Natural England Access to Evidence Information Note EIN005

Summary of evidence: Climate change

1. General introduction

This summary sets out Natural England's assessment of the evidence relating to climate change. It provides a statement of the current evidence base, presenting:

- what we know (with supporting data and key references);
- areas that are subject to active research and debate; and
- what we do not yet know from the evidence base.

It also provides information on Natural England research and key external research programmes to show how we are seeking to fill gaps.

This summary forms part of a suite of summaries covering all of Natural England's remit. The summaries are not systematic reviews, but enable us to identify areas where the evidence is absent, or complex, conflicting and/or contested. These summaries are for both internal and external use and will be regularly updated as new evidence emerges and more detailed reviews are completed.

2. Introduction to climate change

Natural England's work on climate change is shaped by its wider remit for the protection and improvement of the natural environment. Climate change is a major threat to the natural environment, its biodiversity and the services it provides, and *adaptation* is essential to reduce risks, as well as take advantage of any opportunities that arise. Appropriate management of the natural environment can also reduce the risks to people from climate change, for example from flooding or heat stress. The natural environment also plays a role in *mitigating* climate change – reducing the concentration of greenhouse gases in the atmosphere; this is partly dealt with here but is also covered in other summaries, particularly that on soil. As well as covering Natural England's areas of responsibility for adapting to climate change, we also summarise relevant background information on climate science, drawing on authoritative, independent sources.

3. Summary of evidence

We know that:

Climate science

3.1 Climate change is occurring. Warming of the climate system is unequivocal and, since the 1950s, many of the observed changes are unprecedented since the last ice age or before (Intergovernmental Panel on Climate Change (IPCC) 2013). Good instrumental records of temperature go back to the nineteenth century. Over the period 1880 to 2012, global

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temperature increased by 0.85°C. Each decade since the 1970s has been warmer than the one immediately preceding it and they are all warmer than other decades in the record (Royal Society 2010). In the Northern Hemisphere, 1983–2012 was likely the warmest 30-year period of the last 1400 years (IPCC. 2013). The Central England Temperature record has shown an increase of c1°C since the 1970s (Jenkins *et al.* 2008). In England, over the last 50 years there has been no change in overall precipitation, but there has been a shift in the seasonal pattern of rainfall, with an increase in winter rainfall, largely offset by a decline in summer rainfall (Lowe *et al.* 2009).

3.2 Global CO_2 concentrations have increased since the mid 19th century from approximately 280 ppm to around 391 ppm by 2011. CO_2 in air bubbles trapped in ice taken from Antarctica and Greenland, which has built up over long periods of time, shows that present-day concentrations are the highest they have been in an 800,000 year record. Various lines of evidence (including carbon isotopic ratios) point strongly to human activity being the major reason for the recent increase, mainly due to the burning of fossil fuels (coal, oil, gas) with smaller contributions from land-use changes and cement manufacture (Royal Society 2010; IPCC 2013). Concentrations of a range of other greenhouse gases have also increased, including methane which has more than doubled in the past 150 years, also unprecedented in the past 800,000 years (Royal Society 2010).

3.3 The rise in greenhouse gases has had a warming effect (positive climate forcing) over the last century. This has been partially offset by other anthropogenic influences such as an increase in particulate matter in the atmosphere. The expected net effect would have been a warming of approximately 0.4°C since the mid 19th century in the absence of any other processes or interactions in the climate system; however, other processes, such as changes in water vapour concentration are believed to have amplified this (Royal Society 2010) – hence the actual increase of 0.8°C.

3.4 Models indicate that the global climate will continue to warm over the course of this century. How much the global climate warms depends on the sensitivity of the climate system and emissions of greenhouse gases. The lowest emissions pathway considered in the most recent IPCC assessment (IPCC, 2013) leads to projections of warming in the range 0.3-1.7 °C compared to average for 1986-2005 by 2081-2100; the highest (which is closest to current trends in emissions) gives a projected warming of 2.6-4.8°C over the same period. The UK Climate Projections (UKCP09) (Lowe *et al.* 2009) project warming in this approximate range for the UK.

