in these calculations based on current farming practices and industry statistics. For example, the proportions of cows that are currently housed year round could differ by region and we have assumed a constant level of housing by region and projected that level as constant until the end of the century. Also we have assumed a constant cow population distribution by region outwith the FAPRI-UK projects. However, it is likely that as the climate changes and the competition for land for different agricultural practices changes that the cow population distributions will change over time. Also, we know from industry surveys that larger herds are more likely to house cows year round and the current trend in the dairy cattle production is towards fewer and larger herds. To overcome this we used the alternative housing levels to act as a pseudo upper and lower limit to the costs of the impacts, adaptations and the net present value. Further losses are likely in the young stock on dairy farms (replacement dairy calves and cows) during the heat stress. However, we did not include this as there is little information on the level of housing year round for these animals. Industry opinion would suggest that these animals tend to have a far lower level of continuous housing at present, which may or may not continue into the future.

3.4.8 Further research

Although we have focussed on dairy cattle systems other livestock enterprises that have long/continuous housing during the productive and/or reproductive cycles such as pigs and poultry are also likely to experience significant losses as a result of heat stress. Beef and sheep enterprises in England are less likely to be affected by heat stress as only a tiny fraction of these systems would house animals continuously. Other aspects of climate change will also affect livestock production systems such as cold stress for both housed and outdoor managed animals (exacerbated by rain, snow and wind), rainfall influences on production disease such as foot health and mastitis and climatic drivers for livestock disease transmission (discussed elsewhere). Also, all livestock, and their current systems, are less likely to be well able to cope with more extreme fluctuations of weather events under future climate change. There is a need to study, where possible, these complex interactions of climate and weather influences on individual animals and within and between livestock systems to have a more full appreciation of climate change risks and adaptation to livestock production in the UK. Such an exercise will identify key knowledge gaps and map out private and public adaptation route for livestock systems in England. We are also aware that climate change, and wider global challenges, could influence dramatically how different land-use systems are distributed across regions (e.g., livestock pasture as part of flood management programme, competition between agricultural commodity use of prime land through to extensive agricultural land). Research that maps out alternative land-use scenarios for England and the UK could then have climate scenarios applied to them to assess the best mix of cost effective adaptations, and wider costs/benefits, for land managers in England.

3.5 Adaptation Strategies for Soil Measures

3.5.1 Introduction

Soils are vital for the production of food and feed, and their health underpins domestic productive capacity and food security. This section focuses on the low-regrets adaptation measures that would reduce the impact of climate change on soil fertility / health. Human activity can result in soil degradation and as result the soil loses its quality and productivity. This can include the loss of soil by erosion, the loss of nutrients and / or organic matter, and a decline in the soil structure. Erosion will lead to the loss of soil carbon and nutrients from the local area. Across England and Europe, declines in soil organic carbon in arable soils have been reported (Janssens et al. 2003; Bellamy et al.; 2005; Chamberlain, 2010) and there is evidence that the rate of decline in soil carbon increased with soil carbon content (Bellamy at al., 2005). Nevertheless, at the national level, there is little evidence to indicate that the reduction in soil organic carbon has led to a reduction in yield (Knight et al., 2012). However, the effect on yield due to soil erosion, and hence the loss of soil carbon and nutrients, will be affected by nutrient availability, water holding capacity, the rooting characteristics of the crop as well as the crop management and the microclimate (Lal, 1998; Pimental et al., 1995). Cereal yields in Britain have stabilised at half the calculated potential (Gales, 1983). This is partially attributed to soil management issues, inadequate crop nutrition, and failure to control pests, diseases and weeds (Knox et al., 2010); however, spring and summer droughts are also partially responsible (Knight et al., 2012). Soil productivity can also be severely affected by water logged conditions. For example, in 2012, when the rainfall was 36% higher than the 1961-1990 average (http://www.metoffice.gov.uk/climate/uk/summaries/2012/annual/regional-values), the average yield of potatoes fell by approximately 15% (http://www.potato.org.uk/news/first-estimate-total-potato-plantings-great-britain-2013) and the average yield of wheat and oil seed rape both fell by 14%; however, the barley yield only fell by 2.7% (https://www.gov.uk/government/publications/farming-statistics-land-use-livestock-populations-and-agricultural-workforce-at-1-june-2012-uk).

Climate change has the potential to be a major to threat soils, although the evidence is limited (Towers et al., 2006; Schils et al., 2008). The direct effects are soil erosion, which will be exacerbated by extreme events (Lilly et al., 2009); however, Knox et al. (2010) were unable to estimate the potential loss of soil due erosion under climate change. Indirect impacts will occur through the modification of soil water balances, affecting moisture availability, and land management practices including trafficability and workability (Knox et al 2012). In addition, compaction can occur due to waterlogged soils, and there hence the soil structure can deteriorate with a subsequent loss in the ability of the soil to support crop growth. Climate change will also lead to more extreme weather events, and thus potentially more frequent periods of waterlogged soils and / or soil moisture deficit and hence implications for agricultural productivity.

It vitally important to the UK that soil productivity is maintained, and the observed loss in soil carbon is minimised, and hence adaptations to agricultural practices will be required. The low-regrets adaptations are practices that minimise the impact of drought and waterlogged soils, and hence maintain yield. Thus, there is a need to maintain good soil structure, while at the same time maintaining the soil carbon stocks. Soil structure can be assessed by aggregate stability, root penetration and presence of anaerobic zones (Ball et al., 2007), but it is not necessarily correlated to soil carbon stocks. Although declines in soil organic carbon have been reported (Janssens et al., 2003; Bellamy et al., 2005; Chamberlain 2010), Smith et al. (2007) suggests that the reduction in soil carbon can be partly explained by reductions in applications of farm yard manure, more efficient harvesting of crops, and hence less residue return, and deeper ploughing leading to mineralisation of carbon, with the changing climate being responsible for approximately 10-20% of the loss in SOC. It is important to note that the current decline in SOC may also be the legacy effect which is due to management changes in the mid 1800s (Smith et al., 2007).

Visual soil assessment methods (e.g. Ball et al., 2007) are an indicator of soil health and structure. These measures of assessment, which take into account a range of crucial soil properties (e.g. Ball et al, 2007), have been shown to be correlated with crop yield (Mueller et al., 2009; Mueller et al., 2013; Munkholm et al., 2013). It is assumed that yield is a proxy for the soil fertility, although it is recognised the crop pests and disease, nutrient availability and weather are key determinants of yield. Thus any decline in soil fertility / health would lead to a reduction in yield. The ability of air and water to move through the soil profile are fundamental for healthy crop growth (Morris et al., 2010). For example, Mosquerra et al. (2007) estimated that soil compaction reduced yields by an average of 10% from a study that compared yields under conventional and zero till. In some regions of Europe compaction has been reported to reduce yields by between 25 and 50% (Ericksson et al., 1974). Similarly, Armstrong (1978) reported that on clay soils, improving drainage resulted in winter wheat yields increasing by up to 1 t per ha. However, Armstrong et al (1988) reported that the effects of drainage on crop yield vary from year to year, although drainage can increase the length of the working season by up to three weeks in the spring and autumn. Depending on the severity and timing of waterlogging, winter wheat yields can be reduced by between 1 and 32% (Belford et al., 1985).

There is evidence that yields will increase with climate change (Semenov et al., 2012, Knox et al., 2012). However, without adaptation, the modelling work of Osbourne et al. (2013) showed that spring wheat yields tended to be lower in 2050 than current yields. There is also evidence that extreme rainfall events and hence waterlogging will reduce yields. Heat stress at the time of flowering will increase and result in yield loss (Maloney, 2013), and there is the potential for some diseases to increase and hence result in a decrease in yield (Madgwick et al., 2011). The work of Brown (2012) has shown that the relationship between yield and climate vary with both month and crop type, and that the key indicators are sunshine duration and precipitation. On an annual basis, the key bioclimatic metrics are soil moisture and cumulative sunshine. Given the uncertainty and the year-to-year variability of weather and the effect that will have on yields, it was assumed for the purposes of the CBA that the yields were unaffected directly by climate change.

The specific crops assessed are winter wheat, spring barley, potatoes and carrots. The adaptation measures that have been assessed are: (i) drainage; (ii) relieving compaction; (iii) shallow ploughing; (iv) spring cultivation of crops; (v) incorporating a cover crop in the cropping sequence and (vi) contour ploughing. Table 14 describes the adaptation measures and summarises why these adaptation measures were assessed.

Table 14: Adaptation measure and effect the measure will have on soil fertility and soil organic matter

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.	

3.5.2 Key existing reports

In addition to the references listed, the key existing reports include:

a. Defra SP1305 Studies to inform policy development with regard to soil degradation: Subproject A: Cost curve for mitigation of soil compaction
b. Defra SP1606 Cost of soil degradation in England and Wales

3.5.3 Link to hotspot map (i.e. spatial dimension and timing) where relevant

The spatial dimension occurs mainly in relation to the types of soil on which the crops are grown and to which the adaptation measures are applicable. Thus carrots are only assumed to be grown on a light free draining soil, and thus the measures that apply to drainage and compaction are not applicable. In terms of drainage and compaction, these are only applicable to soils that require drainage. The contour ploughing is only applicable to sloped land, which was assumed to be approximately 10% of the arable area (Environment Change Institute et al (2013) for the Adaptation Sub-Committee). This figure is based on a survey conducted by FERA over the period 1985-2010.

3.5.4 Rationale for specific adaptation intervention

The rationale for choosing the adaptation options was because they were likely to improve soil fertility and with the exception of drainage be relatively minor changes in terms of changing farm management practices. It has been assumed that the land degradation resulting from climate change is currently occurring. According to Environment Agency (2004), 17% of agricultural land is showing signs of erosion, and the rate of soil erosion by water in England and Wales has been estimated at 0.1–0.3 tonnes per hectare per year. Forty-four percent of arable land in the England and Wales is estimated to be at risk of water erosion (Environment Agency, 2004). However, the biggest cause of soil degradation is likely to be extreme rainfall events. In addition, extreme rainfall also results in either delayed farm operations and / or damage to the soil structure due to traffic. Nevertheless, the spread sheets used have the option to assess the impact of the adaptation measures assuming that land degradation does not start to occur for another 20 or 40 years. There is evidence that degradation is currently occurring, although not all adaptations measures that reduce soil erosion currently show an associated increase in yield (e.g. Stevens et al. 2008). The impacts of climate change on soils are likely to be because of increased rainfall and extreme events; hence why the delayed degradation scenarios were explored. The degradation of soils, and hence the loss in yield, will be non-linear; however given the time constraints of this exercise and the current status of knowledge, it has been assumed that the effects will be linear. Irrigation has not been assessed because it is assumed that in the relevant timespan that the only crops that would be irrigated under climate change are those that are irrigated under current climatic conditions. In terms of low-regret adaptations, the incorporation farm yard manure into arable systems has not been considered as it would either require transportation of manure or the incorporation of livestock into arable areas; neither of which is perceived to be low-regrets. It is recognised that in areas where intensive poultry and pigs are reared, farmers will already be making use of the manure on arable land from these systems.

3.5.5 The cost and benefit assumptions and the associated uncertainties

With the spring cultivation and the incorporation of cover crops in the cropping sequence, it has been assumed that these adaptation measures are only applicable where spring crops have been grown and therefore there is no opportunity cost associated with growing a lower value / yielding winter crop. It has been assumed that the farmers already have the equipment to implement these measures and therefore with exception of drainage, which requires excavation and installation of drains, there are no capital costs. The capital costs for drainage typically range from 1,730-£2,225/ha http://www.fwi.co.uk/articles/13/01/2012/130966/extreme-weather-means-good-land-drainage-is-vital.htm). The low, medium and high costs for drainage have been set at £1,750, £2,000 and £2,500 respectively. The annual costs associated with the measures are given in Table 15. The CBA has been calculated for the low, medium and high cost scenarios. The crop prices in the model are based on Defra statistics (https://www.gov.uk/government/organisations/department-for-environment-food-rural-affairs/series/commodity-prices). In addition to the impact of climate on soils, the CBA has also been carried out assuming that the price of the commodity is also affected by climate change. Based on Nelson et al (2010), the premise for this is that the global price will rise because of increasing demand as a result population growth, and that climate change at a global scale will reduce yields and hence exacerbate the increase in price (Figure 18 and Table 16). The estimates are from the IFPRI IMPACT modelling suite (Rosengrant et al. 2008) which links, a partial equilibrium agriculture model that emphasizes policy simulations, a hydrology model and the DSSAT crop model suite (Jones et al. 2003). These estimates are the best available at the current time. In the CBA, the change in price has been based upon the pessimistic and optimistic price scenarios for wheat. Sensitivity analysis on the estimated yield losses has been performed on the measures where the NPV is positive for the medium cost scenario. These have been estimated by assessing the tipping point of the CBA; this estimates the value of the yield loss where the where NPV equals zero.

Table 15: On-going costs for each of the adaptations

Measure	On-going costs		
	Low	Medium	High
Drainage	35	40	50
Compacted soils	20	30	40
Cover crops	500	550	600
Shallow ploughing	0	0	0
Spring cultivation	0	0	0
Contour ploughing	0	0	0

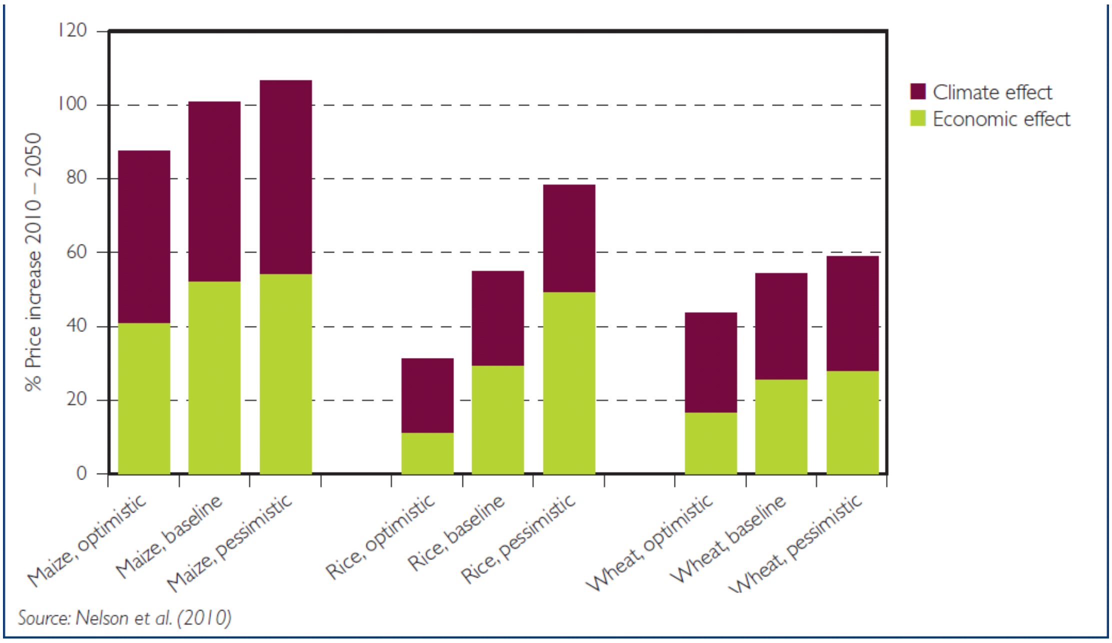


Figure 18. The predicted change in global maize, rice and wheat price.

