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ORIGINAL ARTICLE

Conserving Geodiversity Sites in a Changing Climate: Management Challenges and Responses

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Abstract Climate change, and the human responses to it, represents a serious threat to the natural environment. While the impacts of climate change are now well recognised for biodiversity, little attention has been given to the effects on geodiversity and its conservation. Set in the context of current projections for climate change in the UK, this paper examines some of the likely impacts of climate change, and the human responses to it, on a wide range of geodiversity features and sites. It identifies the conservation management challenges that are likely to arise, proposes responses to these challenges and highlights areas where more evidence is required in order to inform the decision-making and management responses that will be needed. It suggests that all types of geodiversity site will be impacted to some extent by changes in active processes. 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. Whilst climate change will pose many challenges to the conservation of geodiversity, it will also generate new opportunities. Principles and guidance to facilitate the management of geodiversity in a changing climate are now required to inform wider adaptation strategies that address the needs of geodiversity alongside those of biodiversity and society more widely.

Keywords Geodiversity · Geoconservation · Climate change · Adaptation

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Introduction

Whilst the geological record shows that climate change is not a new phenomenon, the addition of anthropogenic influence means that it is now widely regarded as the most serious threat to the natural environment in the coming decades and centuries. Climate change will have far-reaching effects on people, places and society, as well as on the natural and built environment (Parry et al.

2007). There is an urgent need to both reduce global greenhouse gas emissions and develop strategies to enable the natural and built environment to adapt to the impacts of climate change that are already inevitable. Whilst the potential impacts of climate change on society and on biodiversity receive daily attention from governments, decision makers and the media, there has been little consideration, as yet, of the potential impacts of climate change on geodiversity, which provides the foundations of these interests.

The impacts of climate change on biodiversity are now well recognised as posing a major challenge for conservation, despite a great deal of uncertainty about the nature of future climate change and the response of biodiversity to it (Mitchell et al. 2007; Walmsley et al. 2007). A range of impacts has been identified from observational data. These include changes in the timing of seasonal events potentially leading to loss of synchrony between species, changes in the abundance and range of species, changes to the composition of habitats and changes to processes within habitats and ecosystems, such as altered water regimes (e.g. Hickling et al. 2006; Procter et al. 2010; Thackeray et al. 2010). Indirect impacts, such as changes in land use from growing new crops or shifts in arable and livestock production, are also identified as potential threats. In the face of these challenges, many authors (e.g. Heller and Zavaleta 2009) have proposed principles and guidance to assist in the development of adaptation strategies to conserve biodiversity in a changing climate; in the UK the work of Hopkins et al. (2007) and Smithers et al. (2008) has been particularly influential. At a more detailed level, the application of climate change scenarios and impacts modelling has already been undertaken for biodiversity sites, such as at Bosherston Lakes SAC in Wales (Holman et al. 2009).

Geodiversity, defined here as “the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (land form, processes) and soil features, including their assemblages, relationships, properties, interpretations and systems” (Gray 2004), is a fundamental part of the natural environment. As well as being important in itself, it has a vital role in supporting biodiversity and the natural environment on which society depends; however, apart from Gordon et al. (2008), the potential impacts of climate change on geodiversity and its conservation have received little attention. Experience from the UK suggests that while the direct impacts of climate change will affect the conservation of geodiversity sites, it is the human responses to these impacts that are likely to pose a far greater threat. For example, although the direct effects of climate change from rising sea levels and increased flooding may change the nature of geomorphological processes on the coast or in river catchments, it is human interventions, such as the construction of ‘hard’ coastal protection and river management schemes, that are most likely to disrupt natural geomorphological processes and obscure geological exposures in sea or river cliffs.

This paper reflects the outcomes from a seminar on ‘Geodiversity in a changing climate’[1] and is intended to provide an initial assessment of the challenges faced and the potential responses required, particularly in relation to site management. Although developed within a UK context, the issues raised are relevant to geoconservation across Europe and globally.

Nature of the Geoconservation Resource

Geodiversity in the UK

The UK has geology ranging as far back as the Archaean, including rocks belonging to every geological system from the Vendian to the present. It is also rich in fossils, minerals, geomorphological features and processes, and soil types. This rich geodiversity has a major role in providing society with environmental goods and services. These include coastal and river flood buffering, water supply, soil for growing food and aggregates and building stone for construction. Geodiversity also underpins the landscapes and coastal scenery that provide the backdrop to many of the UK’s most popular tourist destinations.