3.5 Other climate changes should be expected. In addition to changes in temperature, a number of other changes are projected by models; in particular a continuing trend towards wetter winters and drier summers has consistently been seen in outputs from Hadley Centre models for the UK (Murphy *et al.* 2009). An increase in the amount of winter rainfall falling in fewer, heavier events has also been observed (Watts *et al.* 2013).

3.6 There is uncertainty in the magnitude and nature of projected climate change. The UK Climate Projections indicate a range of possible outcomes, depending on emissions and different aspects of climate sensitivity. For the UK there is greater uncertainty around changes to precipitation than for temperature (Met Office 2011). We must therefore expect the climate to change and plan accordingly, but ensure that our planning is robust to a range of realistic scenarios, bearing in mind that uncertainty cuts both ways – changes could be more or less than we expect.

3.7 Sea level has risen over the last century and the rate of increase is speeding up. Global average sea level has risen by 0.19±0.2 m since the beginning of the 20^{th} century (IPCC 2013). The rate of increase was 1.7±0.2 mm yr^{-1} between 1901 and 2010, 2.0±0.2 mm yr^{-1} between 1971 and 2010 and 3.2±0.4 mm yr^{-1} between 1993 and 2010. Thermal expansion is thought to have contributed approximately half of the sea level rise, and melting of land-based ice much of the remainder (IPCC 2007). Sea level rise around the UK has been similar to global levels (Horsburgh & Lowe 2010), although isostatic movement of the land tends to exaggerate the changes in the south and decrease them in the north. Thermal expansion will continue to cause rising sea levels, but the additional contribution of melting ice caps is subject to various uncertainties. The UKCP09 scenarios projected 12-76 cm rise compared to 1990 (excluding land movements) by 2095 for the UK. Sea level rise will continue beyond 2100, with sea level rise due to thermal expansion expected to continue for many centuries (IPCC 2013).

3.8 The seas around the UK are warming. The shelf seas around the UK are projected to be 1.5 to 4ºC warmer and ~0.2 practical salinity units (p.s.u.) fresher (lower salinity) by the end of the 21st century (IPCC 2007).

3.9 Increasing atmospheric CO_2 causes acidification of the oceans. This effect is independent of its effects on the atmosphere and occurs when CO_2 dissolves in water. Ocean acidity has increased by 30% since the beginning of the Industrial Revolution, the fastest rate in the last 55 million years (Ocean Acidification Reference User Group 2009).

3.10 The Gulf Stream (Atlantic Meridional Overturning Circulation) is likely to weaken over the 21^{st} century, although it is very unlikely that it will undergo an abrupt transition or collapse in the 21^{st} century (IPCC 2013).

3.11 An altered climate will remain for centuries after net emissions cease. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO_2 emissions. Due to the long timescales of heat transfer from the ocean surface to depth, ocean warming will continue for centuries. Depending on the scenario, 15-40% of emitted CO_2 will remain in the atmosphere longer than 1,000 years (IPCC 2013).

Natural environment

3.12 Climate has a profound effect on the natural environment. Global distributions of biomes, patterns of biodiversity and individual species ranges have long been known to be strongly correlated with climate. Soil formation and characteristics are also subject to climatic influence. Significant changes are occurring worldwide in biotic systems that are generally consistent with the projected impacts of climate warming (Rosenzweig *et al.* 2008; Morecroft & Speakman 2013; Settele *et al.* 2014).