Table 16 Climate change impacts on global wheat yields with 2030, 2050, and 2080 climate (percent change from 2000)

Year	Developed		Developing	
	Rainfed	Irrigated	Rainfed	Irrigated
2030	-1.3	-4.3	-2.2	-9.0
2050	-4.2	-6.8	-4.1	-12.0
2080	-14.3	-29.0	-18.6	-29.0

Source: Nelson et al (2010). They estimated these yields from downscaled CSIRO climate model with the A2 SRES scenario.

The assumption for the effect of the loss in soil fertility as a result of the impact of climate change on yield, and the impact of the adaptation on yield are shown in Table 17. These values are based on discussion with SRUC soil scientists, and therefore are based on expert opinion. With respect to the contour ploughing, it has been assumed that because the land must be sloped, that there is a high risk of soil erosion and phosphorus loss, and as a result the yield loss is higher. Although Stevens et al. (2009) showed no impact on yield of contour ploughing; it has been assumed that because of loss of soils and nutrients that in the long-term there will be a reduction in yield if the practice of ploughing up and down the slope is continued. It has also been assumed that the yield will never fall below 60% of its current value, and thus the maximum yield loss is 40%. These assumptions are based on 'guesstimates', which have been informed by the observed yields in countries where yields are relatively low[49]. For some of the measures and for some of the crops, the change in pollution has also been assessed for both free draining soils and for land that requires drainage. This has been assessed using the Farmscoper model (Zhang et al., 2012), which is an Excel-based (farm scale) tool. The model has been developed to characterise diffuse agricultural pollutant emissions from representative farm types and quantifies the expected impacts to the environment of the control options (Zhang et al., 2012). However, as the pollution savings were small in relation to the yield implications, and in the interest of time and resources this was not carried out for all crops and measures.

With regards to the yield gain, these are all assumed to be one off gains, and do not recur, and therefore the adaptation measure has an immediate effect. With the exception of land drainage, all the adaptation measures are assumed to be reapplied in all subsequent years and therefore degradation is halted. In the case of drainage, it is assumed there is a capital cost of replacing the existing drains that are no longer functioning or putting in new drainage system. It has also been assumed that the farmer will maintain the drains in subsequent years and hence degradation (due to waterlogging) is halted.

[49] Tan et al. (2005) showed that the depletion of nutrients from soils can result in a loss of wheat yield which was estimated to be 11% in developed countries. This was mainly attributed to the loss of phosphorus. Similarly, in developing countries, severe artificial erosion has resulted in higher declines in yield of 45% (Biot and Lu, 1995) and total crop failure (Oeydele and Aina, 2006).

Table 17 Annual proportionate reduction in yield as a result of climate change and the increase in yield due to the adaption measure[50]

Measure	Reduction in yield	Increase in yield
Drainage	0.02	0.05
Compacted soils	0.02	0.05
Cover crops	0.02	0.15
Shallow ploughing	0.02	0
Spring cultivation	0.02	0
Contour ploughing	0.025	0

Note: There is a high level of uncertainty around these estimates. However, it has not been possible to assign confidence intervals.

The land to which the measure is applicable is based on the current hectarage of that crop multiplied by an estimate of the proportion of land that would benefit from that particular measure. Based on the recent report by Anthony et al. (2012), it has been assumed that 41% of the agricultural arable land is free draining and that approximately 24% of the land for which drainage is applicable would benefit from being drained. Based on the survey conducted by ADAS (1996), it has been assumed that 90% of farmers will sub-soil land that is likely to be compacted every 4 years (trimmed mean), and therefore the area of land to which the measure is applied on annual basis is assumed to be 22.6%. It has been assumed that 100% of soils would benefit from shallow ploughing, and 100% of spring cultivated land could benefit from the inclusion of a cover crop. With regards to contour ploughing, it has been assumed that 10% of the arable land area in England is on a steep enough slope to benefit from this measure.

With the exception of compacted crops, for which we have an estimate, the assumptions on uptake are relatively modest (Table 18). This reflects the fact that the uptake rates for the win-win mitigation measures also seem to be relatively low, although there is currently a paucity of data to add weight to this statement. The Scottish Government initiative “Farming For a Better Climate” (FFBC) is encouraging farmers to take-up initiatives that will reduce GHG emissions. However, the FFBC initiative suggests there is a need for a show and tell approach to encourage uptake rates. There is uncertainty associated with uptake rates, and in relation to GHGs, SRUC is currently trying to assess this uncertainty, and the impact that will have on the results. Information on the current level of uptake of the adaptation measures is scant; however, the current level of uptake of shallow ploughing is less than 10%.

[50] These estimates are based on expert opinion. The weather conditions in a given year will impact on the yield loss, and hence the confidence intervals for these estimates are large.

Table 18 The percentage uptake rates for each of the measures

Measure	Percentage uptake rates
Drainage	5
Compacted soils	100
Cover crops	10
Shallow ploughing	5
Spring cultivation	10
Contour ploughing	10

With respect to the cover crops adaptation measure, the inclusion of these crops is mainly applicable to light soils, and in addition there may be issues associated with destroying the cover crop in the spring. The costs were based on Farmscoper and therefore it is assumed that the cover crop is established using seed broadcasting followed by a light cultivation/rolling. It has also been assumed that the cover crop is destroyed through ploughing and therefore normal preparation for the spring crop will be adequate. Hence, the costs of herbicide have not been included, which may be required to destroy the cover crop. Although some of the measures can be applied to the same piece of land at any one time, the yield increases are not additive. The exception to this would be cover crops, which could be applied with all measures bar spring cultivation which is a prerequisite for cover crops. However, the yield increases from a combination of measures are likely to be higher than anyone of the measures applied separately, but it would be less than the combined total of each measure.

3.5.6 Cost Benefit Analysis

The CBA is based on many assumptions with limited evidence for these. The spread sheets provide a tool where these assumptions can be tested. Based on the assumptions above, the results for the baseline are given in Table 19 to Table 24 for the medium cost scenario and assuming degradation is currently occurring. With the exception of cover crops for ahead of spring barley, the NPV is always positive, and therefore there should be advantages in these measures being implemented. The switching values for the NPV to equal zero are shown in Table 25. The blank cells either indicate that the measure is not applicable or the NPV was negative. With the exception of drainage of spring barley, the results indicate that the loss in yield resulting from the loss of fertility was at least a factor of five times smaller than the assumed values. The reason for the yield increase being higher for spring barley is because it is the lowest value crop with the lowest yield per hectare that has been explored in the CBA. Therefore, a greater yield increase from implementing the adaptation measure is required to offset the additional costs of implementing the measure. In addition, the drainage and reducing compaction measures when applied to potatoes was beneficial even if climate change resulted in a slight decrease in yield. The reason for this is because potatoes are a high value crop. The results for the optimistic and pessimistic price scenarios are shown in Annex E.

The impact of these price scenarios on the switching values is small. As the prices rise, the switching values for the adaptation measures decline.

Table 19 Benefit, costs and net present value for drainage

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	0	0	0
W Wheat – required drainage	100	38	62
S Barley – free draining	0	0	0
S Barley – required drainage	8	6	2
Potatoes	54	3	50
Carrots	0	0	0

Table 20 Benefit, costs and net present value for compacted soils

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	0	0	0
W Wheat – required drainage	1919	175	1744
S Barley – free draining	0	0	0
S Barley – required drainage	149	26	123
Potatoes	1009	16	993
Carrots	0	0	0

Table 21 Benefit, costs and net present value for cover crop

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	0	0	0
W Wheat – required drainage	0	0	0
S Barley – free draining	623	146	-83
S Barley – required drainage	88	210	-122
Potatoes	447	131	317
Carrots	155	12	143

Table 22 Benefit, costs and net present value for shallow ploughing

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	178	0	178
W Wheat – required drainage	256	0	256
S Barley – free draining	17	0	17
S Barley – required drainage	24	0	24
Potatoes	122	0	122
Carrots	42	0	42

Table 23 Benefit, costs and net present value for spring cultivation

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	0	0	0
W Wheat – required drainage	0	0	0
S Barley – free draining	50	0	50
S Barley – required drainage	55	0	55
Potatoes	373	0	373
Carrots	130	0	130

Table 24 Benefit, costs and net present value for contour ploughing

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	59	0	59
W Wheat – required drainage	86	0	86
S Barley – free draining	6	0	6
S Barley – required drainage	8	0	8
Potatoes	41	0	41
Carrots	14	0	14

Table 25 Switching values for the reduction in yield resulting from the loss of soil fertility due to climate change

Crop	Measure					
Crop	Drainage	Compacted Soil	Cover crop	Shallow ploughing	Spring Cultivation	Contour ploughing
W Wheat – free draining				1.53E-17		1.4E-16
W Wheat – required drainage	0.00482	0.000199		1.53E-17		2.64E-17
S Barley – free draining				8.2E-17	0.000463	1.25E-16
S Barley – required drainage	0.012357	0.00378		8.28E-17	0.003641	1.25E-16
Potatoes	-0.002	-0.002	0.002094	1.08E-16	0.000	0.000
Carrots			-0.00137	6.31E-17	0.000	0.000

A number of the measures assessed are dependent on the severity of the weather experienced at the time and the location of the farm. Anything that encourages farmers to improve soil health and structure should be given priority, although these measures may not be directly linked to either reducing erosion or necessarily increasing soil organic matter. These may include encouraging farmers to diversify their rotation, and hence have a range of crops with a range of rooting profiles and disease risks. Nevertheless, it would also include drainage, reducing compaction, appropriate management of crop residues and encouraging farmers to better understand the role of soils by for example conducting visual soil assessments, nutrient budgets and/ or soil sampling on a regular basis. The experience from Scotland (FFBC) for the uptake of any new technologies or major changes to farm operations would suggest that the best method for getting farmers to change is a show and tell approach or discussion groups or financial incentives for training and specific fixed capital investment, e.g. drainage. The latter may also be perceived to have benefits for ecosystem services, and therefore there may be options for funding through pillar 2 of the proposed CAP. Alternatively, relatively cheap or free advice on the benefits of some of these practices may encourage farmers to adopt new practices. Nevertheless, the extreme rainfall conditions experienced in 2012 is resulting in some farmers clearing ditches and trying to improve their drainage systems.

The biggest challenges for the industry in terms of climate change is extreme weather events and changes in the patterns of inter-annual variability rather than gradual changes in weather. The latter, farmers are used to dealing with on a day-to-day basis. However, the droughts of 2010 and 2011 followed by the extreme wet year of 2012 make it challenging for farmers to decide how best to change their farming practices , and hence it is crucial for farmers to continue to adopt practices that will at least maintain if not improve soil structure and soil organic matter content. This will allow them to cope with extreme events, including both drought and periods of heavy rain. The actual practices adopted by the farmer will be a function of soil type and farming system. Under changing climate, farmers will make an assessment of the risk and reoccurrence of crop failure, and this will influence the farming practices adopted.

3.5.7 Caveats /further research

This analysis assumes that there is a linear change in yield. Under climate change projections, there is a need to assess the actual risk of drought and of waterlogged soils for a range of relevant soil types. Detailed information is also required on the effect of the adaptation measures on the soil structure and soil carbon stocks for each of the relevant soil types. This would allow an adaptation pathway analysis assessment to be carried out, which would give a more realistic assessment of the costs and benefits. There is evidence from China that links soil organic matter and yield (Pan et al., 2009); however this link has not been established for the UK. Hence there is a need, if the appropriate data is available at a national scale, to determine if this relationship holds for the UK. In addition, further work is required on the social aspects of adaptation in terms of uptake and barriers to uptake. There is also the need to explore other methodologies for assessing the effectiveness of adaptation for example portfolio analysis or adaptation pathways.

3.5.8 Conclusions

Based on the assumptions outlined above, the analysis indicates that shallow ploughing and reducing compaction are the most cost-beneficial measures. The applicability of these measures is affected by the soil conditions, and the expected weather conditions. Clearly, in order to maintain yield, reducing soil compaction is crucial (Carter, 1991; Ball at al., 1994). The inclusion of cover crops in the rotation is only seen to be beneficial for high value spring sown crops; however, the yield losses were assumed to be constant for all measure except contour ploughing, which may over-estimate the beneficial effect of spring cultivation. Land drainage and contour ploughing are of most benefit to winter wheat, which is grown extensively, and potatoes, which are of high value. The results would indicate that the inclusion of cover crops in the rotation results in positive NPV for potatoes; however, there is a cost to the farmer for spring barley.

The main issue is the maintenance of soil health and fertility; this can be assessed by soil structure and nutrient status by using for example the Visual Evaluation of Soil Structure technique (Ball et al., 2007). Maintaining soil health and fertility will result in the maintenance or even enhancement of the productive capacity of soils, which will manifest itself in long-term yield stability. This may require radical changes in crop rotations. There is also a need to be aware of the effect of climate change on crop pests and diseases, which can have a detrimental effect on yield. For example, fusarium epidemics are predicted to be more severe under climate change (Madgwick et al., 2011). Further details on adaptations measures for crop diseases can be found in section 3.2.

3.6 Agricultural water management

3.6.1 Introduction

Climate change projections show changing trends in terms of precipitation and temperature leading to local water scarcities and supply and demand imbalances. These regional scarcities have been mapped within several water company areas for England and Wales.

Agriculture and irrigation use less than 1 per cent of water resources on average, with an average abstraction of just 37 ML/day from a total of 3,035 licences[51] (Frontier & Anglian 2011). However, this masks significant seasonal and regional differences. Climate hotspots can be defined within localities (specific catchments (see RASE)) but are more generally characterised within water resource investment areas. These are the relevant spaces for considering the cost of water (i.e. the actual price paid by farmers) and thus private adaptation decisions. Water demand for agricultural irrigation is concentrated in eastern England, the east Midlands and the South East (Anglian). Thompson et al. (2007) suggest that the Anglian, Southern and Thames Environment Agency regions are clearly the priority regions where most benefits can be realised from reducing water use in agriculture. The Anglian region is dominant as it is by far the largest abstractor of water for irrigation of field crops, where peak demand for water occurs during periods when water availability is lowest. Thus the social opportunity cost of water used is highest in these zones and use in agriculture tends to be allocated to high value crops (e.g. potatoes).

