The role of geodiversity in delivering ecosystem services and benefits in Scotland

JOHN E. GORDON[1]* **& HUGH F. BARRON**[2]

[1]*School of Geography and Geosciences, University of St Andrews, St Andrews, Fife KY16 9AL, Scotland, UK*
[2]*British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, Scotland, UK*
* *Corresponding Author* (email: jeg4@st-andrews.ac.uk)

SYNOPSIS

The ecosystem approach is now a key driver for environmental policy and conservation management both in the UK and globally. Within this, geodiversity provides or underpins many essential provisioning, regulating, cultural and supporting ecosystem services and so it is not only the inherent value of geodiversity that matters, but also its role in ecosystem functioning. Protecting geodiversity contributes to maintaining the resilience and adaptive capacity of biodiversity and supports critical ecosystem services. In addition, the analysis of palaeoenvironmental archives and geomorphological records provides a key long-term perspective on trends, rates of change and future trajectories in ecosystems and service delivery, a acknowledged gap within the Millennium Ecosystem Assessment, as well as informing adaptive management of the effects of climate change, including sea-level rise. Better integration of geodiversity and biodiversity as part of Earth system science is critical for the future-proofing of ecosystems and their services and provides opportunities and challenges for applied geoscience.

> *Knowledge of the Earth system is humankind's insurance policy for the future* (de Mulder *et al*. 2008).

Introduction

Geodiversity is the variety of rocks, minerals, fossils, landforms, sediments and soils, together with the natural processes which form and alter them (Gray 2004, 2011). It provides the foundation upon which plants, animals and human beings live and interact, thus linking people, nature, landscapes and cultural heritage (Stanley 2004). Geodiversity also underpins the aesthetic value of landscapes, contributes to sustainable economic development and benefits public health through opportunities for outdoor recreation and enjoyment of the natural world (Johansson 2000; Gray 2004, 2011; Stace & Larwood 2006; Gordon & Barron 2011). It therefore delivers many benefits for society, contributing fundamentally to most of the ecosystem services recognised in the Millennium Ecosystem Assessment (MA) (2005). Geodiversity is also a key consideration in sustainable management of the land, rivers and the coast and in the assessment of likely ecosystem responses to climate change through alterations in water flows, sediment transport, soil properties and geomorphological processes

(Gordon & Leys 2001; Newson & Large 2006; Orford & Pethick 2006; Viles *et al*. 2008; Murray *et al*. 2009; Brazier *et al*. 2012; Gray *et al*. in press). The importance of geodiversity, particularly through the continued operation of natural processes and the value of applying integrated approaches in land and water management, is becoming more widely recognised for sustaining 'natural capital' (Poff *et al*. 1997; Corenblit *et al*. 2007; Hopkins *et al*. 2007; Vaughan *et al*. 2009). Increasingly, a multi-functional approach to the sustainable management of soils is addressing habitat support and delivery of other ecosystem services (Haygarth & Ritz 2009; Dobbie *et al*. 2011).

The Convention on Biological Diversity (CBD) (1992) and the European Landscape Convention (2000) both call for a more holistic approach to the conservation of living species, habitats and landscapes within and beyond protected areas. In particular, the ecosystem approach advocated through the CBD is now a key conservation policy driver and is embedded, for example, in the EU Biodiversity Strategy (European Commission 2011a) and 'The 2020 Challenge for Scottish Biodiversity' (Scottish Government 2012a). However, the success of the ecosystem approach will depend critically on recognising the functional connections between geodiversity, biodiversity and landscape (i.e. between the geosphere and the biosphere) as well as the links with socio-economic drivers. It will also require more effective integration of geodiversity in environmental policy and its practical implementation in conservation management to deliver multiple economic, environmental and cultural benefits for society in the face of projected changes in climate and sea level (Prosser *et al*. 2011; Gordon *et al*. 2012).

A key part of the ecosystem approach has been the recognition and evaluation of the diverse services and benefits that nature provides for society. These are set out globally in the MA and in the UK National Ecosystem Assessment (UK NEA) (2011). Although both the MA and the UK NEA identified specific components of geodiversity's contribution to ecosystem services, both lack a systematic and fully integrated account. A more holistic approach needs to recognise that geodiversity is of significant value to society and relevant to society's needs (IUCN 2008; Prosser *et al*. 2011; Henriques *et al*. 2011; Gordon *et al*. 2012; Gray *et al*. in press), including helping to deliver the Scottish Government's National Performance Framework and Strategic Objectives (Wealthier and Fairer, Healthier, Safer and Stronger, Smarter and Greener) (Gordon & Barron 2012). In turn, this should help to strengthen geoconservation and the position of geodiversity as the foundation of most ecosystems and the services they provide.