3.13 Distributions of many species are moving in ways consistent with climate warming. The UK is one of the best recorded sites in the world for species distribution, and clear shifts in the northern limits of some mobile animal groups have been identified (Hickling *et al.* 2006; Chen *et al.* 2011), as well as redistributions to higher altitudes (eg Hill *et al.* 2002). The distributions of internationally important wintering shorebird populations in the UK have shifted east and north as winter climate has warmed (Austin & Rehfisch 2005; Pearce-Higgins *et al.* 2011). The evidence for plants and animals with limited mobility is less clear, although experimental evidence is beginning to show that some species may be limited from colonising suitable areas north of their current range due to poor dispersal (eg Marsico & Hellman 2009, Willis *et al.* 2009).

3.14 Spring phenology (seasonal timing of biological events) has advanced consistent with an effect of increasing temperature. A very large number of papers have now shown this for a wide range of species in the UK and internationally (Thackeray *et al.* 2010; Sparks 2013). There is also remote sensing evidence of an advance in the greening of the surface of the earth in spring (Myneni *et al.* 1997).

3.15 Phenological changes are occurring at different rates for different trophic levels leading to temporal mismatching within food chains. A major survey of trends for 762 taxa in the UK shows that secondary consumers are responding slower than plants and animals lower within food chains, leading to the potential for mismatching (Thackeray *et al.* 2010). There is strong evidence for mismatching between migrant birds and their breeding food supplies, with associated population declines (Both *et al.* 2006).

3.16 Climate change represents a serious threat to biodiversity and ecosystem services. The strong influence of climate on ecosystem properties and biodiversity indicates their vulnerability to climate change in general terms (Chapin *et al.* 2000). The National Ecosystem Assessment found that climate change was one of the most serious future threats to ecosystem services (UK NEA 2011). Morecroft & Speakman (2013) reviewed climate change effects for the UK and concluded that 'there is strong evidence that climate change is already affecting UK biodiversity. Impacts are expected to increase as the magnitude of climate change increases'.

3.17 A range of strategies can be adopted to adapt to climate change and reduce the risks to biodiversity and ecosystems. These range from building resilience to accepting change as inevitable (Morecroft *et al.* 2012). The Climate Change Adaptation Manual (Natural England & RSPB 2014) presents evidence to inform adaptation by conservation managers.

3.18 Risks to geodiversity features are not uniform. Some features are likely to be resilient to climate change, whilst others are more vulnerable. Sites located on the coast, adjacent to rivers or on active slopes, and the associated geomorphological processes, are most likely to experience the greatest changes, particularly from sea level rise, increased erosion or flooding. The human responses to these changes, in the form of 'hard' coastal protection or river and slope engineering are, however, likely to have the greatest impact on geodiversity (Prosser *et al.* 2010).

3.19 Risks to landscape character may result from changes in ecological impacts and changes in human behaviour. These effects are likely to be specific to particular places (eg Wilson *et al*. 2013). For example beech trees, which are a distinctive feature of landscapes such as the South Downs, are vulnerable to drought (Taylor *et al.* 2013). Renewable energy infrastructure, particularly wind farms, is influencing the character of some areas and the current drive for more tree planting as a response to climate change may alter the character of other more open landscapes.

3.20 The features of protected sites (Special Areas of Conservation (SACs), Special Protection Areas (SPAs) Sites of Special Scientific Interest (SSSIs)), including species, will change but most sites will remain valuable for conservation (Johnstone *et al.* 2013). There is evidence that existing protected sites may be colonised preferentially by species spreading northwards, compared to the surrounding landscape (Thomas *et al.* 2012).

3.21 There is a consensus that bigger, better, more and joined up wildlife sites form a more resilient ecological network (Lawton *et al.* 2010). The best way to achieve such a resilient network remains an active area of research (see below).

3.22 There are geographical differences in the vulnerability of the environment to climate change. We are able to identify those places where vulnerability is highest on the basis of habitat type and condition, topography, and spatial configuration of semi-natural habitats within the landscape (Taylor *et al.*, 2014.)

3.23 Extreme events, including drought, wildfires and floods can have a disproportionate effect on the natural environment. Although these events are difficult to model, some of the impacts of historical droughts have been quantified (Morecroft & Speakman 2013) showing that species vary in their response, with some much more sensitive than others.