Geoconservation is well established in the UK. Nature conservation legislation, including geoconservation, was first passed in 1949 and has been strengthened by various revisions over the last 60 years (Thomas and Cleal 2005; Prosser 2008). The conservation value of the UK’s geodiversity has been assessed through the Great Britain-wide audit, the Geological Conservation Review, undertaken to identify nationally important sites (Wimbledon et al. 1995; Ellis et al. 1996), and audits of regionally and locally

[1] The seminar at the University of Chester, England, on 4 June 2009, was convened by the UK conservation agencies (the Countryside Council for Wales, the Joint Nature Conservation Committee, Natural England, Scottish Natural Heritage and the Northern Ireland Environment Agency) and the Geoconservation Commission of the Geological Society of London. Delegates included staff from government conservation agencies, the Geological Society of London, the British Geological Survey, the geological conservation voluntary sector, land managers, land owners and interested academics. The seminar explored the impacts of climate change, and the social responses to it, on geodiversity and its conservation, discussed the responses and adaptation strategies required to manage and conserve geodiversity in a changing climate and identified the evidence gaps that need to be filled in order to better understand the likely impacts of climate change.

important sites undertaken by locally based voluntary groups (Burek 2008). The UK's geodiversity is now accorded various levels of protection. This is delivered through a suite of nationally important sites designated as Sites of Special Scientific Interest (SSSIs) (Areas of Special Scientific Interest in Northern Ireland), local or regionally important sites (usually referred to as Local Geological Sites or Regionally Important Geological Sites), and a number of European Geoparks and geologically important World Heritage Sites. In addition, there are important soils and geological and geomorphological features and processes outside protected areas in the wider landscape that are offered some limited protection through development planning policy and guidance.

It has long been recognised that it is the characteristics of different site types, rather than their designation status, that is most useful in assessing and addressing conservation management needs. In order to understand better and plan for the protection and management of geodiversity sites, especially SSSIs, a 'site type' classification has been developed in the UK (Nature Conservancy Council 1990). This classification, refined and revised by Prosser et al. (2006), incorporates three broad 'site type' categories, namely exposure or extensive sites, integrity sites and finite sites, based upon the physical character of a site, the threats to which it is susceptible and the management required to maintain its conservation interest (Table 1). This classification, slightly modified so that it includes a subset of active process geomorphological sites, provides the basis for the analysis in this paper and is broadly applicable elsewhere in the world.

Table 1 Geodiversity 'site types' as classified in Prosser et al. (2006)

	Type of site
Exposure or extensive	Active quarries and pits
	Disused quarries and pits
	Coastal cliffs and foreshore
	River and stream sections
	Inland outcrops
	Exposure underground mines and tunnels
	Extensive buried interest
	Road, rail and canal cuttings
Integrity	Active process geomorphological
	Static geomorphological
	Caves
	Karst
Finite	Finite mineral, fossil or other geological
	Mine dumps
	Finite underground mines and tunnels
	Finite buried interest

For the purposes of this study, sites were analysed in three groups: (1) exposure or extensive sites, (2) integrity and finite sites (excluding active processes) and (3) active process geomorphological sites

Exposure or Extensive Sites

These contain geological features which are relatively extensive below the surface. The basic conservation principle is that removal of material does not damage the resource as new exposures of the same type will be freshly exposed. The main management requirement is to achieve and maintain an acceptable level of exposure of the interest features. Site types include active and disused quarries and mines, coastal cliff and foreshore exposures, road and rail cuttings and inland outcrops. It is important to remember that exposure or extensive sites (henceforth referred to as exposure sites) may comprise a wide range of geology ranging from very hard to very soft rocks.

Integrity and Finite Sites (but Excluding Active Process Sites)

Integrity sites are geomorphological sites that require holistic management; finite sites comprise features of limited extent that will be depleted and damaged if any of the resource is removed or lost. Integrity sites include static geomorphological features such as eskers and more active features such as caves and karst. Finite sites require close control over the removal or loss of material and include many mineral and fossil deposits, mine dumps, finite underground mines and buried interests.

Active Process Sites

Although classified under the integrity category by Prosser et al. (2006), active process sites are considered separately here because of their unique characteristics in terms of their likely responses to climate change. The principal conservation management objective is to maintain the capacity of the active processes to evolve naturally, allowing them to operate across their natural range of variability and hence to maintain natural rates and magnitudes of change. A consequence is that the landforms produced by them may change over time and some may be transitory. For example, gravel bars in a river bed may be destroyed in a large flood but may reform as the discharge and sediment transport readjust to 'normal' flow conditions. They may also reform in different locations. Active process sites are also susceptible to changes outside the conservation site boundary (e.g. through upstream changes that affect river discharge and sediment inputs). This is more likely to occur on sites with river, coastal or slope (mass movement) processes and their associated features. Some sites may also contain inactive or relict landforms that form part of the total landform assemblage.

Summary of Climate Change Projections for the UK

The latest UK Climate Projections (UKCP09) (Defra 2009; Jenkins et al. 2009; http://ukclimateprojections.defra.gov.uk) provide a key tool to assess the potential impacts on the conservation of geodiversity sites in the UK. Although there are many important assumptions and uncertainties, these projections represent strong and credible climate science. They show, through three different greenhouse gas emission scenarios, how the future climate could change dramatically. If a 'high emissions' path is followed, global temperatures could rise by over 5.5°C by 2100, compared with the pre-industrial period. For the UK, this could mean an average summer temperature rise of 5°C in the southeast of England by the 2080s. Even under a 'low emissions' path, southern England could see a rise of 3°C by the 2080s.