The EA forecasts that by 2020, climate change is likely to result in increasing summer demand for irrigation water, of between 15-55%, in all regions. Also, irrigation requirements could shift northwards and westwards. By the 2020s, central England and eastern Wales could experience conditions similar to those currently typical of the south and east of England (EA 2009).

The priority for agricultural producers is to rationalise demand and/or augment supply. The former can involve activity switching and using new and improved varieties of drought tolerant plants and animals. Some of these will be occurring autonomously on many farms. Supply side augmentation can involve installation of irrigation systems and the construction of water storage capacity to capture rainwater and to store water abstracted at times of high flows to be used during low-flow periods. Given the nature of these options and the future forecast for water prices as set out below, reservoir construction is the clearest no/low regrets adaptation option.

3.6.2 Rationale for specific adaptation intervention

As previously noted, both demand and supply side interventions are possible for dealing with water scarcity. Demand side measures can focus on the pricing of water (including trading), which, aside a concluding note, is out of scope for this report. Technical demand side alternatives include alternative irrigation technologies (drip versus spray), crop switching (including to new drought tolerant varieties), cover crops (to reduce evaporation) and soil management options.

[51] Irrigated potatoes account for around half of all water used for agricultural in irrigation in England, and is justified by farmers in terms of the benefits accrued through extra crop yield and quality. Therefore, the economics of potato irrigation provide a useful benchmark for irrigation economics in England as a whole.

Crop switching can reduce water demand and potential yield penalties, although the latter may vary depending on the switch (e.g. between spring wheat to winter barley) Switches are made with a view to avoiding early season droughts and to increase cover on soils prone to evapotranspiration. Specific water savings can depend on the variety of biophysical conditions that are difficult to characterise precisely.

Surprisingly, irrigation technology switching does not afford the significant water savings initially anticipated (see Knox et al. 2007). Deriving a plausible scenario for the other measures was potentially confounded by the measures considered under the 'soil management' category. It is also unclear whether these measures are no/low regrets.

This analysis focussed on the option of investing in on-farm storage reservoirs as a means to maintaining a buffer supply and to facilitate storage of water abstracted at times of high flows (which currently occurs mostly in winter).

3.6.3 Costs

The costs of storage infrastructure are determined by storage volume and reservoir design (plastic lined versus clay). Environment Agency & Cranfield University guidance was used to select 4 volumes under the assumption that the smaller were maintained by individual farms, while the latter are shared installations between two or more enterprises. The guidance provides estimated installation and maintenance costs per m^3. The cost estimates do not appear to include any estimate of the opportunity cost of land use.

3.6.4 Benefits

Investment costs are balanced against returns represented by the value of water over the relevant time horizon, which we assume to be 100 years. Water valuation can be considered from either a private or public perspective. The private perspective considers the value of water in its likely highest value use, which in Eastern England are generally field vegetables (potatoes). A public perspective values water in terms of its marginal social opportunity cost. This is the next highest value use obviated by water abstraction, which in water scarce regions is potentially the value of the marginal unit left in stream[52]. The valuation of this and other uses of water is contested and is conceptually challenging since the valuation of water use is complex under current and (particularly) future demand and supply conditions. Water saved by agriculture obviates an opportunity cost that is measurable in terms of the (marginal) alternative use value. Since water has several competing uses[53], we must assume that water not used in agriculture is not abstracted from rivers and is therefore valued in terms of an amenity or recreational resource, or in terms of its abstraction value for use in public supply. The alternatives engender different assumptions about how water is valued in those uses, and there is a shortage of good data on competing water values. Instead, what we typically have is information on the price of water (in turn related to costs) of supply, and data from a range of non-market valuation studies, which do not allow us to infer information about the price elasticity of demand under future demand/supply (i.e. climate) scenarios.

[52] This is basically the application of the principal of resource allocation up to the point of eqi-marginal returns to competing activities

[53] We are also abstracting from potential quality differences between uses, and assuming a uniform quality. Relaxing this assumption complicates valuation further.

The price of water is suggested as one basis for valuation based on the concept of the average incremental (in turn reflecting theoretical long run marginal) social costs of supply (AISC). AISC is the forward looking investment costs collapsed back to the present then divided by the volume of water supplied by the corresponding investment. Some of the investment cost is for environmental improvement mandated by regulators. This has led some (e.g. Anglian and Frontier 2011) to suggest that AISC is the best/only proxy for a future value of water. In truth, such a cost-based measure is not equal to a theoretical valuation. But the AISC estimates currently available look like plausible future water prices and are remarkably close to existing non-market values.

A fairly comprehensive review of market and non market values for water uses has been conducted by Moran and Dann (2007), see Table 27. The marginal value for treated water ranges from £0.50/m3 to £1.20/m3. For raw water, the marginal value for irrigation water ranges between £0.23/m3 and £1.38/m3 for the Scottish case, comparable with values well in excess of £1.5/m3 for irrigated potato and salad crops in eastern England (Knox et al. 1999; Morris et al. 2004). Note that we do not have a value for in stream flows, which would be dependent on different flow conditions and highly site-specific. According to NEA these vary from £0.003 to £0.06/m3 for abstracted raw water, through to £1.50/m3 for metered, treated, potable water piped to households. The NEA (2011) also points out that prices grossly underestimate the very considerable consumer surplus that water users enjoy over and above the prices paid for this essential good.

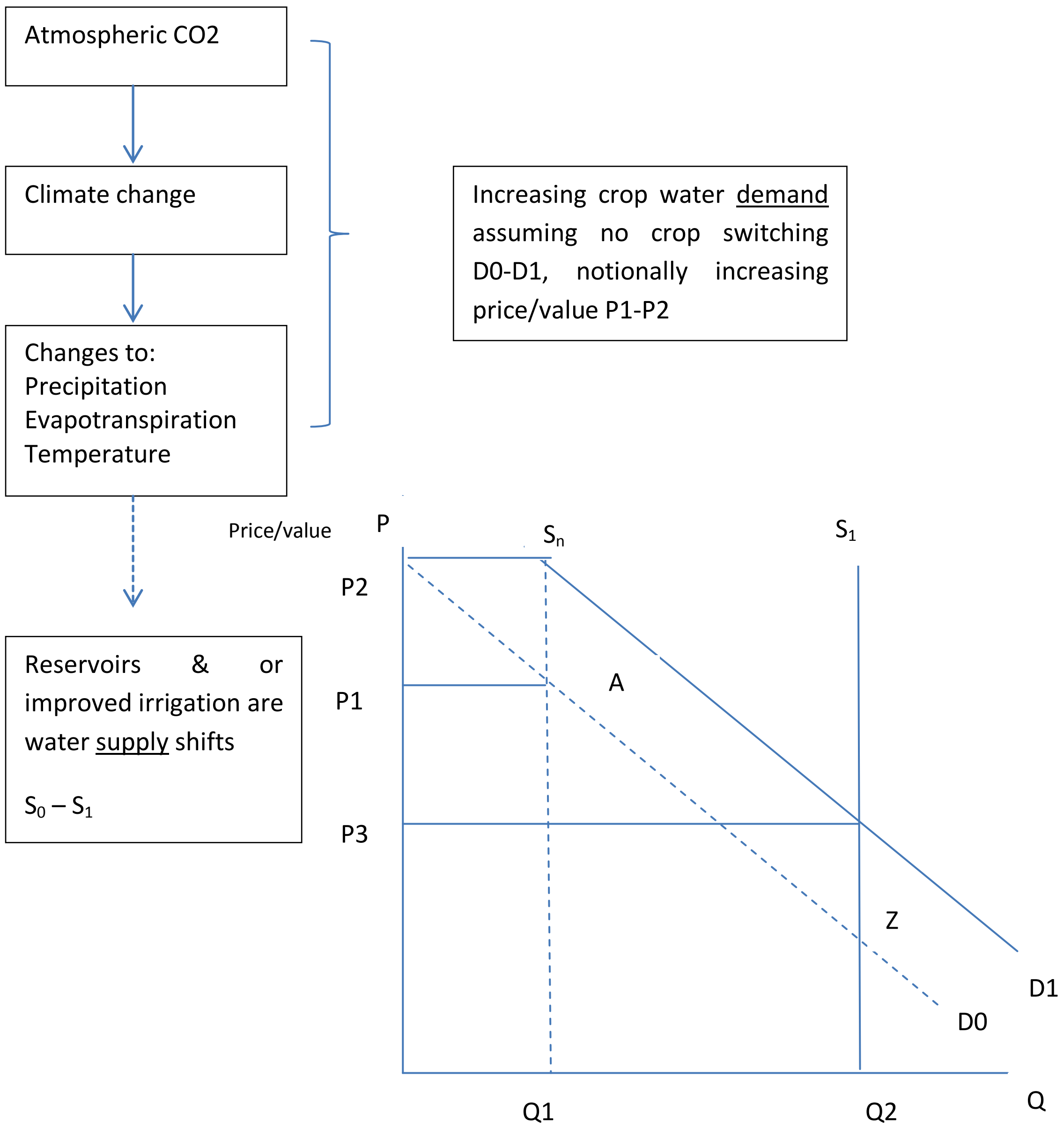
For our purposes we can consider the agricultural and household water use values as indicative opportunity water values. Hence a range starting from 0.23/m3 and £1.38/m3 is appropriate. These will increase as water becomes scarcer with climate change and there is a challenge in estimating what this value might be. Some approximation is necessary.

3.6.5 Uncertainty

Climate change is expected to affect both the supply side and the demand for water – some areas are known to be in deficit and others in surplus, hence different baselines for analysis and implicitly different supply and demand values. Climate change can be factored into the determinant of price and valuation in a partial or ideally a more general equilibrium way. In a partial sense we can expect reduced supply to be moving leftwards across a largely inelastic but initially fixed demand curve, thereby increasing the price and value of water as expected. A more dynamic representation of demand and supply might consider how the demand curve may shift and a new equilibrium price will engender new supplies. However, our analysis of price and value can only remain comparatively static in this study. Even in this simplified case we have no sound basis for the precise shape of these curves since they will vary at different hotspots according to local conditions.

Figure 19 sets out the intuition of which climate change enters the analysis and what costs and benefits are relevant.

Figure 19 Where climate change enters and what costs and benefits are relevant?



As drawn the initial demand and supply case is D0/S0, with price and quantity as P1 and Q1. Increased climate-induced demand to D1 with no supply response, increases price/value to P2 (potentially also reducing consumer surplus CS). Without crop switching we would rationally expect this to feed into a decision to produce less output. Attempting to maintain production under unfavourable water availability conditions will reduce yield.

But increased supply Q1 –Q2 notionally returns price/value to P1 (with initial CS). Producers have adapted and hence derive value form the water supply but this provides little or no incentive to produce more given his or her notional water valuation and maintained yields.

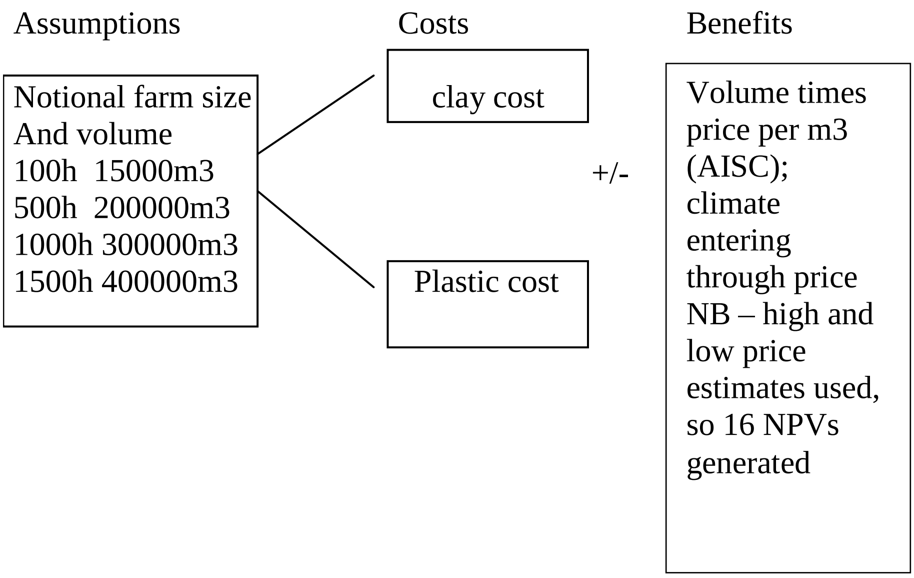
Normal appraisal of water supply augmentation might not account for the climate-induced demand shift D0-D1. In that case the supply shift reduces the price of water (increases consumer surplus) to P3 (P1AB to P3ZB). In this case, we could expect the benefits reduced water value to translate into increased production (not shown).

What is the net result of the adjustment? In essence supply costs should still be compared to the benefit of increased water availability. But the value of the latter is conditioned by specific hotspot conditions. At any specific hotspot we cannot be specific (with current data) about the dynamics of these demand shifts over the relevant time period. Water company areas produce figures for scarcity based on supply and demand balances, but this does not easily translate into information about future value or water, which is in turn dependent on the shadow value of water in all alternative uses in these areas. At best some surrogate of future demand can be made using average incremental social cost forecasts. However, the interaction of supply and demand, hence future value is essentially an estimate based on current water values.

3.6.6 Benefit-cost analysis and scaling-up

The pragmatic cost-benefit analysis is summarised in Figure 20 that summarises the data included in the background spread sheet.

Figure 20: Understanding reservoir costs and benefits



Key assumptions concern the volume of reservoirs and their construction material (clay or plastic), and the value of water and how this value will increase through time. The current assumption is that the NPVs can be calculated by using a range of values low from £0.36/m3 rising to £0.75 (by 2100) and a high value £1.20 rising to £2.50. Note that these values are likely to be a conservative approximation. Table 26 shows the NPVs and benefit-cost ratios for these values. Note that for the assumed water values all reservoirs are economically efficient. Water values have to be significantly lower than they currently are for NPVs to switch. Under current climate scenarios this is unlikely to be the case.

It is also important to consider that private reservoir investment decisions are unlikely to be made with a 100 year time horizon. Rates of return for shorter (private) time horizons may not look so attractive to farmers. It is important to combine this insight with the current abstraction costs faced by farmers. On this point, Morris et al. (2013) suggest that investing in winter storage is always a more expensive option than direct summer abstraction, even though summer water charges are higher than winter by a factor of 10. Though the costs of a reservoir might be seen as an insurance against unreliable summer water this option value is not high enough to see wide uptake of reservoirs. Restrictions on existing and new summer licences are likely to make farm reservoirs a necessary adjunct of irrigation development in future. This will serve to focus irrigation development on high value, water responsive crops that can carry the additional cost of winter storage. This is the key point in relation to scaling up. While we can speculate that there is wide potential for reservoir installation, it is only when abstraction costs increase that we can expect more to be constructed as farmers see a demonstrable rate of return. We are clearly not approaching such switching values (in terms of abstraction charging) yet.