3.24 Some areas, termed refugia, allow species to persist longer under a changing climate (Suggitt *et al.* 2014). The factors that promote this include varied topography, slower local rates of temperature increase (eg at the coast), and large areas of semi-natural habitats.

3.25 Some habitats store significant amounts of carbon and this can be increased by appropriate land use and management (Alonso *et al*. 2012). The amounts differ considerably between habitats. Peatlands and woodlands are particularly important carbon stores. Grassland stores less carbon per unit area than these but is important because of the large area. Marine habitats are less well understood than terrestrial ones but the evidence suggests that estuaries are important areas for carbon storage and sequestration.

3.26 Peatlands are an significant net source of greenhouse gases in England. Much of the carbon stored in peatlands is vulnerable to loss due to desiccation and erosion as a result of degradation through cultivation, drainage, burning, overgrazing and air pollution (Natural England 2010).

3.27 The Land Use, Land Use Change and Forestry (LULUCF) sector changed from being a net source to a net sink for greenhouse gases in the UK over the course of the 1990s, as shown in the national inventory of greenhouse gas emissions (DECC 2014). This reflects an increasing uptake of carbon dioxide by trees as they reach maturity, following significant tree planting over the course of the last century and a shift to less intensive agricultural practices, for example conversion of arable land to permanent pasture. In 2012 the net uptake was 7 $MtCO_2e$ (million tonnes carbon dioxide equivalent). This compares with total net emissions for the UK across all sectors of 581.17 $MtCO_2e$. Agriculture is treated separately and its total net emissions were 56.6 $MtCO_2e$, mostly the result of nitrous oxide and methane emissions.

Areas that are subject to active research and debate:

Climate science

3.28 How greenhouse gas emissions will change in future. The international community has agreed in principle to limit emissions so that global mean temperature rise remains less than 2°C, but the most recent IPCC report (IPCC 2013) indicates that to have a greater than 66% chance of limiting global temperature rise to 2°C it would be necessary to limit total cumulative emissions of carbon dioxide to 800 gigatonnes of Carbon, of which 531 gigatonnes had already been emitted by 2011 through human activities over history, and the rate of emissions continues to rise.

3.29 Global carbon cycle feedbacks. Over half of the CO_2 emitted by human activities has probably been absorbed by the oceans and ecosystems (IPCC 2013). How long this will continue, and how it will be affected by climate change and other influences, is an active area of research. Earth system models indicate that over the 21st century net carbon cycle feedbacks are likely to become positive, tending to increase the amount of CO_2 in the atmosphere and exacerbate warming; positive feedbacks have been identified during earlier natural warming phases (IPCC 2013). Mechanisms include increases in wildfire, degradation or loss of tropical forests and thawing of permafrost in tundra.

3.30 The magnitude of other factors affecting climate forcing and sensitivity. Other factors, in addition to greenhouse gas concentrations, also influence global temperature trends. These include variations in solar radiation, particulate matter, aerosols and water vapour in the atmosphere. For any given change in greenhouse gas concentrations there is a degree of uncertainty about the extent of warming that will result. Modelling attempts to take account of these uncertainties together with uncertainties in the emissions of greenhouse gases. Understanding is, however, improving and it is ‘extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century’ (IPCC 2013).

Natural environment

3.31 Defining and quantifying the risk to the natural environment is an ongoing challenge. One well quoted example is that of Thomas *et al.* (2004) who estimated from a sample of regions and taxa that 15-37% of species were likely to be ‘committed to extinction’ assuming mid-range climate change scenarios (these extinction estimates were substantially different under other emissions scenarios). These estimates have been challenged as underestimating uncertainty (eg Thuiller *et al.* 2004).