The major likely changes in the UK, in the absence of action to cut global greenhouse gas emissions, are expected to be warmer and wetter winters, hotter and drier summers and increased sea-level rise. Based on a 'medium emissions' pathway, which is closest to the current global emissions trajectory, average summer temperatures could increase in southeast England by about 4.2°C and in the Scottish Islands by 2.5°C by the 2080s. At the same time, winter precipitation could increase by up to 33% along the western side of the UK, but with small decreases in the Scottish Highlands. Summer precipitation may be down by 40% in the far south of southern England but remain at current levels in northern Scotland. There are likely to be more extreme weather events, but changes in storminess are not known.

To illustrate key changes in climate expected in the shorter term, Table 2 summarises the changes expected in the UK by the 2050s, based upon a medium emission scenario.

Impacts of Climate Change on Geodiversity Sites

Exposure Sites

The management objective for exposure sites is to retain or create exposures of the geological features for which the site is important. Exposure sites vary considerably in terms of their nature and location, and the direct impacts of climate change on them will depend on whether they are subject to coastal and fluvial processes or comprise hard rock, soft rock or unconsolidated sediments.

All exposure sites will be subject to impacts from processes such as weathering that may operate more quickly or differently as a result of climate change. Heavy rain and flooding or drought and drying out will also affect the condition and management needs of exposures. Such processes may vary geographically in intensity and periodicity, with corresponding variations in the impacts on a particular exposure 'site type'.

For sites located in close proximity to coastal or fluvial processes and often dependent on them to maintain their exposure, there are likely to be significant impacts from

Table 2 Summary of key UKCP09 projections relative to the 1961–1990 mean for the 2050s in the UK, based on a 'medium emissions' scenario (from Defra 2009)

Variable	Projected changes
Summer (JJA) mean temperature	All areas of the UK will get warmer, more so in the south. With central estimates of temperature rise between 2.0 and 2.8°C across the UK, and very unlikely to be less than 0.9–1.3°C and very unlikely to be more than 3.4–4.6°C dependent on location.
Winter (DJF) mean temperature	All areas of the UK will get warmer, more so in the south. With central estimates of temperature rise between 1.6°C and 2.2°C across the UK, and very unlikely to be less than 0.6–1.1°C and very unlikely to be more than 2.8–3.4°C dependent on location.
Summer (JJA) mean precipitation	Summer precipitation is projected to decrease across the UK, more so in the south. With central estimates of precipitation between −11% and −23% across the UK, and very unlikely to be less than −24% to −48% and very unlikely to be more than +1% to +9% dependent on location.
Winter (DJF) mean precipitation	Winter precipitation is projected to increase across the UK. With central estimates of precipitation between +9% and +17% across the UK, and very unlikely to be less than +1% to +5% and very unlikely to be more than +19% to +38% dependent on location.
Sea-level rise	Central estimates show that sea level (taking into account land movement) is projected to rise by 21.8 cm in London and Cardiff, and 13.9 cm in Edinburgh. Under the low probability, high-impact H++ scenario an average sea level rise of 1.9 m is projected around the UK.

rising sea levels, increased erosion and flooding. The scale of the impacts will depend in part on the geological exposures concerned and their resistance, but are likely to include:

- Accelerated cliff retreat where there is increased frequency and intensity of wave attack at the foot of cliffs. This may be exacerbated by 'coastal steepening' (Taylor et al. 2004) which reduces the amount of shoaling that an approaching wave experiences. In poorly consolidated sediments, the combination of high tide, a swell and a storm may be capable, in extreme circumstances, of causing cliff retreat of several metres in a matter of hours. Elsewhere, such increased wave action may keep coasts permanently clear of the supporting toes of landslip debris, accelerating the rate of slope failure.
- Foreshore lowering. The combined effect of relative sea-level rise, dwindling coastal sediment supply and changing wave climate are thought to be causing changes to the foreshore (Taylor et al. 2004). These changes have been monitored over the last 100 years through the changing position of mapped high and low water lines. Generally speaking (away from river mouths), low water mark has retreated landwards faster than high water mark. This 'coastal steepening' results in a diminished foreshore area, which combined with higher water levels, also means less exposure available for study and a reduction in the length of time when it is accessible.
- Exposure redistribution. River sections may be affected by increased return periods of flooding events, leading to sudden or large incremental changes in the distribution of exposures both through erosional and depositional processes.

Even on coasts where the rocks are sufficiently well consolidated to resist these impacts, sea-level rise may affect access to the exposures either by drowning them completely or impeding access at low tide. An additional effect of accelerated coastal erosion will be an increased volume of sediment released into coastal waters. While the ultimate sink for this sediment may be further offshore, some of it may be deposited inshore with the potential for exposures to become obscured in the longer term through siltation and vegetation growth. Since rapid erosion of exposure sites is not usually damaging in itself and results largely in changes in location, rather than damage, to the geological exposures, the loss of access and foreshore exposure are potentially the greater threats. Not all impacts will be negative, however, as enhanced erosion may expose, or help to retain, coastal and riverbank exposures.

For inland exposure sites, away from rivers or coasts, it is the acceleration of processes that are already active today, such as weathering, along with a potential increase in the number of geomorphologically significant events, which are likely to generate the greatest impacts. For example, increased winter rainfall may increase the probability of the mechanical failure of poorly consolidated sediments through elevated pore-water pressures. By contrast, extreme drought may remove sufficient water from sand, reducing the grain-to-grain cohesion to such an extent that failure of the face or slope occurs. Any increase in the wetting and drying of clays will result in more frequent spalling events, and as a consequence a more rapid decay of slopes and faces formed of such materials. In England, exposures in quarries of Cretaceous and Carboniferous clays are particularly susceptible to this type of degradation. Where clays and sands exist in combination with more competent rocks, more 'catastrophic' failures may occur.