3.6.7 Caveats /further research

More granular economic analysis is possible under a number of conditions. First, an improved understanding of how climate enters water demand would potentially improve our understanding of the demand supply balance and future water values. In relation to scaling up, key switching values could include shorter investment time horizons combined with scenarios of higher abstraction charges. These would be a basis for understanding the private decision to invest in more storage. At present the best indicator of the farm's likely investment is provided by a map of water company zones and associated water supply costs/pricing (see Figure 21).

Table 26: NPVs and benefit cost ratios

Capacity m3		Water price	NPV	B/C
150000	Clay	High	7,881,098	26
		Low	7,175,008	8
	Plastic	High	2,136,164	8
		Low	1,430,074	2
200000	Clay	High	10,508,130	26
		Low	9,566,677	8
	Plastic	High	2,848,219	8
		Low	1,906,766	2
300000	Clay	High	15,762,195	26

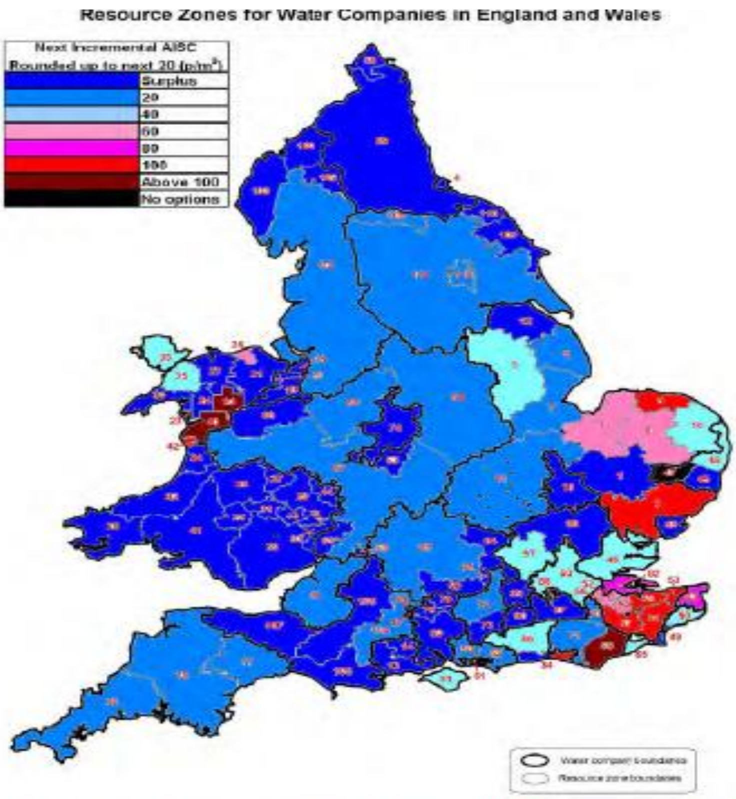
		Low	14,350,016	8
	Plastic	High	4,272,329	8
		Low	2,860,149	2
400000	Clay	High	21,016,260	26
		Low	19,133,354	8
	Plastic	High	5,696,438	8
		Low	3,813,532	2

Table 27 Summary of the valuation techniques and results for sectors considered

Sector	Valuation technique	Key assumptions and limitations	Marginal / average/ total value	Value
Households	Gibbons' willingness to pay formula	Assumes all consumers pay volumetric charges levied to metered customers in England, Wales and Scotland Includes value of both clean and dirty water	M	0.102 - 0.244 p/m^3
	Benefits transfer from stated preference study	Only considers value of supply of clean water	M	0.067 p/m^3
Agricultural irrigation	Net-back analysis	Assumes that the West Pfeffer catchment is representative of other areas where potatoes are irrigated Value includes both naturally available water and water applied through irrigation	T	£5128 /ha
	Transfer of net-back analysis	Data from England and Scotland combined despite different agricultural support arrangements and climate	A	23 - 138 p/m^3
Aquaculture	Avoided cost	Costs calculated based on running costs of the largest effluent filters bought without a loan Considers water use for disposal of solid waste only Assumes filters remove all solid waste	A	0.126 p/m^3
Salmon angling	Benefits transfer of travel cost method study	Assumes salmon anglers in Donegal are representative of others throughout Scotland and Northern Ireland	T	£175 / day
Industry	Benefits transfer from marginal productivity approach study	Industrial water use in Scotland and Northern Ireland assumed to be the same as for Canada Assumes no improvements in water efficiency since 1991	M	0.3 - 15.7 p/m^3
Power generation	Avoided cost	Compares generation costs associated with hydropower with generation costs from other fuels and technologies	M	0.00 - 0.049 p/m^3 (compared to gas, nuclear and coal) 0.245 - 0.817 p/m^3

				(compared to wind power)
Source: Moran and Dann (2007)				

Figure 21: Water company zones and associated supply costs



Source: Ofwat 2010 – A study on potential benefits of upstream markets in the water sector in England and Wales (Ofwat calculations based on draft WMRPs).

3.7 Forestry

3.7.1 Introduction

Climate change presents a serious threat to England's forests. Considerable research has been conducted into the likely impacts over the rest of the century. Moffat et al. (2012) in the Climate Change Risk Assessment for the Forestry Sector, identify a range of impacts that are likely to pose serious problems for forestry. From the long list of over 30 impacts, four were analysed in more detail due to their significance under climate change. These four risks are:

- Forest pests and pathogens, whose presence may change in prevalence and severity under climate change
- Drought, which is likely to have a significant effect on productivity
- Forest productivity, which is likely to change under climate change, with differential effects across the UK, but generally negative effects in England
- Wildfires and forest fires, the occurrence of which may increase under climate change

The aim of this analysis as mentioned in earlier sections of this report, was to identify the key low-regrets adaptations that would be cost effective to implement within the next five years, or those with long lead times. Forestry as a sector does have long lead times of over 30 years, and potentially difficult decisions about which species to plant will need to be made in the next few years. The projected future climate needs to be balanced against current conditions, for example, planting more heat tolerant species for the 2050s climate may not be worthwhile if they cannot tolerate current cold winter temperatures (Kirby et al. 2009).

The forestry analysis in this report is based on modelling carried out in Frontier et al. (2013)[54]. This is due to time and resource constraints, however it does mean that not all the potential adaptations were able to be analysed, as the analysis was restricted to the adaptation scenarios modelled in Frontier et al. Thus all the assumptions about climate change and forest response are the same as those in Frontier et al.

The modelling carried out in Frontier et al. is based at the national level in most cases and therefore the analysis for this study is also based at the national level, therefore upscaling is not necessary/appropriate. This does mean that per hectare costs and benefits are not provided.

3.7.2 Climate change impact

The impact of climate change on the potential production of UK forests is modelled with the Forest Research Ecological Site Classification (ESC) model (Pyatt et al. 2001) in the CCRA (Moffat et al. 2012) and extrapolated by Frontier et al. (2013). Detail on the model and assumptions can be found in both Moffat et al. and Frontier et al. (2013), the main feature is that a measure of potential production is used which combines temperature and moisture deficit variables with information on windiness, continentality, soil type and fertility and tree species characteristics to calculate suitability, which is assessed as the potential yield class (YC). YC is an indication of performance for a stand of forestry over its rotation, and not necessarily at a point in time (Moffat et al. 2012).

[54] The authors would like to gratefully acknowledge Isis Walsh-Ebbatson of Frontier Economics who provided invaluable background information and spent considerable time explaining the scenarios and assumptions made in their modelling. Any errors in the interpretation of the Frontier modelling are all our own.

The ESC considers yields of 14 different species in 16 different regions across the UK.

A number of simplifying assumptions are made, particularly that no weeds, pests or pathogens are considered, and no CO_2 effects or extreme events are modelled.

Projected yield classes are multiplied by estimates of the area (public and private) of each species growing in each UK country in the 2050s and 2080s, in the absence of climate change. However, the age structure and management effectiveness of the forest cannot be projected with any certainty for the 2050s and 2080s, so all numbers must be treated with caution.

It should also be noted that UKCIP02 climate scenarios are used in this analysis as modelling productivity requires multiple climate variables, which were not all available in the UKCP09 resources at the time (Moffat et al. 2012, p.22).

Forest cover aspiration assumptions

All of the UK countries have aspirations for increasing forest cover over this century. England's aspiration, expressed in the Natural Environment White Paper (2011) and the Government Forestry and Woodlands Policy Statement (Defra 2013) are an increase in woodland cover from 10% to 13% by 2060. The scenarios presented here assume a **medium** level of forest cover aspiration is met – which means the current restocking rate plus half of the aspirations for increased forest cover are met.

Climate change impact on production

Moffat et al. (2012) present the impact of climate change on UK forest production in the CCRA, and these are the values used in this analysis, using the UKCIP02 high emissions scenario.

3.7.3 Rationale for specific adaptation interventions

Forestry is an interesting case to consider for adaptation as unlike in the agricultural sector, rotations are very long and the consequences of decisions made now will not be realised for several decades. Forestry more than many other sectors must be thinking about adaptation to climate change in a very strategic way.

Potential adaptations are identified in Moffat et al. (2012), as well as Frontier et al. (2013), Broadmeadow and Weir (2012), Kirby et al. (2009), and Seppälä et al. (2009). Kirby et al. note that clarity is required on what is being conserved in a changing climate; whether the past emphasis on use of native species and local provenances is still valid, and where might species and provenances from elsewhere be better suited to future conditions, or provide refuge for rare and threatened species. This chapter considers primarily managed forests, where adaptation measures are possibly easier to implement than in natural forests. The principle for successful adaptation should be to develop the forest's own capacity to adapt rather than adaptation towards one specific, predicted climate change (Kirby et al. 2009). Kirby et al. summarise adaptations into four main processes:

- Creating resistance to change – examples include changes in rotation length, tree species composition, and reducing the impacts of other stressors on the system

- Promoting resilience to change – assisting forest and woodland areas to be more suitable under future conditions, examples include encouraging a variety of species and contingency planning for pest outbreaks or extreme events, including fire risk
- Monitoring the processes taking place and their outcomes – examples include tracking how the climate is changing and whether this is as expected, identify successful and unsuccessful examples of adaptation, and validating models of species' responses to climate change
- Accepting that new landscapes will develop.

A limited range of adaptation options are suggested in the CCRA in response to the four main risks identified and shown in Table 28.

Table 28 Climate risks and adaptation options identified from CCRA

Climate risk	Adaptation option
Pests and pathogens	Adaptation measures appear limited, and are likely to require specific actions for each organism, making generalisation and economic analysis challenging. Similar approaches to those taken for animal and crop disease (such as increased surveillance) may be an option.
Drought damage	Planting of more drought tolerant species, wider tree spacing, watering
Change in tree species suitability and productivity	Species change
Forest fires	Redesigning forest areas, reservoirs.

The Frontier et al. (2013) report considers four adaptation scenarios, but disaggregated data for England alone was only available for two of these scenarios. The two scenarios address the change in tree species suitability and productivity, and are described in some detail below.

Adaptation Scenario 1: This assumes that species with the highest yields in the 2050s and 2080s are used for restocking, instead of the current species mix.

Modelling assumptions: The highest yielding conifer and the highest yielding broadleaf species of the 8 conifer and 6 broadleaf species considered in the ESC model are considered, for each location of the 15 locations modelled, which include seven English regions (East England, East Midlands, North East England, North West England, South East England, South West England, West Midlands, Yorkshire and the Humber).

For both conifers and broadleaves, the highest yield is weighted by the proportion of total conifer or broadleaf forest of that location within its country. This gives a weighted average of highest yield for each country, and the difference between this and the average yield for each country (total yield in the 2050s/conifer area), which is then applied by country to the restocking and new forest cover growth areas for each country (personal communication with Walsh-Ebbotson 2013).

Adaptation Scenario 2: This assumes that sub-species or provenances of each species will be identified that are resilient to climate change and new planting would use these species.

Modelling assumptions: It is assumed that a new seed will be developed for each of the 14 species assessed. For example, assuming that silver birch will be restocked with silver birch, in the West Midland it has a yield class today of 8.63 and 2.96in 2080, so it is assumed that a new provenance of the silver birch will be developed which will have a yield class of 8.63 under 2080 climate (pers. comm. Walsh-Ebbotson 2013).

Table 29 shows potential production (million m^3 per year) (under the mid-range forest cover increase assumption), under the current climate, the high emissions scenario, and both adaptation scenarios, for conifers (softwood) and broadleaves (hardwood). Unfortunately disaggregated information for conifers and broadleaves is only available to 2050 in Scenario 2.

Table 29 - potential production (million m3 per year)

	2050s		2080s	
	Conifer	Broadleaf	Conifer	Broadleaf
Current climate	5	7	5	7
High emissions scenario	4	6	3	4
Adaptation Scenario 1	5	6	4	5
Adaptation Scenario 2	4	6	n/a	n/a

Frontier et al. do consider two more adaptation scenarios based around pest management; however the results of these modelling scenarios were not available by country (only at the UK level) so these scenarios were not considered at this stage.

Assumptions for this analysis

Frontier et al. present results for potential production under the current climate, under the climate change scenario, and under the two adaptation scenarios, for the 2050s and the 2080s. In this analysis we assume that the current levels of production continue until 2050, the 2050 levels continue until 2080, and the 2080 levels continue until the end of the century. It should be noted that these figures from Frontier et al. can only realistically represent one point in time, and the analysis in this study has had to make assumptions about how the values will change over time that may not be realistic

3.7.4 Benefits

The benefits of the adaptation strategy are assumed to be the potential production levels (measured in million m^3 per year) in the adaptation strategy compared with the production levels under climate change, as identified previously. Both market benefits and non-market benefits were considered.

Market benefits

Market benefits are estimated in this study using the market value of timber. Moffat et al. (2012), based on Forestry Commission timber prices, value softwood at £10.75/m3 at 2010 prices, and assume that hardwood is valued at twice the price of softwood (£21.50/m3) in the absence of available unit values for hardwood(Moffat et al. 2012). However information in Frontier et al. (2012) indicates that prices received by private forest managers are more commonly twice those used in Moffat et al. 2012, so these prices are likely to be an underestimation.

Prices are held at 2010 levels throughout this analysis, an assumption that is unlikely to be realistic however forecasting the direction and rate of change in forest market prices is beyond the scope of this analysis.