3.32 Future change in species distributions within the UK. All species have a range of climatic conditions within which they can survive, and a narrower range within which they thrive. As the climate warms, species’ optimal conditional conditions (their ‘climate space’) will tend to shift northwards and to higher altitudes in the UK. This shift in distributions has been quantified for climate change scenarios by programmes such as MONARCH (Berry *et al.* 2007). The most recent analysis, commissioned by Natural England (Pearce Higgins *et al.* in press) indicates that the area of suitable climatic conditions is likely to increase for more species than for those in which it decreases. However this needs to be interpreted in terms of the availability of suitable habitat, capacity for dispersal and interactions with other factors many of which are likely to exacerbate the impact of changes in climate space, and different species will respond differently (Morecroft & Speakman 2013).

3.33 Tipping points in the interactions between climate and ecosystem responses. Tipping points are critical thresholds after which a system undergoes a major qualitative change. These often reflect the potentially non-linear responses of ecosystems to gradual climate change, and include major changes to the Atlantic Meridional Overturning Circulation (see above) that would result in a major sudden cooling of the UK; loss of Arctic summer sea ice leading to amplified warming in the UK and linking of Pacific and Atlantic basins; melting of the northern tundra permafrost with release of greenhouse gases and amplified warming (Lenton *et al.* 2008). The identification of the proximity of tipping points is an important area of research and some recent advances have been made with regard to animal population declines (eg Drake & Griffin 2010). Tipping points may also be crossed as a result of an extreme climatic event or series of events that push an ecosystem into an alternative stable state (Anderson *et al.* 2008) – an example of such an ecological “regime shift” would be a storm surge and coastal flooding event that transformed a coastal reedbed habitat into a saltwater marsh.

3.34 The scope for increasing the resilience of species and communities within their existing range. It has been suggested that increased area and heterogeneity of habitat patches increase the chances of population survival as climatic suitability decreases. Larger populations in better managed sites are likely to be more resilient to extreme events such as droughts. Larger sites are less vulnerable to edge effects such as desiccation during droughts. Microclimate can vary substantially between northern and southern slopes and with height of vegetation. There is increasing evidence to support the case that these variations have ecologically significant effects (eg Oliver *et al.* 2013).

3.35 The factors that promote functional connectivity and species dispersal across landscapes. The highly fragmented nature of English habitats is widely recognised as a constraint on dispersal for many species and hence on their ability to colonise new sites. However the best methods to ameliorate this are an area of uncertainty. Possibilities include: increasing existing site size and quality to boost source populations; providing ‘stepping stones’ or ‘corridors’ of semi-natural habitat across the landscape; and improving the quality of the wider agricultural matrix for dispersing species (its “permeability”) (Lawton *et al.* 2010). There is little quantitative data to test their relative merits (eg Davies & Pullin 2006) and still considerable controversy over the rationale for some of these measures (eg Gilbert-Norton *et al.* 2010 vs. Boitani *et al.* 2007). There are risks associated with increasing connectivity, particularly that it may increase the spread of invasive species (Knight *et al.* 2014).

3.36 Effects of climate change on complex interactions between species. In addition to the differing rates of change in phenology leading to mismatched timings within food chains (see above), species have a wide range of interactions with competitors, parasites, diseases and predators that could be altered as a result of climate change and its effect on habitats (Morecroft & Speakman 2013; Evans & Pearce Higgins 2013; Harrington *et al.* 1999). As some species’ distributions change more radically than others, novel combinations of species will occur with unknown consequences for interactions (Walther 2010). Furthermore, there are likely to be local climates that have no analogy with any currently existing ones, potentially leading to the formation of novel ecological communities (Hobbs *et al.* 2009; Keith *et al.* 2009). Plant-soil interactions may also change, with consequences for nutrient relations (Varallyay 2010).

3.37 Non-native species. Most non-native species in Britain are not a threat (Hill *et al.* 2005) and with climate change we may well want to accept and protect many species whose potential range is expanding into the UK, whilst retracting in other, more southerly areas. At the same time, however, some non-native species may prove a threat as a result of their invasive nature or because they are pests and diseases. The identification of species that might pose a future risk as a result of climate change or as a result of encouraging habitat connectivity as an adaptation measure is an area of active research (eg Mueller & Hellman 2008, Broennimann & Guisan 2008).