Changes to vegetation may also generate impacts. Extreme drought and consequential fires, for example, may result in the loss of vegetation and lead to some surfaces becoming much more susceptible to scouring and gullying when subjected to intense rainfall. Again by contrast and depending on aspect and location, some exposures may not be affected by drought but, in combination with a longer growing season and increased seasonal rainfall, may suffer instead from the growth of vegetation. This could lead to problems with access to exposures and, in some cases, especially where the importance of a site depends on its detailed stratigraphy, to damage through root penetration and disturbance.

Integrity and Finite Sites (but Excluding Active Process Sites)

As with exposure sites, the greatest impacts on integrity and finite sites are likely to result from changes in geomorphological processes, especially where sites are near to coastlines or rivers where erosion and/or inundation due to sea-level rise or fluvial flooding is likely to occur. For example, foreshore fossil forest and peat deposits, mine dumps, mineral veins, cave systems or limestone pavements at sea level (e.g. Anglesey, North Wales and Morecombe Bay, northwestern England) (Willis et al. 2009) could potentially be damaged by erosion or become inaccessible as a consequence of inundation (Figs. 1, 2, 3). The degree of impact is likely to depend on the scale of the features involved. Erosion to part of a large drumlin is likely to be much less significant in terms of damage caused than inundation of a small kettle hole. Again, not all impacts will be negative as intense rainfall events and erosion may expose, or help to retain, exposure of important finite fossil and mineral deposits and provide new exposures that reveal the internal structure of landforms such as drumlins. Enhanced weathering, however, may have adverse effects

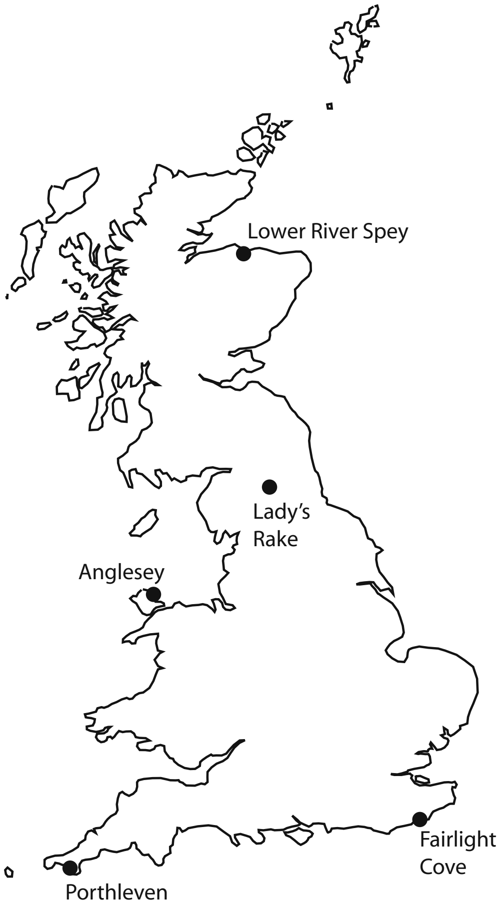

Fig. 1 Outline of Britain showing the location of sites illustrated in Figs. 2, 3, 4, 5, 6

where it results in increased degradation of minerals and fossils.

As the proportion of integrity and finite sites located on the coast or near to rivers is likely to be significantly less than in the case of exposure sites, it is also likely that the direct impacts of climate change on integrity and finite sites will be less.

Fig. 3 A limestone pavement close to sea level in Anglesey, North Wales—an example of a site potentially impacted by rising sea levels. Photograph: Cynthia Burek

Away from the coast and rivers, weathering, increased rainfall and drought are likely to have some impact on integrity and finite sites. For integrity sites, such as caves and karst, weathering and especially increased erosion, are likely to have an impact (Harrison et al. 2001), although more research and monitoring are needed in order to understand the implications. Limestone pavement, a protected habitat under the European Habitats Directive, requires a better understanding of the responses of both its biodiversity and geodiversity, as its conservation depends on balancing the requirements of both of these interests (Willis et al. 2009; Burek and York 2010).

Changes in weather patterns, such as increased seasonal rainfall, could impact on karst landscapes,

Fig. 2 Lady's Rake, a mineral-rich mine dump in northern England increasingly threatened by the impacts of fluvial flooding. Photograph: Mick Murphy/ Natural England

flooding, eroding or increasing sediment flow into cave systems or generating slope failure or increased rates of chemical degradation in mine dumps. On the positive side, increased rainfall may help support some existing peatlands. Equally, some sites important for their peat or pollen records may suffer from drying out during periods of drought.