In common with the rest of the analysis in this report, future values are discounted to present values using the discount rates specified in the Treasury Green Book.

Non-market benefits

The value of the non-market benefits are taken from a comprehensive study of the social and environmental benefits of forests in Great Britain (Willis et al. 2003). The values from the Willis et al. study are presented in the more recent National Ecosystems Assessment (Bateman et al 2011), updated with 2010 values.

Willis et al. review the existing literature at the time to develop aggregate values of non-market benefits. All of these values are subject to considerable uncertainty. The total values depend on individual values as well as the numbers to which they are applied (e.g. number of visits to forests, number of houses with a forest view etc.), but in general are deemed to be reliable "ball-park" figures. Each category is discussed in more detail below but for further clarification, please refer to Willis et al. (2003) directly.

Recreation- the value depends on characteristics of the forest and recreational opportunities within it, as well as the availability of substitute sites in the area, and the income and taste characteristics of the population in the area surrounding the forest.

Forest attributes consist of: total forest area in hectares, percent coverage of broadleaves, larch, presence of nature reserves (all had positive effects on utility), conifers, and a measure of congestion (both had negative effects on utility).

Landscape – Six forested landscapes were used within which to explore public preferences. Defined by two generic forest types (broad-leaved and conifer) each set within three landscape contexts. WTP for forest views are consistent with hedonic price models estimating the effect of local trees on house prices.

Biodiversity – the values here were developed based on a framework by Garrod and Willis (1997) for remote coniferous forests, extended to include other types of forests. WTP for forest biodiversity was elicited through focus groups. Values for the categories of ancient and semi-natural woodland, replanting, and new broadleaves were developed. As the forestry part of this study focuses on commercial forestry, only the replanting and new broadleaves values were used.

Carbon sequestration – carbon sequestration varies depending on woodland coverage, structure (i.e. species mix), tree growth and soil conditions. The models reviewed also accounted for carbon emissions involved in harvesting, which reduces the total carbon sequestration values. Willis et al.

use a social cost of carbon value of £6.67/ tC in their aggregation, which is based on a range of literature.

Air pollution – the value estimates the net health effects and reduction in associated economic costs attributable to current woodland in Britain. These results should be viewed as a lower bound of the net health effects of pollution absorption from trees.

Willis et al. also cover the benefits of the protection that woodlands give to archaeological sites, however these benefits are less applicable to commercial forestry so were not included here, as well as the impact of forestry on water supply and water quality. Forestry can affect both the quality and quantity of water available to other uses, which may be of particular concern under climate change when water may become scarcer. On the other hand, trees contribute to reduce flood risk, so due to the complexity and uncertainty water quality and quantity were not considered in this analysis.

The approach initially taken in this analysis to account for the non-market values of forestry was to link them to the productivity changes, in the absence of forest area and composition and other relevant attribute data. However, because it is unclear how changes in tree species and composition will affect particularly wildlife and habitats, but also the other benefits of recreation, landscape and carbon sequestration, it was decided to omit the non-market values from this analysis.

For interest, the non-market values based on Willis et al., updated to 2010 prices, are shown in Table 30.

Table 30: Annual social and environmental benefits of forests in England (£millions, 2010 prices)

Environmental Benefit	Values used in this analysis (2010 prices)
Recreation	425.09
Landscape	148.70
Biodiversity	73.20
Carbon sequestration	51.73
Air pollution	0.34

(Based on Willis et al. 2003)

An alternative approach would be to use marginal values of ecosystem service provision, such as provided in Chiabai et al. (2009), who provide values for ecosystem services per hectare. However as the modelling results from Frontier et al. are presented based on potential production rather than per hectare values, it would be difficult to apply these marginal values to them.

3.7.5 Costs

Adaptation Scenario 1 was assumed to be **cost-free.** This assumption was made because the adaptation consists only of restocking with currently available varieties, and did not require any research and development into new varieties.

Costs for adaptation scenario 2 were calculated based on the costs of bringing 14 new species into development. Estimates for these costs were based on Savill (2013) and assume an overall cost of £2m per species, spread over 20 years, with about 20-30% of the total spent in the first five years on identifying plus trees, seed/scion collection, nursery work, design of the orchards, site preparation including fencing, planting and early maintenance (mostly weeding). 20 percent of the cost occurs towards the end, involving measuring, statistical analyses, and removal of less well performing trees. The remaining cost is spread evenly over the years mostly on maintenance, but some on assessments of the trials.

3.7.6 CBA Results and discussion

Results of the CBA are presented in Table 31, showing the range of NPVs for softwoods and hardwoods where possible. Because disaggregated information for the two wood types was not available beyond 2050 for scenario 2, the NPV was also calculated for the aggregation of softwoods and hardwoods, using both the lower softwood price and the higher hardwood price to provide a range of values to 2100 (as well as to 2050 for comparison). As the assumption in scenario 1 was that there would be no costs to the adaptation, the NPVs are positive for all types of wood and both when calculated to 2050 and to 2100. Interestingly by 2050 the vast majority of the benefit accrues to softwood, the hardwood benefits pick up in the latter part of the century. On this basis it would be clear that this adaptation should go ahead.

In scenario 2, the adaptation strategy actually has no effect by 2050 and the NPV is negative, as there are reasonably high costs involved with no quantifiable benefit. However, when the NPV out to 2100 is calculated (using the combined softwood and hardwood values), the NPV ranges from £224.4 to 470m. This illustrates the importance of the time horizon one uses when doing these calculations, and highlights the long time horizons involved in forestry. Using the NPVs calculated out to the end of the century clearly indicates that both these adaptations strategies would be worth doing.

Table 31 - Results of the CBA, £m

		£m				
		PV benefits		PV Costs	NPV	
		to 2050	to 2100	PVCosts	to 2050	to 2100
Adaptation Scenario 1	Softwood	87.4	183.4	0.0	87.4	183.4
	Hardwood	0.4	58.3	0.0	0.4	58.3
	Total	87.8	241.7	0.0	87.8	241.7
	softwood/hardwood combined	87.2 - 174.2	222.9 - 445.6	0.0	87.2 - 174.2	222.9 - 445.6
Adaptation Scenario 2	Softwood	0.0		10.7	-10.7	
	Hardwood	0.0		10.7	-10.7	
	Total	0.0		21.3	-21.3	
	softwood/hardwood combined	0.0	245.8 - 491.3	21.3	-21.3	224.4-470.0

There are a number of caveats to this analysis. One is that the analysis is based on forest cover inventory as at today and makes a simplifying assumption that the mix of species will remain the same going forward. As mentioned previously the assumption is made that half of the aspirations for increased area of forest cover are met. The production numbers were available for only two time-periods, 2050 and 2080, and were assumed to change linearly in between, however this assumption may be false.

3.7.7 Implications and further research

These results, while based on several assumptions and really only providing an indication of the magnitude of costs and benefits, clearly show that taking action to avoid the impacts of climate change will have significant economic benefits. If no action is taken until later in the century, it is likely to be too late to avoid some of the major impacts of climate change, as the development of new varieties requires a long lead time, and trees need time to mature. Therefore work does need to begin now on planning for future climates.

If there was more time to undertake the analysis and the detailed modelling figures were available it would be more accurate to consider the age structure of the forest and how this changes over time and what the implications for potential production would be.

Further research is needed to model the effect of other adaptation options, as well as provide a tool to look at extreme events, in order to weigh up the relative costs and benefits of occasional significant losses versus regular but suboptimal delivery, for example.

4 Conclusions/insights

Climate change is expected to have significant impacts on the stock of England's natural resources, yet the overall picture on these impacts is surprisingly under-researched in terms of the comparative magnitude of impacts on different categories of resources, and the likely returns to appropriate adaptation interventions.

This report considers the climate impacts anticipated across a key set of resource categories of interest to the Adaptation Sub-Committee of the Committee on Climate Change, in terms of their perceived contribution to the provision of ecosystem services. It then identifies a number of corresponding no or low regrets adaptation options that can be subject to economic appraisal. This analysis compares notional adaptation costs with anticipated benefits (avoided impacts), the latter arising over the time horizons up to 2100.

The analysis raised a number of challenges, some of which were foreseen in advance, and others that were not. Specific difficulties are encountered in characterising average illustrative adaptation cases that enable results to be generalised or "scaled-up" to provide a nationwide picture of costs and benefits. In some cases e.g. livestock productivity impacts, it is more straightforward to generalise results but in other cases, e.g. coastal managed retreat schemes, costs and returns to investment are highly site specific.

Each impact category presented specific information challenges, largely related to the patchy scientific evidence on one or more stages of the integration of information for climate impact valuation. Valuation of impacts (or benefits) is particularly challenging in the case of non-market goods, where data are, out of necessity, transferred from existing studies that were not specifically designed for the impacts considered to arise in our cases.

In other cases however, the nature of specific adaptations were contested, either the basis of scientific evidence on 'adaptation effectiveness', or more mundane data gaps on the cost or spatial applicability of measures. More generally, impact assessment was hampered by a clear view of how alternative climate signals lead to precise and distinct impacts that could be valued. With current scientific and valuation data it is generally not possible to be completely precise about the scope of damages. Related uncertainties become increasingly difficult the longer the time horizon under consideration. All that is possible is to provide illustrative example for the cost-benefit comparison accompanied with reasonable sensitivity analysis.

Table 32 provides indicative net present values emerging from the research, where possible (some were too site specific to include in the table).

Table 32: Summary NPVs across all sectors

Sector	NPV (£m)	Comments
Peatland		Site and assumption specific
Managed realignment		Entirely site-specific. Spread sheet model allows NPV to be

		calculated once site-specific data has been entered.
Protected areas	37	For the South East Region of England
Crop disease	1.1-12	A range of 8 different adaptation options - covering wheat at the national level
Animal disease (exotic incursions)	1280 (median value)	National (England) level. Potential benefit is very assumption specific; see figure 14 for a full range of values.
Transport	36	National level
Animal productivity	0.82 – 3279	National level
Soil management	-122 – 1744	A range of 6 different adaptation options – covering a range of crops
Water	1 – 21	Covers a range of water storage capacities
Forestry	222 – 470	National level

Note that while these values are informative, the comparison of adaptation choices based on NPVs raises many conflicting equity and resilience issues that are not explored here and that in fact go to the heart of the rationale for adaptation in this 'sector'. In other words, while there is no *a priori* assumption on expected or hurdle NPV, nor is there any suggestion that say, high return to adapting livestock should take precedence over more modest returns to say coastal zone adaptation. Note also that the results represent a mix of private and public perspectives without always clarifying the incidence of costs and benefits, responsibilities and incentives. Indeed, attractive NPVs mask numerous underlying barriers, including for example that private adaptation actions generally plan over shorter time horizons, or that in some cases the adaptations will need to be facilitated by public investments (e.g. coping with animal diseases).

Overall this exercise has demonstrated many of the difficulties in reconciling theoretical concepts about adaptation with practical realities. It also raises the question of whether a cost-benefit approach is uniformly applicable under conditions of high uncertainty, which may point to modified methods (such as real options, robust decision making, portfolio analysis or iterative adaptive management for example) and methods with less grounding in economic theory but which appeal to a broader qualitative consensus on adaptation needs and responses (e.g. multi criteria analysis).

5 References and supporting literature

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6 Annexes

Annex A – Individuals offering further views for Peatland restoration

Name	Institution	Method
Penny Anderson	Penny Anderson Associates	Email
Rebecca Artz	James Hutton Institute	Email
Clifton Bain	IUCN	Email
Aletta Bonn	Freie Universität Berlin	Email
Steve Chapman	James Hutton Institute	Email
Dan Charman	University of Exeter	Email
Mike Christie	University of Aberystwyth	Phone
Stewart Clarke	Natural England	Email, Phone
Frank Essl	Austrian Environment Agency	Email
Chris Evans	CEH	Email
Angela Gallego-Sala	University of Exeter	Email
Martin Gillibrand	Moorland Association	Phone
Emilie Grand-Clement	University of Exeter	Email
Nick Hanley	University of Stirling	Email
Joseph Holden	University of Leeds	Email, Phone
Hans Joosten	University of Greifswald	Email
Paul Leadbetter	North Pennines AONB	Phone
Richard Lindsay	University of East London	Email, Phone
Harriet Orr	Environment Agency	Email
Kay Prichard	Scottish Natural Heritage	Email
Mark Reed	Birmingham City University	Email
Alex Scott	Yorkshire Water	Phone
Charles Scott	University of Newcastle upon Tyne	Email

Matthew Shepherd	Natural England	Email
Mary Ann Smyth	Crichton Carbon Centre	Email, Phone
David Smith	South West Water	Phone
Kate Snow	United Utilities	Phone
Andrew Walker	Yorkshire Water	Phone
Adam Ward	Ex-Natural England	Phone
Fred Worral	Durham University	Email

Individuals were contacted proactively by Email to seek their views on the costs and effects of restoration and/or climate change pressures. Individuals were selected on the basis of either (co)authorship of relevant academic papers/reports and/or practitioner involvement with restoration activities and/or access to relevant data. Many, but not all, individuals were known through previous involvement with the IUCN Peatland Programme and the NERC Valuing Nature Network project on peatlands.

Annex B: Alternative simulation results

Tables B1a &b and B2a & b summarise selected results from an alternative spread sheet simulation model that did not consider carbon explicitly, but rather used WTP values encompassing climate regulation and other ecosystem services. As with the model reported in the main text, the alternative model was run for different assumed parameter values, using NPV (but including capital costs in the calculation) as a measure of the societal worth of restoration as an adaptive response to climate change.

The body of each table below shows differences across NPV timeframes, restoration costs (monitoring/management & opportunity costs are combined into "on-going costs" for presentational ease), rates of climate-induced degradation and the effectiveness of restoration in delaying the onset of degradation.

Rates of climate-induced degradation were approximated as a linear annual rate of decline to achieve total loss by a specified future date (40 to 160 years). Restoration was assumed to delay the onset of such degradation by a fixed period (30 to 90 years), during which on-going costs would be incurred but enhanced ecosystem service benefits would be enjoyed – both would cease with the onset of degradation. These representations are acknowledged as simplistic and arbitrary, but are sufficient to demonstrate some sensitivity to different time-related assumptions.

Following Harlow et al. (2012), Tables B1a & b are for higher WTP figures than Tables B2a & 2b. Specifically, the higher WTP values reflect an assumption that peatlands and peatland restoration are associated with a full range of ecosystem services, including contributions to flood management. However, given that this may not be universally true, the lower WTP values reflect a more conservative assumption of excluding flood management.

All tables report three levels of capital cost (£500, £1000, £1500), but Tables B1b and 2b have higher on-going costs than Tables B1a & 2a. Specifically, monitoring & management costs are fixed at £60/ha/yr throughout, but opportunity costs are set at either zero or £100/ha/yr. Possible higher capital costs and opportunity costs associated with forestry are not presented explicitly here since the selected results are sufficient to show the effect of more modestly higher costs on NPVs.