3.38 Ocean acidification is already affecting some species detrimentally. Species of marine plants and animals with calcium carbonate skeletons or shells are sensitive to some degree to acidification, as the calcium carbonate begins to dissolve or is harder to sequester from the sea (Wootton *et al.* 2008; Ocean Acidification Reference User Group 2009). Squid haemoglobin is sensitive to the relative pH of sea water and blood, and there is the possibility that it will become less effective as an oxygen carrier as acidification rises (Pörtner *et al.* 2004), with serious economic and ecological impacts. Other unexpected impacts of acidification include the increase in sound transmission through water, with implications for marine mammals, and detrimental impacts on the olfactory sense of fish (Ocean Acidification Reference User Group 2009).

3.39 How ecosystems can best provide adaptation benefits for human society. We have a number of good exemplars of 'ecosystem based adaptation', including flood defence from coastal and flood plain wetlands, cooling from urban trees, and sustainable urban drainage systems (Natural England 2009). The evidence base is increasing (eg Doswald & Osti 2011) but there is an urgent need for further studies.

3.40 The economic benefits of using ecosystem approaches for societal adaptation to climate change. The economic benefits of "natural solutions" to climate change adaptation are beginning to be understood (Natural England 2009), but there is an urgent need for more studies that assess the full range of costs and benefits, including non-monetisable costs, such as has been undertaken with the coastal realignment at Alkborough Flats (Everard 2009).

3.41 Understanding how farmers, site managers and conservation partnerships are responding to climate change. We have advanced our understanding through surveys of site managers (Macgregor & van Dijk 2014) and through working with Nature Improvement Areas (NIA) partnerships (van Dijk *et al.* 2013). Climate change is slowly being incorporated into conservation planning, but not uniformly, with some areas and people taking more initiative.

3.42 The impacts of renewable energy on biodiversity. One of the best studied examples is the effect of wind turbines on birds (Pearce Higgins *et al.* 2013) but it is still an active area of debate.

What we don't know:

3.43 What the actual specific impacts of climate change will be in future. We have a good evidence base of the sort of changes we can expect in future, but unanticipated changes are likely as a result of, for example, extreme events, complex interactions between species and interactions with other variables. Ongoing monitoring and research to establish cause and effect are essential to address this.

3.44 The effectiveness of adaptation measures in practice. We can to some extent infer this from looking at historical trends, but this is no substitute for effective evaluation of different interventions in reducing impact, or taking advantage of opportunities resulting from climate change. This is particularly important for prioritisation and assessment of costs and benefits of different approaches.

3.45 Patterns of carbon storage and sequestration by ecosystems at a detailed level. Much assessment of carbon storage by semi-natural habitats has relied on inference from a relatively small number of primary datasets; measurements of sequestration are restricted to very few sites indeed.

3.46 How climate change will affect the character of the landscape. We have a broad awareness of some of the potential ways in which climate change might interact with individual components of the landscape, but our understanding of the likelihood, likely scale, geographical distribution and significance of landscape change is limited. For effective landscape planning we need to know what landscape changes are most likely, where these changes are likely to occur, which landscapes and parts of the country could experience the greatest change, and what these changes might mean for landscape character.

3.47 Why there is stronger evidence of species advancing at their leading range edge than retreating at their trailing edge. Greater monitoring of the population dynamics processes that have been predicted to eventually lead to range shift at the trailing edge would be desirable, to put this pattern in context.

3.48 How the direct effects of rising carbon dioxide concentration interact with climate variables. Carbon dioxide has a direct effect on plants and can, for example, increase growth rates and/or water use efficiency. It is however rarely studied in intact natural systems because of the technical difficulties of locally elevating carbon dioxide concentrations.