Changes in vegetation cover may also be an issue. Increased vegetation cover arising from enhanced natural regeneration may obscure the morphology of features such as drumlins or eskers, reduce access to mine dumps or alter the biological and geological character of limestone pavements (Willis 2008). Limestone pavements are already a damaged resource (Ward and Evans 1976) and any further adverse effects arising from climate change will make conservation of what remains an even greater challenge. Loss of vegetation, and thus its role in stabilising soils, during periods of drought could lead to increased sediment discharge into cave systems during subsequent periods of heavy rainfall.

Active Processes

The direct impacts of climate change on active process sites, including coastal, fluvial and mass movement processes, are likely to result in changes to the processes, rather than to their destruction. The responses will be complex and spatially variable and depend on the geomorphological system dynamics and other factors (e.g. Burt et al. 2002; Gordon et al. 2002; Lane et al. 2007) (Table 3). They may result in the following scenarios:

- Changed distributions of coastal and river landforms in response to altered patterns of erosion and deposition—this could cause the designated scientific interests to shift out of existing spatially defined sites and, in doing so, lose their protection.
- Changes in seasonality of river flows, including: increased occurrence and duration of droughts and low flows, and increased frequency of flooding, enhancing rates of erosion, deposition and channel adjustment.
- Enhanced coastal retreat and steepening, coastal squeeze (where landward migration of landforms and habitats is impeded) and enhanced landslide activity on susceptible coasts.
- The combination of rising relative sea level, varying storminess and riverbank and coastal protection works (sterilising feeder bluffs) will increase the likelihood of conflict between coastal change and existing development.
- Decreased periglacial activity on some mountains, including loss of semi-permanent snow beds and related processes, shorter snow line, increased frequency of snowmelt events and a reduction in higher magnitude snow-melt events.
- The possibility of accelerated soil erosion in both arable and upland environments, especially during windy or very wet conditions, as a result of land use changes and increased recreation pressures.

Table 3 Potential responses of dynamic land forming processes to climate change (from Gordon et al. 2008)

Location	Key properties	Key weather variables	Key human impacts	Potential effects
Soft sediment coast	• Sediment type and availability • Wave energy • Beach profile • Sea-level rise	• Wind direction and speed (affecting both wave energy and sand movement)	• Interruption of sediment movement • Sea walls—'coastal squeeze' • Development in flood-prone areas	• Increased erosion • Increased flooding • Changes to salinity of brackish waters • Increased conflict between coastal land uses
Rivers	• Sediment type and availability • Runoff • Changes in slope	• Precipitation duration and intensity • Antecedent conditions • Drought	• Interruption of sediment movement • Re-profiling channels • Development in flood-prone areas	• Increased erosion • Increased flooding
Regolith: soils, slopes & summits	• Sediment type—friction and cohesion • Slope • Soil moisture • Soil organic matter	• Precipitation duration and intensity • Antecedent conditions • Drought • Wind direction • Snow cover • Temperature regime	• Land use change altering vegetation cover, drainage, overuse of soils • Oversteepening of slopes/cuttings • Trampling during dry conditions	• Increased erosion by water and deflation • Loss of soil fertility • Loss of soil organic carbon

- Changes in the magnitude and/or frequency of slope failure and potential consequent increase in slope–channel coupling and increased rates of sediment transport and deposition.
- Changes in soil biochemical processes and accelerated peat erosion, leading to increased release of greenhouse gases and loss of soil carbon.

Overall, there may be greater dynamism and geomorphological heterogeneity (variety of features) and changes in landscape character (e.g. more bare slopes as a result of accelerated soil erosion). Changes in the magnitude and frequency of the processes, the process rates and the nature and spatial distribution of the processes may result in enhanced rates of process activity, including less recovery time between extreme events, which in turn may impact on habitats (e.g. Gordon et al. 1998). There are also likely to be changes in the distributions of landforms in response to altered patterns and rates of both erosion and deposition (e.g. Pethick 2001). Landform readjustment times to extreme events may be longer due to reactivation by subsequent events. In some circumstances, geomorphological processes and soils may become especially vulnerable to irreversible changes or changes in process regimes, so that an understanding of geomorphological sensitivity and the capacity of the system to absorb externally imposed stresses is a key consideration (e.g. Werritty and Leys 2001; Burt et al. 2002; Harvey 2001).

Impacts of Human Responses to Climate Change on Geodiversity Interests

Although it is hard to predict the exact nature of the human responses to climate change, the major indirect impact on geodiversity will almost certainly arise from 'hard' engineering schemes designed to counter coastal erosion and flooding, fluvial flooding and slope failure, although renewable energy schemes, such as tidal barrages, may also prove to have a major impact on coastal processes.

'Hard' engineering schemes are likely to involve the construction of sea walls, coastal protection schemes, river flood barriers, drainage schemes and slope re-profiling. Such activities will inevitably result in the loss of exposure sites behind walls and riverbank protection schemes and as a consequence of engineered slope re-profiling and drainage. The disruption to active processes operating on the coast, in fluvial systems and on natural slopes is also likely to lead to loss of, or damage to, geodiversity interests. For example, sea walls reflect waves and lower beaches, groynes interrupt sediment supply, and both of these may also result in additional erosion occurring in directly adjacent areas. Coastal engineering schemes (Figs. 4, 5) and land stabilisation works already impact upon some exposure sites and it may be expected that without alternative solutions or policy changes, the demand for, and provision of, such schemes will only increase as climate change impacts become more evident.