The results are expressed on a per hectare basis, meaning that they could easily be scaled-up to any given site size (e.g. a "hotpot" identified in Project 1). Moreover, although not explicitly describing any particular level of peatland condition nor cover type (e.g. purple moor grass, forestry, bare peat) the different cost levels and different degradation rates could be interpreted in terms of such and thus combined with (if available) detailed information on the composition of a given site or region (cf. Harlow et al., 2012). For example, results for lower cost assumptions would fit lightly degraded sites under agricultural use whilst higher cost assumptions would fit restoration of more degraded sites (although very expensive capital costs and opportunity costs for, e.g., afforested sites are note presented here). However, the generic per ha values are themselves sufficient to reveal some patterns to the results.

In brief, the results indicate that the merits of restoration improve as the (assumed) pace of climate-induced degradation increases and the (assumed) delay achieved by restoration to the onset of such degradation lengthens. Hence, for example, the most right hand column in Table 1a shows values increasing as the degradation rate reduces moving down each group of five scenarios, and each group of five scenarios has higher values than the preceding group in that column. However, this intuitive outcome is conditional on other assumptions.

In particular, for any given pairing of degradation rate & delay length, the economic benefit values assumed for avoiding degradation loss and enhancing service flows are critical, as are the assumed costs of restoration. For example, even a rapid rate of degradation and long delay can yield an unfavourable cost-benefit outcome if the values attached to the service gains are low and the restoration costs are high. Hence, for example, the lower values in Tables B1b and 2b when compared to the corresponding cells in Tables B1a and 2a due to the lower WTP unit values used, and the greater preponderance of negative values in Tables B1b and 2b relative to Tables B1a and 2a due to the higher on-going costs assumed.

In addition, high discount rates and/or short time-frames down-play longer-term aspects of slower rates of climate-change induced degradation and longer restoration delays to the onset of degradation. Hence, for example, the increase in values running rightwards between each group of three columns as the NPV time-frame lengthens from 25 to 50 and then 100 years. Issues surrounding discounting are frequently encountered in relation to sustainability debates and are highly relevant here in that the service benefits of restoration may be extremely durable. That is, if the anticipated effects extend beyond the short-term, they still need to be accounted for.

Notwithstanding the need to test the robustness of the assumptions and values underpinning the above illustrative figures, the policy implications of the assessment are that peatland restoration can be worthwhile as an adaptive response but that this is conditional upon circumstances. In particular, whilst low cost restoration of (presumably) lightly degraded sites may offer a low regrets option, higher capital costs for (presumably) more degraded sites can easily outweigh any benefits, as can modestly higher opportunity costs.

Table B1a: Illustrative Net Present Value(£/ha) of peatland restoration under different climate-induced degradation assumptions and NPV timeframes
Value gain from restoration = +£136/ha; value loss of degradation = -£275/ha (following Christie et al., 2011; Harlow et al., 2012)

NPV timeframe	25 years			50 years			100 years		
Capital cost	£500/ha	£1000/ha	£1500/ha	£500/ha	£1000/ha	£1500/ha	£500/ha	£1000/ha	£1500/ha
On-going cost	£60/ha/yr	£60/ha/yr	£60/ha/yr	£60/ha/yr	£60/ha/yr	£60/ha/yr	£60/ha/yr	£60/ha/yr	£60/ha/yr
R40+30	£1,411	£911	£411	£3,070	£2,570	£2,070	£3,292	£2,792	£2,292
R70+30	£866	£366	-£134	£1,939	£1,439	£939	£2,525	£2,025	£1,525
R100+30	£648	£148	-£352	£1,449	£949	£449	£1,996	£1,496	£996
R130+30	£530	£30	-£470	£1,185	£685	£185	£1,606	£1,106	£606
R160+30	£457	-£43	-£543	£1,020	£520	£20	£1,362	£862	£362
R40+60	£1,411	£911	£411	£3,957	£3,457	£2,957	£5,333	£4,833	£4,333
R70+60	£866	£366	-£134	£2,635	£2,135	£1,635	£4,158	£3,658	£3,158
R100+60	£648	£148	-£352	£2,068	£1,568	£1,068	£3,319	£2,819	£2,319
R130+60	£530	£30	-£470	£1,763	£1,263	£763	£2,762	£2,262	£1,762
R160+60	£457	-£43	-£543	£1,573	£1,073	£573	£2,414	£1,914	£1,414

R40+90	£1,411	£911	£411	£3,957	£3,457	£2,957	£6,256	£5,756	£5,256
R70+90	£866	£366	-£134	£2,635	£2,135	£1,635	£4,812	£4,312	£3,812
R100+90	£648	£148	-£352	£2,068	£1,568	£1,068	£3,866	£3,366	£2,866
R130+90	£530	£30	-£470	£1,763	£1,263	£763	£3,250	£2,750	£2,250
R160+90	£457	-£43	-£543	£1,573	£1,073	£573	£2,866	£2,366	£1,866

Scenario code interpretation example: R40+30 denotes site expected to degrade completely over 40 years, but restoration delays onset of this by 30 years.

Where NPV timeframe is less than the delay period, some values will repeat down scenario groups in a column.

Table B1b: Illustrative Net Present Value(£/ha) of peatland restoration under different climate-induced degradation assumptions and NPV timeframes
Value gain from restoration = +£136/ha; value loss of degradation = -£275/ha (following Christie et al., 2011; Harlow et al., 2012)

NPV timeframe	25 years			50 years			100 years		
Capital cost	£500/ha	£1000/ha	£1500/ha	£500/ha	£1000/ha	£1500/ha	£500/ha	£1000/ha	£1500/ha
On-going cost	£160/ha/yr	£160/ha/yr	£160/ha/yr	£160/ha/yr	£160/ha/yr	£160/ha/yr	£160/ha/yr	£160/ha/yr	£160/ha/yr
R40+30	-£237	-£737	-£1,237	£1,266	£766	£266	£1,488	£988	£488
R70+30	-£782	-£1,282	-£1,782	£135	-£365	-£865	£721	£221	-£279
R100+30	-£1,000	-£1,500	-£2,000	-£355	-£855	-£1,355	£193	-£307	-£807
R130+30	-£1,118	-£1,618	-£2,118	-£619	-£1,119	-£1,619	-£198	-£698	-£1,198
R160+30	-£1,191	-£1,691	-£2,191	-£784	-£1,284	-£1,784	-£442	-£942	-£1,442
R40+60	-£237	-£737	-£1,237	£1,499	£999	£499	£2,698	£2,198	£1,698
R70+60	-£782	-£1,282	-£1,782	£177	-£323	-£823	£1,523	£1,023	£523
R100+60	-£1,000	-£1,500	-£2,000	-£389	-£889	-£1,389	£684	£184	-£316
R130+60	-£1,118	-£1,618	-£2,118	-£695	-£1,195	-£1,695	£127	-£373	-£873
R160+60	-£1,191	-£1,691	-£2,191	-£885	-£1,385	-£1,885	-£222	-£722	-£1,222

R40+90	-£237	-£737	-£1,237	£1,499	£999	£499	£3,212	£2,712	£2,212
R70+90	-£782	-£1,282	-£1,782	£177	-£323	-£823	£1,769	£1,269	£769
R100+90	-£1,000	-£1,500	-£2,000	-£389	-£889	-£1,389	£823	£323	-£177
R130+90	-£1,118	-£1,618	-£2,118	-£695	-£1,195	-£1,695	£207	-£293	-£793
R160+90	-£1,191	-£1,691	-£2,191	-£885	-£1,385	-£1,885	-£177	-£677	-£1,177

Scenario code interpretation example: R40+30 denotes site expected to degrade completely over 40 years, but restoration delays onset of this by 30 years.

Where NPV timeframe is less than the delay period, some values will repeat down scenario groups in a column.

Table B2a: Illustrative Net Present Value(£/ha) of peatland restoration under different climate-induced degradation assumptions and NPV timeframes
Value gain from restoration = +£94/ha; value loss of degradation = -£170/ha (following Christie et al., 2011; Harlow et al., 2012)

NPV timeframe	25 years			50 years			100 years		
Capital cost	£500/ha	£1000/ha	£1500/ha	£500/ha	£1000/ha	£1500/ha	£500/ha	£1000/ha	£1500/ha
On-going cost	£60/ha/yr	£60/ha/yr	£60/ha/yr	£60/ha/yr	£60/ha/yr	£60/ha/yr	£60/ha/yr	£60/ha/yr	£60/ha/yr
R40+30	£423	-£77	-£577	£1,431	£931	£431	£1,569	£1,069	£569
R70+30	£86	-£414	-£914	£732	£232	-£268	£1,094	£594	£94
R100+30	-£49	-£549	-£1,049	£429	-£71	-£571	£768	£268	-£232
R130+30	-£122	-£622	-£1,122	£266	-£234	-£734	£526	£26	-£474
R160+30	-£167	-£667	-£1,167	£164	-£336	-£836	£376	-£124	-£624
R40+60	£423	-£77	-£577	£1,891	£1,391	£891	£2,720	£2,220	£1,720
R70+60	£86	-£414	-£914	£1,073	£573	£73	£1,994	£1,494	£994
R100+60	-£49	-£549	-£1,049	£723	£223	-£277	£1,475	£975	£475
R130+60	-£122	-£622	-£1,122	£535	£35	-£465	£1,131	£631	£131
R160+60	-£167	-£667	-£1,167	£417	-£83	-£583	£915	£415	-£85

R40+90	£423	-£77	-£577	£1,891	£1,391	£891	£3,236	£2,736	£2,236
R70+90	£86	-£414	-£914	£1,073	£573	£73	£2,344	£1,844	£1,344
R100+90	-£49	-£549	-£1,049	£723	£223	-£277	£1,759	£1,259	£759
R130+90	-£122	-£622	-£1,122	£535	£35	-£465	£1,379	£879	£379
R160+90	-£167	-£667	-£1,167	£417	-£83	-£583	£1,141	£641	£141

Scenario code interpretation example: R40+30 denotes site expected to degrade completely over 40 years, but restoration delays onset of this by 30 years.

Where NPV timeframe is less than the delay period, some values will repeat down scenario groups in a column.

Table B2b: Illustrative Net Present Value(£/ha) of peatland restoration under different climate-induced degradation assumptions and NPV timeframes
Value gain from restoration = +£94/ha; value loss of degradation = -£170/ha (following Christie et al., 2011; Harlow et al., 2012)

NPV timeframe	25 years			50 years			100 years		
Capital cost	£500/ha	£1000/ha	£1500/ha	£500/ha	£1000/ha	£1500/ha	£500/ha	£1000/ha	£1500/ha
On-going cost	£160/ha/yr	£160/ha/yr	£160/ha/yr	£160/ha/yr	£160/ha/yr	£160/ha/yr	£160/ha/yr	£160/ha/yr	£160/ha/yr
R40+30	-£1,225	-£1,725	-£2,225	-£372	-£872	-£1,372	-£235	-£735	-£1,235
R70+30	-£1,563	-£2,063	-£2,563	-£1,071	-£1,571	-£2,071	-£709	-£1,209	-£1,709
R100+30	-£1,697	-£2,197	-£2,697	-£1,374	-£1,874	-£2,374	-£1,036	-£1,536	-£2,036
R130+30	-£1,770	-£2,270	-£2,770	-£1,537	-£2,037	-£2,537	-£1,277	-£1,777	-£2,277
R160+30	-£1,815	-£2,315	-£2,815	-£1,639	-£2,139	-£2,639	-£1,428	-£1,928	-£2,428
R40+60	-£1,225	-£1,725	-£2,225	-£567	-£1,067	-£1,567	£85	-£415	-£915
R70+60	-£1,563	-£2,063	-£2,563	-£1,384	-£1,884	-£2,384	-£642	-£1,142	-£1,642
R100+60	-£1,697	-£2,197	-£2,697	-£1,734	-£2,234	-£2,734	-£1,160	-£1,660	-£2,160
R130+60	-£1,770	-£2,270	-£2,770	-£1,923	-£2,423	-£2,923	-£1,505	-£2,005	-£2,505
R160+60	-£1,815	-£2,315	-£2,815	-£2,041	-£2,541	-£3,041	-£1,720	-£2,220	-£2,720

R40+90	-£1,225	-£1,725	-£2,225	-£567	-£1,067	-£1,567	£193	-£307	-£807
R70+90	-£1,563	-£2,063	-£2,563	-£1,384	-£1,884	-£2,384	-£699	-£1,199	-£1,699
R100+90	-£1,697	-£2,197	-£2,697	-£1,734	-£2,234	-£2,734	-£1,284	-£1,784	-£2,284
R130+90	-£1,770	-£2,270	-£2,770	-£1,923	-£2,423	-£2,923	-£1,665	-£2,165	-£2,665
R160+90	-£1,815	-£2,315	-£2,815	-£2,041	-£2,541	-£3,041	-£1,902	-£2,402	-£2,902

Scenario code interpretation example: R40+30 denotes site expected to degrade completely over 40 years, but restoration delays onset of this by 30 years.

Where NPV timeframe is less than the delay period, some values will repeat down scenario groups in a column.

Indeed the balance between the value of enhanced benefits delivered from restoration and on-going costs is key, with the avoidance of climate-induced degradation alone not being sufficient to justify restoration – enhanced ecosystem service values are required. This emphasies the need for further scientific research into degradation and the effectiveness of restoration at combating it plus socio-economic research into unit values and costs.

Although presenting a different approach to assessing the merits of peatland restoration, the results of the two simulation models are broadly similar in that they highlight sensitivity to key assumptions but identify a range of conditions under which restoration is merited.

Further research

The simulation results presented above are sufficient to illustrate how the social benefit of peatland restoration *might* vary under different assumptions. By presenting the assumptions clearly, their reliability and thus the robustness of the results can be subject to scrutiny and debate. Several points for consideration are immediately apparent and could be tested under different model configurations and/or revised in light of further scientific information or research.

First, in the absence of quantitative guidance on rates of degradation under climate change, a simple linear rate of decline is a reasonable initial approximation. However, alternative functional forms could be considered. For example, an exponential rate of decline might better fit an initially slow but accelerating pace of climate change. Further scientific research may offer other suggestions.

Second, similarly, representing the effect of restoration as delaying the onset of climate-change induced degradation for a fixed period may be a reasonable first approximation. However, a more nuanced effect may be more likely, with more gradual shifts between different degrees of degradation. Indeed, although results can be interpreted in the context of transitions between different levels of degradation, the model does not explicitly consider them. Again, further scientific research may inform such choices.