3.49 Better understanding of the effects of climate change on migration including resource requirements of migratory species throughout their life cycle especially on stop-over/fuelling sites and whether these are vulnerable to climate change. Of particular interest are those bird species migrating from Africa - it is thought that significant mortality occurs during migration but the extent and timings have not been demonstrated.

3.50 The dispersal ability of many individual species and the extent to which they may be able to track suitable climatic conditions. The effects of landscape configuration including the impact of fragmented habitats on dispersal and gene flow across landscapes requires further research. Further evidence is required on the relative importance of different climatic variables and extreme events (drought, heat wave, flooding) in driving observed abundance and range shifts.

3.51 What attributes of ecological network design are most effective in increasing the resilience of species, habitats and other environmental characteristics. We are making progress, but we still need to know a lot more about the relative merits of different approaches: bigger, better, more or joined up sites, together with landscape heterogeneity and the presence of different sorts of refugia.

3.52 How we can identify spatial priorities for climate change adaptation. We need to bring together our vulnerability and adaptation studies to identify areas which are the highest priority for interventions.

3.53 How to manage ecosystems best to provide adaptation benefits for people. This requires a better understanding of ecosystem function and the practical ways to deliver ecosystem based adaptation.

3.54 Understanding the effects of climate change on ecosystem function. It is necessary to understand something of the complex processes and interactions at the ecosystem level in order to predict impacts on individual species. A particular issue is the interactions between freshwater, wetland and terrestrial habitats in a catchment.

3.55 The area requirements and habitat preferences of many species that might colonise the UK are unknown in their current ranges. Filling this knowledge gap will help inform future habitat creation in the UK.

3.56 The impact of climate change on soil formation and nutrient cycling and associated ecosystem services, including changes in soils and soil biota.

3.57 The relative importance of changes in rainfall and soil water, including increases in heavy rain events and interactions between summer and winter rainfall to non-wetland habitats.

3.58 How bryophytes and lichens respond to changes in micro habitat conditions and their wider interactions with macro climatic gradients.

3.59 There is insufficient information and understanding of the productivity, nutrient cycle and other ecosystem processes and services in habitats, particularly coastal, and therefore their response to climate change is poorly understood.

3.60 What happens to the carbon in peatlands when eroded. How much is lost to the atmosphere, deposited in stream/river beds, etc?

3.61 What are the key barriers to climate change adaptation and mitigation and how can they be overcome?

3.62 How to enhance the adaptive capacity of species, habitats, ecosystems and ecosystem services to both gradual climate change and episodic but increasingly frequent extreme events. Gradual climate change is likely to be accompanied by an increase in the frequency of extreme events, such as droughts, wildfires and floods, although this has a high degree of uncertainty (Murphy *et al.* 2009). The responses of biodiversity and ecosystem services to these different aspects of climate change are likely to differ, requiring different conservation responses.

3.63 How to address the possibility of tipping points and more extreme (4°+) warming, around which there is greater uncertainty. To date most work on climate change adaptation has concentrated on low risk, 'no regrets' type approaches such as increasing landscape heterogeneity and connectivity. As climate change increases over the course of this century these approaches are likely to be less useful, and more radical measures may need to be adopted.

3.64 Indirect effects of climate change through markets and human behaviour. People will respond to the impacts of climate change in a wide variety of ways, some of which will be sympathetic to the natural environment and others potentially detrimental. For example, farmers will begin to grow crops that are more suited to new climates and in response to national and international market forces that will be influenced by climate change (Macgregor & Cowan 2010). Society is likely to change its priorities as the resource pinch points on energy, food, and water in the context of human population growth and climate change all coincide in *c.* 2030 (Beddington's "Perfect Storm", Beddington 2010). Furthermore, there will be social responses based on people's perceptions of environmental change (Upham *et al.* 2009). This whole area is a major source of uncertainty and in need of an evidence base.