Although generally preferable from a geoconservation viewpoint, it cannot always be assumed that 'softer' engineering will have less impact on exposure sites. Some elements of flood management may be delivered by permitting river channels to flow naturally as well as allowing flood plains to function as flood storage areas, thereby delivering potential gains for geodiversity; however, other approaches, such as increased afforestation of the upper part of a catchment to attenuate discharges, may well have significant impacts on the visibility of, and accessibility to, landforms, interest features exposed in disused quarries and inland

Fig. 4 Eroding cliff exposures, Fairlight Cove, East Sussex, England, threatened by the human response to climate change. Blocks of rock used as 'hard' coastal protection are starting to result in slowed erosion and degradation of the exposures. Photograph: Jonathan Larwood/Natural England

Fig. 5 Concrete sea wall, Porthleven, Cornwall, England. Increased demands for similar coastal protection schemes, constructed in response to coastal erosion, will result in further losses of cliff exposures. Photograph: Mick Murphy/Natural England

exposures, unless geodiversity interests are incorporated in catchment management plans.

There will also be indirect impacts arising from complex shifts in land use associated with changes in population, agricultural production and recreation (Parry et al. 2007), along with potential impacts from new technology related to renewable energy production or carbon sequestration. Development associated with potential climate-related population migration could directly obscure or damage features and increase demand for aggregate that could be taken from integrity sites such as eskers or kames. Greater demand for new sources of water may necessitate increased abstraction that could result in damage to hydrologically sensitive sites such as cave systems and rivers, whilst new storage (a water resource planning adaptation measure) could potentially result in submersion of geodiversity sites such as disused quarries or mines. Climate amelioration, combined with carbon mitigation policy promoting more localised leisure visits, is projected to increase tourism in the UK (McEvoy et al. 2006) and in northern latitudes more generally. This could result in greater pedestrian erosion of integrity sites (exacerbated by episodic drought and flooding events) or the construction of new and damaging infrastructure such as marinas or hotels. Equally, increased tourism, combined with greater awareness of climate change issues, should provide positive opportunities for geotourism (Dowling and Newsome 2006) and for the use of interpretation of geodiversity to help explain environmental change. Changes in agricultural and forestry practices made in order to produce energy crops, sequester carbon or increase food production could all result in exposure, integrity or finite sites being obscured or damaged without adequate protection measures.

Management Challenges

Given the impacts on geodiversity described above, arising from both climate change and the human responses to it, it is possible to identify five major challenges facing the conservation of geodiversity sites:

1. Accelerated processes of weathering, erosion and vegetation growth or loss will require increased frequency of intervention in order to maintain the conserved geodiversity interest. For some exposure sites, the direct threats arising from this may be minimal. Conversely, for some integrity and finite sites, they will lead to increased degradation.
2. Changes in the type of processes taking place will necessitate the application of a modified or different set of management techniques. Adapting geoconservation methodology to address this challenge will be relevant to all types of geodiversity sites and processes.
3. Process change and management at a wider landscape or catchment scale will become more significant. Geomorphological processes operate at wider scales than the site boundaries of geodiversity features and processes being managed for conservation. If climate change results in accelerated or changed processes, the significance of these changes in the wider catchment or elsewhere on the coast, for example in relation to sediment budgets, may increase. These changes could generate management challenges that may increasingly need to be addressed in the context of the wider landscape.
4. The repositioning of geological exposures and geomorphological features in response to active geomorphological processes will provide increasing conservation challenges. Exposure sites are likely to migrate as a result of erosion, and some coastal and river features may shift their spatial locations and migrate outside existing designated areas; for example the landwards or long-shore migration of coastal landforms (Pethick 2001). This will provide challenges if new and damaging engineering schemes are initiated to restrict movement of features where people or property are affected and in terms of spatially defining features and designations for conservation purposes (Fig. 6).
5. Human responses to climate change will impact on geodiversity conservation, for example through engineering schemes working against natural processes, water resource management inhibiting fluvial processes or changes in land use and agricultural practice obscuring or damaging features. The impacts are hard to anticipate but are most likely to affect sites subject to dynamic processes, such as coastal and fluvial erosion, and areas where water resource use becomes unsustainable due to increased demand or reduced supply, partly as a consequence of climate change.

Fig. 6 High rates of channel and bed instability, and associated flooding, present challenging management problems on the lower River Spey, Scotland, in order to balance the requirements for flood and erosion protection while minimising the impact on the natural processes. In the future, such dynamic rivers may also migrate outside the boundaries of their designated sites. Photograph: copyright P. Gordon Smith

Responses

Responses to these challenges will require a significant shift in thinking within the geoconservation community and by its key stakeholders. There will be many challenges but also new opportunities. There will need to be greater awareness of a broad range of land management issues, engagement with different and additional stakeholders and new and more flexible approaches to site management and interpretation. These responses are likely to include:

1. Demonstrating and raising wider awareness of the dynamic nature of landscapes and of the need to accept and work with changing geomorphological processes. This is fundamental not only to the conservation of geodiversity, but also to the delivery of wider ecosystem-based goods and services that depend on underlying geomorphological processes (confer Newson and Large 2006). It means recognising the inevitability of natural change, maintaining or restoring the capacity of natural systems to absorb change and understanding landscape sensitivity and the potential for tipping points.
2. Promoting a 'conservation' rather than 'preservation' approach (Burek and Prosser 2008), encouraging conservationists, planners, decision makers and local communities to work with, rather than resist, natural change. In terms of geoconservation, this approach can be illustrated by accepting that fossil-rich sediments or iconic geomorphological features like Durdle Door, in the Jurassic Coast World Heritage Site in Dorset, England, will erode and change as a result of sea-level rise. In the longer term, such changes may be offset by positive benefits elsewhere arising from the creation of new exposures or landforms.
3. Developing and applying new conservation techniques to allow for the conservation of geodiversity in the face of increased rates of process activity, more frequent extreme events and new process regimes. This could include learning from engineering techniques and conservation practice used under different climatic conditions, adapting existing conservation techniques to address accelerated processes (e.g. managed realignment, where a stretch of coastline is allowed to evolve naturally in order to reach a more sustainable state), developing techniques for in situ and rescue conservation (e.g. with regard to submerged forests) and reviewing the practicality of conserving some geodiversity features given the anticipated impacts of climate change.
4. Improving our understanding of natural processes and their sensitivity to change. Landscape change occurs when the balance between forces of resistance to change and forces promoting change is unevenly weighted (Gordon et al. 2001). We need to understand when the land forming environment would be able to recover and therefore able to absorb any impacts, when it would be triggered into a prolonged period of attempted readjustment and whether it would change irrevocably. The concept of geomorphic sensitivity (Werritty and Brazier 1994; Werritty and Leys 2001; Burt et al. 2002) provides a useful starting point from which to consider the response to externally imposed

change. Robust behaviour is characteristic of land forming systems where current processes are able to self-correct or absorb the impact in a relatively short time. Active geomorphological systems are defined as 'sensitive' where a fundamental change in the nature and rate of the way they form and reform occurs and they are susceptible to crossing a limiting threshold into a new process regime. For example, a dynamic gravel-bed river may be robust to small-scale and intermittent flood events, but more frequent geomorphologically significant floods could lead to accelerated scour and bank erosion and a fundamental change in channel pattern and behaviour (e.g. switching from meandering to braiding). Werritty et al. (2005) provide a practical application of geomorphological sensitivity zonation in the management of the River Feshie alluvial fan in Scotland.

5. Developing strategies to enable features of geodiversity importance to be identified, safeguarded and managed in situations where the features are likely to be increasingly mobile. This will require some flexibility in defining the boundaries of designated sites for potentially mobile features, as well as the development of alternative or 'soft' engineering management solutions that involve minimal intervention and work with natural processes, not against them (e.g. Pethick and Burd 1995; Hoey et al. 1998; Scottish Natural Heritage 2000). New administrative procedures to accommodate the conservation of eroding, and thus mobile features, such as coastal cliff exposures, and to manage sites that may be subject to increased degradation from weathering may also be required. Existing systems of spatially fixed designations and current levels of site management activity, such as face clearance, are unlikely to be adequate in a significantly changed climate. As such, new approaches to site designation and additional funding for site management, or a greater role for the voluntary geoconservation sector, are likely to be required. Adaptive management strategies will not only help safeguard features of geodiversity importance but will also enable the delivery of wider ecosystem services and benefits (e.g. natural forms of flood protection) through the restoration of natural landform functions and help to maximise nature conservation outcomes (e.g. Poff et al. 1997). They may involve:

   - Creating room for rivers and 'natural' forms of flood management (e.g. floodplain/wetland restoration and increasing floodplain storage)
   - Managing coastal realignment and restoration of coastal landforms and habitats (e.g. salt marsh, mudflats and sand dunes)
   - Taking a long-term, inter-generational view of adaptive management
   - Adopting new approaches to 'sediment husbandry' in the face of sediment deficit at the coast (Orford and Pethick 2006)
   - Applying management solutions at appropriate spatial scales (e.g. catchments and coastal zones)

6. Working with government, policy makers, the planning system and affected communities to consider and plan for the conservation of geodiversity as part of planning for adaptation to climate change (cf. Ledoux et al. 2005). This should seek to include the needs of geodiversity conservation within strategic visions, spatial planning and development planning, and in doing so, to raise the profile of geoconservation. Ideally, such plans would take account of all geodiversity designations and geodiversity processes in the wider landscape and be informed by a National Geodiversity Action Plan (Burek et al. 2007) and Local Geodiversity Action Plans (Burek and Potter 2006), where they exist, and through the involvement of local geoconservation groups. This should also include promoting better awareness of the value of the 'services' and benefits to society provided by geodiversity.
7. Addressing the potential conflict between geoconservation and social demands, for example, by developing strategies that allow coastal communities the time and means to adapt to the impacts arising from increased coastal erosion. In England, the government-funded Pathfinder Programme, running from 2009 until 2011, and with a budget of £11 million to spend across 15 coastal sites, is exploring this approach (www.defra.gov.uk/environment/flooding/manage/pathfinder/purpose.htm). The economics and extremely sensitive politics involved mean that simply resisting every coastal management scheme requiring 'hard' engineering is unlikely to work and may become counterproductive in the long run. Geoconservationists need to understand what the main obstacles are to achieving a more sustainable system of coastal and river management. The social, economic and environmental benefits of sustainably managed coastlines and rivers need to be articulated to all stakeholders to help overcome such obstacles.
8. Recognising that there will always be difficult choices and trade-offs to make. These may include decisions that favour a geomorphological process such as erosion over preservation of a finite site, such as a drumlin, or may in some cases require society to balance the competing requirements of geodiversity, biodiversity or development priorities. For example, some landforms and habitats may need to be sacrificed to maintain sediment supply to others. Wherever possible, however, solutions that deliver multiple benefits should be sought.