Third, the benefit valuation figures used were borrowed from other studies in which the scenarios considered were not identical to those considered here. In particular, the effects of climate change and the possibility of restored sites subsequently degrading[55] were not represented and thus transferred benefit values may be inaccurate. Whilst the effort required for bespoke valuation exercises is not trivial, more accurate figures could be

[55] This link to the second point above in that valuing the loss of a previously restored site may be different to that of a degraded site, but the valuation process needs to be informed by the nature of transition between different states.

obtained by specifying scenarios more appropriately in a future study. Equally (cf. Morris et al., 2010; Harlow et al., 2012), values could be transferred from other valuation studies such as Eftec (2009 & 10), Bateman et al. (2011) or GHK (2011).

Fourth, separately, the use of WTP valuations is one-step-removed from the biophysical realities of peatland restoration and may not accurately reflect changes to ecosystem services delivered. Although this could be corrected by providing more information (if available), an alternative would be to disaggregate the bundle of ecosystem services associated with peatlands and attempt to more precisely quantify the magnitude of service flow changes and then to value these changes with reference to damage costs. For example, Harlow et al. (2012) show how changes to GHG emissions can be valued by reference to published carbon prices and changes to DOC levels can be valued by reference to water treatment costs. However, scientific uncertainties over emission levels mean that this approach is not necessarily superior to the use of WTP valuations.

Finally, the indicative cost figures used here are averages and could be improved through more consistent reporting – especially for monitoring costs and opportunities foregone. In addition, explicit linking of costs to degree of degradation would be useful not only to improve the matching to different initial site conditions but also to perhaps reflect how restoration costs may increase over time as the resource base deteriorates.

Annex C - Guidance on the use of the coastal management cost-benefit xls tool

Tab 1 – Project spec 1

		Comments
1	Length of defences before project (km)	Refers to length of existing defences
2	Length of defences after project (km)	Is not necessarily equal to 1 minus 3, because in the case of MR natural topographic features may be part of a natural defence line
3	Length of realigned defences (km)	Only relevant to MR
4	Length of unsatisfactory defences (km) at time t (0,20,25) of replacement	Does not specify what is considered 'unsatisfactory' – but can relate to flood defence standards
5	NAI: Probability of breach at time t (over decade)	Either fill in 5 or 6. If you fill in 5, set 6 to 'no'. Probability of breach is NOT used in calculations, it is simply a tool to determine the expected time when defences breach. 5 and 5a can relate to flood protection standards. The impact of different assumptions on breach time can be tested in a sensitivity analysis.
5a	NAI: Threshold value for breach to be expected within decade	see above
5b	NAI: Decade when breach is expected based on 5a	-
6	NAI: Specify year breach is expected in NAI exactly? (yes/no)	Alternative to 5, see above
6a	NAI: Directly enter year breach is expected	Alternative to 5, see above
	NAI: Year of breach used in analysis	Gives time of breach from 5 OR 6 (depending on entry to 6)
7	MR: Amount of intertidal habitat lost due to project (ha)	Included as a possibility. Net of this and created habitat is then used in the analysis.
8	NAI: Amount of intertidal habitat lost due to project (ha) at time = as specified in 5 or 6	Included as a possibility. Net of this and created habitat is then used in the analysis.
9	MR: Amount of intertidal habitat created by project (ha)	Linked to habitat values follow guidance in Eftec (2010) - http://www.environment-agency.gov.uk/research/planning/116707.aspx, 'Flood and Coastal Erosion Risk Management: Economic Valuation of Environmental Effects'. Values do not include value of carbon storage. Values included are: ES provision of water quality improvement, recreation (non-consumptive), biodiversity, and (only for lower bound) aesthetic amenity. Values assume: i) avg. population density for England and Wales (345 per km2); ii) non-consumptive recreation at site; iii) non-consumptive amenity and aesthetics ES. Simple on/off adjustments to this can be made by entering values to 14-17. Values in 2012 prices using GDP deflators. Benefits are assumed to accrue immediately - typically there's a delay (see Spencer et al,

		2008, Estuarine, Coastal and Shelf Science 76, 608-619)
10	NAI: Amount of intertidal habitat created by project (ha) at t = as specified in 5 or 6	See 9 above.
10a	NAI: Additional amount of intertidal habitat created by project (ha) at t =25	See 9 above. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
10b	NAI: Additional amount of intertidal habitat created by project (ha) at t =50	See 9 above. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
10c	NAI: Additional amount of intertidal habitat created by project (ha) at t =75	See 9 above. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
10d	NAI: Habitat value reduction relative to MR (%)	This allows simple adjustments to account for potentially lower benefits associated with habitat creation in NAI relative to MR, based on a lack of active management of habitats
11	Area of substitute wetlands within ~50km radius (ha)	For detailed guidance see Eftec (2010). The value per ha of habitat is expected to decrease with an increasing availability of substitutes in the area – follows an application of the Brander et al (2008) benefit transfer function.
12	Population density (50km radius) > UK average (345 per km2), eg London (yes/no)	For detailed guidance see Eftec (2010). The value per ha of habitat is expected to increase if the site is located in a densely populated area – follows an application of the Brander et al (2008) benefit transfer function.
13	MR/NAI: Recreation access to site (site NOT accessible to informal recreation) (yes/no)	For detailed guidance see Eftec (2010). The value per ha of habitat is expected to decrease if there is limited access for informal recreation activities – follows an application of the Brander et al (2008) benefit transfer function.
14	Site (MR/NAI) is NOT judged to provide aesthetic amenity (yes/no)	For detailed guidance see Eftec (2010). The value per ha of habitat is expected to decrease if the site does not provide aesthetic amenity – follows an application of the Brander et al (2008) benefit transfer function.
15	MR: Amount of lost agricultural areas (ha), per grade	Average prices in England per grade. Source: http://archive.defra.gov.uk/evidence/statistics/foodfarm/farmgate/agrilandsales/index.htm 2004 prices adjusted to 2012 prices using GDP deflators. Following recent Defra guidance (http://archive.defra.gov.uk/environment/flooding/policy/guidance/project-appraisal.htm, suppl. Guidance 'treatment of agric. Land), £600 pounds are subtracted to account for subsidies. Assumes that there is no (agriculturally related) income (eg from salt marsh grazing or habitat 'payments') from MR or NAI. Price statistics are also available per region, but nut per grade and region.
16	NAI: Amount of lost agricultural areas (ha) at time= as specified in 5 or 6	See 15 above.
16a	NAI: Additional amount of lost agricultural areas (ha) at time=25	See 15 above. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years

		as assumed here.
16b	NAI: Additional amount of lost agricultural areas (ha) at time=50	See 15 above. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
16c	NAI: Additional amount of lost agricultural areas (ha) at time=75	See 15 above. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
17	MR: Number of residential properties affected by scheme by type	In 17 and 18, either fill in number of properties per type, or for the average dwelling (all dwellings), but not both. This is linked to average prices for dwelling type – it does not distinguish new and preoccupied properties. Source: https://www.gov.uk/government/statistical-data-sets/live-tables-on-housing-market-and-house-prices. House prices for 2010 – unadjusted.
18	NAI: Number of residential properties affected by scheme by type at year t = as specified in 5 or 6	as 17
18a	NAI: Number of additional residential properties affected by scheme by type at year t =25	as 17. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
18b	NAI: Number of additional residential properties affected by scheme by type at year t =50	as 17. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
18c	NAI: Number of additional residential properties affected by scheme by type at year t =75	as 17. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
19	MR: Housing land (Residential building land) lost (ha)	Linked to weighted valuations per hectare. Source: https://www.gov.uk/government/statistical-data-sets/live-tables-on-housing-market-and-house-prices. As of July 2010 – unadjusted.
20	NAI: Housing land (Residential building land) lost (ha) at year t = as specified in 5 or 6	as 19
20a	NAI: Additional housing land (Residential building land) lost (ha) at year t =25	as 19. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
20b	NAI: Additional housing land (Residential building land) lost (ha) at year t =50	as 19. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
20c	NAI: Additional housing land (Residential building land) lost (ha) at year t =75	as 19. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
21	MR: Amount of carbon stored (t CO2 eq/yr)	Net carbon gains based on Adams et al. (2012), Science of the Total Environment

		434,240-251, who report a study of GHG fluxes in the Blackwater estuary. Linked to carbon prices (non-traded) published by DECC (2011) - https://www.gov.uk/government/publications/guidance-on-estimating-carbon-values-beyond-2050-an-interim-approach. Adjusted to 2012 prices.
22	NAI: Amount of carbon stored (t CO2 eq/yr) from time t = as specified in 5 or 6	see 21 above
22a	NAI: Additional amount of carbon stored (t CO2 eq/yr) from time t =25	see 21 above. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
22b	NAI: Additional amount of carbon stored (t CO2 eq/yr) from time t =50	see 21 above. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
22c	NAI: Additional amount of carbon stored (t CO2 eq/yr) from time t =75	see 21 above. May be used to incorporate effects of sea level rise. Obviously the impact would spread over time, with varying impacts across years, and not occur in single years as assumed here.
23	Additional fish production impacts of MR/NAI (seabass nursery function of saltmarsh) (yes/no)	The values are derived from Luisetti et al. (2011), Ocean and Coastal Management 54, 212-224. Details of their estimation can be found therein. It should be noted that i) strictly speaking values apply to wild-caught bass only; ii) market prices are volatile and can therefore have changed since; iii) the fish production function used (Fonseca (2009) cited in Luisetti et al (2011)) may be site-specific and related to the habitat condition of saltmarsh.
23a	Proportion of saltmarsh relevant to fish production impacts (%)	see 23 above
24	Discount rate applied (%)	Following current guidance for long-term appraisals – see HM treasury Green Book.
25	Project region (leave blank/yes) - choose only one	This triggers regional differences in market prices for residential dwelling and residential building land.

Tab 2 – Project spec 2

		Comments
1	Capital costs	
	Cost of constructing new defences (MR) (£/km)	May be highly variable and site specific; also, economies of scale may play a role. DEFRA NADNAC guidance: linear structures (revetments, seawalls): £2.7m/km; beach management schemes: £5.1m/km; Groyne field costs: £0.6m/km
	Other capital costs associated with MR scheme in year	Sometimes listed in viability assessments related to Shoreline Management Plans (SMPs)

	0 (site prep and pre-implementation) (£)	
	Other capital costs associated with HTL scheme in year 0 (£)	E.g., urgent changes to increase standard of protection.
	Cost of defence replacement (£/km)	May increase over time as higher/improved defences are needed to meet standard of protection given sea level rise.
2	Maintenance cost reduction after realignment (%)	Lower costs relative to HTL because of less pressure, lower height etc; eg Luisetti et al (2011) use a 50% reduction
3	Maintenance costs (£/km/yr)	Maintenance costs are assumed to be the same every year for the lifetime of the defence - in reality less in early years, more later. Maintenance cost of NAI assumed to be zero.
	Non-realigned defences	May be highly variable. Defra NADNAC guidance is £10000 for linear structures and groynes, £20000 for beach management.
	Realigned defences	Uses factor specified in 2.
4	Other maintenance and operating costs	
	Other - £/yr eg MR habitat management	If applicable.
	Other - £/yr eg pumping costs - HTL	Does not include eg pumping-associated GHG emissions
	Other - £/yr eg pumping costs - MR	Does not include eg pumping-associated GHG emissions
5	Adjustment factors (sea level rise) for 1 and 3 at time t	Allowance is made for an increase in costs due to climate change. Structures need to become higher, deeper and more resilient to increased exposure. See Defra NADNAC and Penning Rowsell et al. 2005 (Multi-coloured Handbook).
6	Optimism bias (% of PV capital costs)	Optimism bias in accordance with most recent Defra guidelines should be applied to all costs (at 60%) to reflect uncertainty in broad level analysis e.g. at SMP scale. For small scale projects with reliable data or ex-post assessments, it can be reduced or set to zero. Note that only capital and maintenance costs associated with defences are made subject to optimism bias here, not other maintenance, eg related to pumping or habitat management.
7	Market value of agricultural land (£/ha) - 2004 prices	see tab 1 – 15. Hidden from view (Unhide to make visible)
8	Market value of agricultural land (£/ha) - 2012 prices	see tab 1 – 15. Hidden from view (Unhide to make visible)
9	Adjustment for agricultural subsidies paid (£/ha)	see tab 1 – 15. Hidden from view (Unhide to make visible)
10	Agricultural land values adjusted - 8 minus 9 (£/ha) 2012 prices	see tab 1 – 15. Hidden from view (Unhide to make visible)
11	MR: Market value of commercial property (£) affected by scheme	Calculate separately – they are too variable and situation specific. Indicative values for different types can be found here: http://www.voa.gov.uk/dvs/propertyMarketReport/pmrJan2011.html. Also consider to use rates as displayed in the Multi Coloured Manual (Penning Rowsell et al. 2005) - or updates of those; could be area specific linked to lookup table
12	NAI: Market value of commercial property (£) affected by scheme at time t =	see 11 above

Tab 3 – NPVs

Note that high, central and low estimates of PVB, PVC and NPV relate to high, central and low estimates for i) habitat benefits, ii) carbon benefits and iii) fishery benefits.

Hidden Tabs (Unhide to make visible):

PV cost calculation

PV benefits calculation

Benefits – input variables

Costs – input variables

Habitat value tables

Habitat value support table

C and Fish value tables

House prices and housing land

House price support table

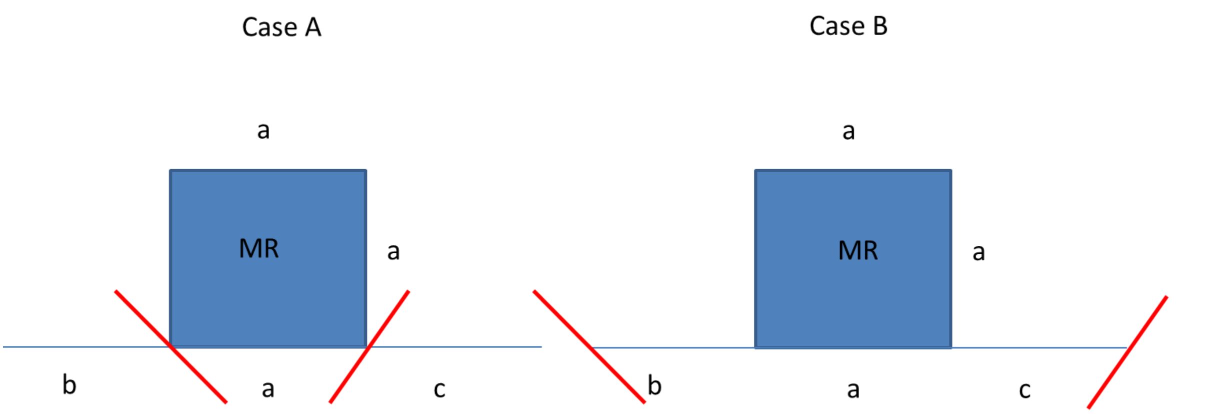
Other info, GDP deflators

Annex D – Issues and assumptions for using the cost-benefit tool in an abstract high-level analysis; suggested factors to be included in a sensitivity analysis

Project specification:

1. Length of defences before realignment [km]
2. Length of defences after realignment [km]

The length of realigned defences is assumed to be equal to 2., i.e. to be equal to the length of defences after realignment. **This is a rather strong assumption and only applies if project 1 treats each MR case as in Case A below**, i.e. measures changes only from the point in the coastline that is being realigned. If project 1 analyses across whole stretches of coastline (Case B) the assumption does not hold and results may thus be flawed. Both cases may, from an engineering perspective, not represent a realistic approach to identifying the length of realigned defences.