3.65 Interactions between different aspects of environmental change. Climate change will interact with all the other pressures on ecosystems, including land use change, air pollution and invasive species. These complex interactions are very poorly understood but have the potential to reduce the capacity for the natural environment to adapt autonomously or to influence human adaptation interventions.

3.66 A better understanding of what climate change means for our designations. We need a better understanding of sites as dynamic systems of which climate change will be one of a number of impacts that need proactive management change.

4. Current Natural England evidence projects

4.1 Long-term integrated monitoring project, LTIMP (RP0316). Environmental monitoring is essential if we are to track the impacts of climate change on species and habitats; to provide early warning of detrimental changes and to monitor the effectiveness of adaptation and mitigation action. This project aims to integrate monitoring activities within Natural England on climate change impacts, adaptation and mitigation and includes the Environmental Change Biodiversity Network (ECBN). Outputs will include a report on methodologies and sampling strategies, as well establishing new monitoring work at key sites.

4.2 Impacts of storms and flooding: Long- term lessons from the winter of 13/14 extreme events (RP2047). Projections of future climate indicate an increase in winter rainfall and incidence of extreme events. Extreme events can have disproportionate impacts on geodiversity, ecosystems and biodiversity. However, occasional severe storms and long duration floods are part of the normal range of variation. This project aims to learn lessons from the winter of 2013-14 for climate change adaptation, taking account of other long-term trends eg rising sea level. It will identify the impacts of storm surge and flooding (fluvial, coastal and ground water) and test which site and species have been most affected.

4.3 UK Climate Change Impact Report Card for Biodiversity. An overview of climate change impacts and detailed reviews of topics produced in collaboration with the wider scientific community as part of the Living with Environmental Change (LWEC) partnership.

4.4 Evidence Project Database. A list of current climate change (and other) research and monitoring projects is available on Natural England's internal systems. We are currently working on making this available to everyone. In the meantime a list of Natural England's evidence projects that were current in 2014 can be seen on the National Archives at: **http://webarchive.nationalarchives.gov.uk/20140711133551/http://www.naturalengland.org.uk/ourwork/evidence/register/default.aspx**

5. Key external research programmes

5.1 Living With Environmental Change (LWEC). This is a ten-year programme which connects natural, engineering, economic, social, medical, cultural, arts and humanities researchers with policy-makers, business, the public, and other key stakeholders. Funded jointly by 22 partners it aims to encourage the co-design, co-production and co-delivery of policy- or delivery-relevant research on environmental change. The current budget for LWEC projects is £600 million across its 6 main "challenges" of climate change, ecosystems, sustainable food and water; health, infrastructure and social science. (Natural England is a full partner.) More details: **www.lwec.org.uk**.

5.2 UK Environmental Change Network (ECN). A long-term monitoring programme measuring a wide range of biological and physical variables (including detailed climate recording) at intensively studied sites. Part of the International Long Term Ecological Research (ILTER) Network. (Natural England is on the Steering Group). Further information from: **www.ecn.ac.uk**.

5.3 UK Climate Change Risk Assessment (CCRA). The CCRA is a requirement under the Climate Change Act 2008 and it provides an assessment of the risks and opportunities posed by climate change to all sectors of the national economy, compares those risks with other pressures on the Government and prioritises adaptation policy. The first CCRA was published in 2012 and work is underway for the second one.

5.4 The Biodiversity and Ecosystem Service Sustainability Programme (BESS) aims to understand the functional role of biodiversity in UK ecosystems across a range of ecosystem goods and services, environmental gradients and scales typical of real landscapes; to identify critical levels of biodiversity required to deliver a range of ecosystem services that meet societal needs, and the land and resource use associated with these biodiversity levels; and to develop impact assessment tools to explore the implications of land and resource use change on biodiversity and a range of ecosystem services in a changing environment.

6. References

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Author

Mike Morecroft **mike.morecroft@naturalengland.org.uk**

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