Summary of Evidence Needs

From the analysis above, it is clear that we need to do much more to understand, plan for and adapt to the impacts of climate change on geodiversity. In order to enable the responses to be implemented, we need to improve the evidence base to provide:

1. Evidence and examples that illustrate the benefits of taking a 'conservation' rather than 'preservation' approach to the management of sites, especially for geomorphological processes and dynamic systems such as coastlines, river systems and slopes.
2. Greater understanding, at a range of spatial scales, of the likely impacts of climate change on geodiversity, where these impacts are likely to occur and the 'site types' most likely to be affected. This could include long-term monitoring of impacts and responses for a range of geodiversity site types (e.g. cave systems (Hodgson 2008)) in a range of climatic regimes and using remote sensing techniques, such as LIDAR, to evaluate erosion and depositional processes.
3. Better understanding of geomorphological processes and their response and sensitivity to change. We need to understand how geomorphological processes operate in a range of climatic regimes. Adaptive management in coastal, fluvial and slope environments will need to be informed by understanding of natural processes. In developing adaptive management, we need to enhance our understanding of how landforms will adapt to the speed and scale of projected climate changes. A particular concern in Scotland is the likely loss of the buffering effect of isostatic uplift. An analysis of recent land-level changes based on continuous GPS records and absolute gravity measurements indicates that this is already occurring and that there is now a net sea-level rise throughout Scotland (Rennie and Hansom 2010). Projected rates of change seem likely to exceed those in the last 7,000 years. These future rates of change may be too fast for some landforms to adjust (e.g. Orford and Pethick 2006) as they exceed a potential threshold rate for widespread coastal reorganisation of around 3–5 mm/year (Carter et al. 1989; Pethick 1999). Scenario modelling of likely geomorphological responses/projected trends for coasts and river catchments is needed to help assessment of ecosystem vulnerability and inform adaptive management as processes adjust to climate change and sea-level rise. Monitoring of erosion, dissolution and sedimentation rates under manipulated high temperature and carbon dioxide regimes could also help to inform impact modelling, for example to build on the work on karst systems undertaken for the MONARCH project carried out in Britain and Ireland (Harrison et al. 2001).
4. A greater understanding of the environmental responses to climate change in the geological record, especially from the Quaternary and Neogene periods. While there are unlikely to be any exact analogues for a future warmer world, the Quaternary and Neogene records provide insights and data for testing possible scenarios over different temporal and spatial scales. For example, comparison of UKCP09 relative sea-level rise rates with those for the mid and late Holocene allows a means of scaling potential future coastline changes (e.g. Rennie and Hansom 2010), and past changes in slope stability, sediment production, landform distributions and floodplain and wetland histories can provide pointers for future catchment responses (e.g. Higgitt and Lee 2001).
5. A greater understanding of the nature and distribution of socioeconomic change likely to result from climate change and the potential impacts of this change on the geodiversity resource, including identification of the geographical areas and 'site types' where these changes are likely to impact on geoconservation.
6. New geoconservation techniques, proven through pilot studies, which will be effective in the conservation of geodiversity in light of the anticipated impacts of climate change.
7. Evidence-based principles and guidelines to enable geodiversity to be considered and conserved as an integral part of climate change adaptation strategies. As well as the development and piloting of new geoconservation techniques, in particular with regard to active processes, this will require a greater understanding of the constraints and uses of spatially defined designations in the conservation of geodiversity in a changing climate.
8. Understanding of the impacts of climate change, and the human response to it, on the ability of geodiversity to deliver and support ecosystem services on which society depends. This is a key issue in terms of demonstrating the wider value and relevance of geodiversity, and the need for geodiversity to be taken account of, and included within, the implementation of an ecosystem approach and wider adaptation strategies.

Conclusion

Geodiversity and its conservation will inevitably be impacted by climate change and the societal responses to it. There will be many challenges but also opportunities. In order to meet these challenges and take the opportunities, we need to understand these impacts and develop evidence-based strategies to enable adaptation to take place. In some situations existing conservation techniques will need to be modified, but in others, new ones will need to be developed and applied. This will require a concerted effort to do more to understand the impacts that are likely to arise and then to work with governments, planners, decision makers and local communities to ensure that geodiversity is managed sustainably as part of wider, long-term adaptation strategies. In order to do this, the geoconservation community urgently needs to develop principles and guidelines for the conservation of geodiversity in a changing climate. This paper is a first step in that direction.

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