Length of existing defence = a

Length of defence after realignment = 3a

Length of realigned defences = 3a

Length of existing defence = a + b + c

Length of defence after realignment = 3a + b + c

Length of realigned defences = 3a

Also, natural topographic features can serve as natural defence after MR. This is an aspect that could be considered in the sensitivity analysis.

Further, given lack of robust information no replacement needs for unsatisfactory defences are identified for HTL. Consideration of replacement needs can have a great negative impact on NPV of HTL. This assumption therefore tends to favour HTL. A percentage of the considered coastline could be assigned to require replacement in a sensitivity analysis if **useful high-level data on replacement needs were available (e.g. % of artificial defences in UK anticipated to require replacement in next 5, 10, 20 years)**.

3. Area of agricultural land behind existing defences flooded as a consequence realignment by grade [ha]

This does not take into account changes in habitat/land area in front of defences, which are likely to be affected by coastal squeeze.

Benefits:

It is also assumed that 3. equals the habitat area created through MR schemes. A further assumption regarding the type of habitat created is that 50% of the newly created habitat area will be mudflats, the remainder saltmarshes.

The following assumptions will be made for the estimation of habitat benefits:

- The habitats develop immediately after implementation; typically, this will be a process spawning over several years, and habitat quality depends on previous land use and/or preparation of land in the course of MR implementation, which is assumed not take place
- The area of substitute wetlands (habitat areas) in a 50km radius of any of the MR sites considered is assumed to be greater than 100ha
- Population density within a 50km radius of any of the MR sites considered is assumed not to be significantly higher than UK average (345 km2)
- Recreational access to MR sites is available
- MR sites provide aesthetic amenity
- Potential fisheries impacts are considered for 25% of saltmarsh habitat created

Costs:

Cost of constructing new defences and maintenance costs will be taken from literature, as will cost of defence replacement in case this is being considered in sensitivity analysis.

The reduction in maintenance cost for realigned defences is assumed to be 50% of maintenance cost of HTL defences. It is not assumed that MR has a positive impact on maintenance cost of existing defences (eg by reducing pressure on such adjacent defences).

It is assumed that there are no other operating costs such as pumping costs, or costs of habitat management in case of MR.

Adjustment factors will be applied to capital and maintenance costs as recommended, i.e. a factor of 1.5 for years 20-49 and a factor of 2 for years 50-99.

Optimism bias in line with HR treasury recommendations is applied as 60% of the PV of costs.

Suggestions for sensitivity analysis:

	Factor	**Change**
1	% of HTL defences needing replacement at t=0 or t=20	Depends on availability of useful information on replacement needs
2	Cost of constructing new defences	+- 50%; +- 50%

3	Maintenance costs (HTL)	+-50%
4	Maintenance cost reduction (MR) relative to HTL	0%; 25%
5	Discount rate	+- 1% for each epoch
6	Optimism bias	0%; 30%

Possibly some combinations of 1,2,3 and 4 are reported.

Further, if for the base case NPV(MR) > NPV(HTL), then the required increase in value of agricultural land needed to set NPV(MR) = NPV(HTL) will be calculated in £, and related to the PV (market price) of an average residential property. The resulting number of average residential property can then be divided by the area flooded under MR to get an indication of a potential threshold value in terms of density of built property **for further consideration or analyses that are not part of this project**.

Annex E: Adaptation Strategies for Soil Measures – CBA Analysis for the scenarios incorporating Nelson et al (2010) optimistic and pessimistic price scenarios

The CBA for the optimistic price scenario for yield are shown in Tables E1.1-1.6 and the associated switching values are shown in Table E1.7. The corresponding tables for the pessimistic scenario are shown in Tables 1.8-1.13 and the switching values are shown in Tables E1.14.

Table E1.1 Benefit, costs and net present value for drainage for the pessimistic price scenario

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	0	0	0
W Wheat – required drainage	140	38	102
S Barley – free draining	0	0	0
S Barley – required drainage	11	6	6
Potatoes	73	3	69
Carrots	0	0	0

Table E1.2 Benefit, costs and net present value for compacted soils for the pessimistic price scenario

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	0	0	0
W Wheat – required drainage	2668	175	2493
S Barley – free draining	0	0	0
S Barley – required drainage	219	26	194
Potatoes	1365	16	1349
Carrots	0	0	0

Table E1.3 Benefit, costs and net present value for cover crop for the pessimistic price scenario

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	0	0	0
W Wheat – required drainage	0	0	0
S Barley – free draining	84	146	-62
S Barley – required drainage	120	210	-91
Potatoes	605	131	474
Carrots	210	12	198

Table E1.4 Benefit, costs and net present value for shallow ploughing for the pessimistic price scenario

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	252	0	252
W Wheat – required drainage	362	0	362
S Barley – free draining	24	0	24
S Barley – required drainage	34	0	34
Potatoes	172	0	172
Carrots	60	0	60

Table E1.5 Benefit, costs and net present value for spring cultivation for the pessimistic price scenario

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	0	0	0
W Wheat – required drainage	0	0	0
S Barley – free draining	69	0	69
S Barley – required drainage	83	0	83
Potatoes	512	0	512
Carrots	178	0	178

Table E1.6 Benefit, costs and net present value for contour ploughing for the pessimistic price scenario

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	81	0	81
W Wheat – required drainage	116	0	116
S Barley – free draining	8	0	8
S Barley – required drainage	11	0	11
Potatoes	55	0	55
Carrots	19	0	19

Table E1.7 Switching values for the reduction in yield resulting from the loss of soil fertility due to climate change for the pessimistic price scenario

Crop	Measure					
Crop	Drainage	Compacted Soil	Cover crop	Shallow ploughing	Spring Cultivation	Contour ploughing
W Wheat – free draining				3.37E-16		1.4E-16
W Wheat – required drainage	0.002781	-0.00035		3.35E-16		2.64E-17
S Barley – free draining				4.78E-16	0.000324	1.25E-16
S Barley – required drainage	0.007504	0.002086		4.79E-16	0.002518	1.25E-16
Potatoes	-0.002	-0.002	0.000948	0.000	0.000	0.000
Carrots			-0.00144	0.000	0.000	0.000

Table E1.8 Benefit, costs and net present value for drainage for the optimistic price scenario

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	0	0	0
W Wheat – required drainage	127	38	89
S Barley – free draining	0	0	0
S Barley – required drainage	10	6	5
Potatoes	67	3	63
Carrots	0	0	0

Table E1.9 Benefit, costs and net present value for compacted soils for the optimistic price scenario

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	0	0	0
W Wheat – required drainage	2427	175	2251
S Barley – free draining	0	0	0
S Barley – required drainage	197	26	171
Potatoes	1250	16	1234
Carrots	0	0	0

Table E1.10 Benefit, costs and net present value for cover crop for the optimistic price scenario

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	0	0	0
W Wheat – required drainage	0	0	0
S Barley – free draining	77	146	-69
S Barley – required drainage	109	210	-101
Potatoes	554	131	423
Carrots	192	12	180

Table E1.11 Benefit, costs and net present value for shallow ploughing for the optimistic price scenario

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	228	0	228
W Wheat – required drainage	327	0	327
S Barley – free draining	22	0	22
S Barley – required drainage	31	0	31
Potatoes	156	0	156
Carrots	54	0	54

Table E1.12 Benefit, costs and net present value for spring cultivation for the optimistic price scenario

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	0	0	0
W Wheat – required drainage	0	0	0
S Barley – free draining	63	0	63
S Barley – required drainage	74	0	74
Potatoes	467	0	467
Carrots	162	0	162

Table E1.13 Benefit, costs and net present value for contour ploughing for the optimistic price scenario

Crop	Crop benefit (£million)	Cost (£million)	NPV (£million)
W Wheat – free draining	74	0	74
W Wheat – required drainage	106	0	106
S Barley – free draining	7	0	7
S Barley – required drainage	10	0	10
Potatoes	50	0	50
Carrots	18	0	18

Table E1.14 Switching values for the reduction in yield resulting from the loss of soil fertility due to climate change for the optimistic price scenario

Crop	Measure					
Crop	Drainage	Compacted Soil	Cover crop	Shallow ploughing	Spring Cultivation	Contour ploughing
W Wheat – free draining				-7.5E-19		2.63E-16
W Wheat – required drainage	0.003285	-0.00021		-1.6E-18		2.63E-16
S Barley – free draining				8.19E-17	0.000359	2.59E-16
S Barley – required drainage	0.00863	0.002505		8.19E-17	0.002801	2.59E-16
Potatoes	-0.002	-0.002	0.001232	9.87E-17	0.000	0.000
Carrots			-0.00143	2.5E-17	0.000	0.000

Annex F: Responses to main high level comments from the peer reviewers

Reviewer	Comment	SRUC Response
General		
Paul Morling, ead of economics, Royal Society for the Protection of Birds (RSPB), UK.	Contextual information in each section quite long and could be trimmed.	This varies by chapter and is generally necessary to justify the choice of sector and the definition of adaptation measures. Due to the process, the explanation of this can vary. If we cut information then some of this may be unclear.
	Would be useful if the annexes could summarise methods for all sections.	The methods for all sections are basically variants of CBA which is outlined in section 1.5 and most of the sections do not warrant an annex, which is only used for more complex sections where numerous assumptions have been made for the purpose of providing comprehensive spreadsheets or ready reckoners.
Dr Iain Brown, Principal Investigator - Ecosystem Services & Biodiversity, The James Hutton Institute, Scotland.	Section 3 generally stronger and more concrete than Section 2 which has more hypothetical analysis.	The nature of the adaptation options differs between sections 2 and 3, with section 3 adaptations generally being much more specific with fewer uncertainties. Adaptations in section 2 had significant uncertainties on many levels - given this, the Section 2 numbers are designed to explore ranges of possibilities.
	Analysis against UKCP09 future projections not used in Section 2 but some good examples of forward projections in Section 3.	P10 & P90 now included in Section 2 for peatland. Again the nature of the adaptation in many of the section 2 examples meant that use of projections were not always appropriate.
	General - some conflation of use between ' impacts' and 'risk' in places (e.g. section 1.5) an it would be useful to standardise this, notably against the ASC framework.	Agree we need to be consistent – have amended text (in section 1.5) to use impact in terms of effect of climate change (following IPCC definitions) both in terms of potential impact and residual impact. Would argue that in

		some cases the two are not conflated, and where risk is used this indicates a probability of harmful impacts occurring.
	Would be useful to distinguish risk factors related to increased exposure from those associated with vulnerability/resilience (eg current condition).	We disagree about this distinction as vulnerability is a function of exposure, sensitivity and adaptive capacity, so it is very difficult to disentangle them. Furthermore, vulnerability and resilience are not only associated with the current condition. However, I understand the point about indicating which risk factors may increase due to increased exposure – this is indicated in figure 1.
	General - it is often implied (e.g. section 1.5) that climate change (and hence adaptation) is an issue for the future, whereas it is happening now and adaptation is also happening (planned and unplanned). Reference to current climate change (as in parts of section 3 such as 3.5) helps to ground the analysis and provides a reference point (baseline) for quantifying any adaptation deficit .	We agree adaptation is already occurring and this is indicated in various sections of the report. Section 1.5 states that "we currently tolerate a certain level of weather-related damage", which I think is sufficient to indicate that weather is already changing, without being drawn into whether it can be attributed to climate change or not. I have added a line in section 1.5 indicating that adaptation is already occurring.
	Section 1.3 The adaptations identified for each climate risk are presumably just a selection as others can also be highlighted (e.g. I noted several more for biodiversity). Why were these chosen? Availability of data?	The adaptations proposed initially were identified in response to the main climate risks identified in the CCRA. Those ultimately focused on were a result of discussion with the ASC as well as expert judgement from the team in terms of which are perhaps the most urgent or appropriate, as well as pragmatic reasons such as data availability.
	Section 1.5 Seems to imply that climate change and adaptation is not already happening. It is, and the baseline includes this and provides a reference point for measuring future climate change and any adaptation deficit.	See response to previous comment regarding this.
	Section 2 suggested to be distinguished from Section 3 by the former	Essentially this is an artificial distinction that comes back to

	being about land use changes whereas the latter is land management changes. This distinction is less apparent in the text and there are elements of both in each section.	the original specification/request - that we include land management changes, with particular emphasis on peat and coasts at the request of the ASC. The rationale for choosing these land use types is presented in the ASC's progress report; both land uses are sensitive to changes in climate, but also provide ecosystem services which will help the country to adapt to climate change.
	Section 4. Agree with last sentence: need for a broader suite of methodological approaches.	
	Iain makes several comments in the text relating to the adaptations initially proposed by us (tables 1 -3).	We recognise that these adaptations are not the only ones: they were the ones original suggested by the project team on the basis of the measures that were likely to be low-regret. The lists are not trying to be exhaustive.
Professor Tim Wheeler, Professor of Crop Science, University of Reading, UK.	The key question is whether the range of NPVs in Table 34 provides sufficient information for decision-makers? Some do, but others such as those for soil management (NPV from -121.97 to 1744.1) do not and require either a more generic conclusion or further interpretation. I always favour a degree of openness in the interpretation of climate adaptation – If the range of responses is so wide that there is effectively no useful information using the best analytically techniques available, then say so.	This information now has further qualification in terms of how robust the information is. As well as being of use to the customer (i.e. ASC) now the information is another step in terms of understanding how well we can appraise adaptations in this context.
	I recommend a complete rewrite of the Executive Summary so that it clearly states the headline results, draws these into conclusions, before touching on some of the major assumptions and drawbacks of the methods used. It seems essential to have clear statements on what adaptation measures meet the low-regret criteria on the current analysis, which ones don't, and those ones which the researchers can make no judgement one way or the another, and why.	We have redrafted parts of the ES. Although note that the process of identifying and agreeing low-regrets measures is more nuanced than the review appreciates; i.e. some things (e.g. the choice of peatlands) were decided for us