As a step towards developing a more integrated approach, we outline and assess the contributions of geodiversity to ecosystem services in Scotland. In particular, we draw attention to those services that are less explicitly addressed in the MA and UK NEA, notably certain provisioning and cultural services; in other cases, such as biogeochemical and hydrological cycling, the role of geodiversity, including soils, is more widely acknowledged (e.g. Aspinall *et al*. 2011; Bardgett *et al*. 2011). In doing so, we seek to open up a wider debate on the value of geodiversity and encourage a greater engagement of geoscientists in both ecosystem assessment and management. The ecosystem approach provides new opportunities, as an additional strand of applied environmental geology (McKirdy 2002), to demonstrate the societal relevance of geoscience. This forms part of a broader challenge of integrating Earth system science, global environmental change and sustainable development to address society's needs (Carpenter *et al*. 2009; Murray *et al*. 2009; Reid *et al*. 2010; van der Leeuw *et al*. 2011).

Geodiversity and ecosystems

By definition, an ecosystem integrates the living (biotic) and non-living (abiotic) elements of an interdependent system, highlighting their interaction as a functional unit (Tansley 1935; Campbell *et al*. 2009; UK NEA 2011). The abiotic elements are those parts of the non-living environment with which living organisms interact, including the passage of energy and the cycling of materials through the system. The ecosystem approach seeks to achieve an holistic way of looking after the natural environment and delivering more sustainable development. It is defined under Decision V/6 (May, 2000) of the Conference of the Parties of the CBD as "…a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way." Essentially, this means the inclusion of all relevant biotic and abiotic features of a natural system.

Ecosystem goods and services are the benefits that people obtain from ecosystems. They include the provisioning, regulating, and cultural services, which directly affect people, and the supporting services needed to maintain the other services (Millennium Ecosystem Assessment 2005). Geodiversity underpins many different types of ecosystem service (Fig. 1; Table 1). It is a primary component of supporting services, but also contributes to the provisioning, regulating and cultural categories (Gordon & Barron 2011; Gray 2011, 2012; Gray *et al*. in press). Some authors (Gray 2008, 2011) have used the term 'geosystem services' for geodiversity-based goods and services, but the term 'abiotic ecosystem services' is preferred here (see Gray *et al*. in press) in order to emphasise their inclusion within the ecosystem framework. In some cases, the benefits from the geosphere are direct (e.g. the provision of fresh water), whereas in others they are delivered through the influence that geological, hydrogeological or geomorphological factors and processes have on the biosphere. Geodiversity also provides essential raw materials (e.g. minerals, aggregates, building stone and fossil fuels) considered to be non-renewable capital assets in the MA and environmental services in the UK NEA. However, they should be treated as an integral part of ecosystem goods and services (Gray *et al*. in press) (Table 1), requiring prudent management and efficient use, since they form part of the package of natural resources that national and global economies and quality of life depend upon, as recognised by the European Commission (2011b). In addition, geodiversity also benefits society through 'knowledge capital', including records of past climate change from environmental archives (Gray, 2011). In many cases, such records are vulnerable to development pressures and require appropriate management interventions or protection. Many geodiversity-based services and benefits contribute directly to delivering European/national policy objectives or targets, for example the Water Framework Directive 2000/60/EC and the Groundwater Daughter Directive 2006/118/EC (Gordon & Barron 2011). Nevertheless, not all the services and benefits provided by geodiversity have monetary values and are easily overlooked (Table 1).

The UK NEA includes significant elements of geodiversity within some individual chapters (e.g. Jones *et al*. 2011 on coastal margins), but as a rule geodiversity is not well integrated or evaluated systematically in the overall conceptual framework (Gray *et al*. in press). The UK NEA framework acknowledges in passing the role of geodiversity in providing basic raw materials, its effects on ecosystem processes in freshwater, coastal and upland systems, and the importance of the heterogeneity of geological formations in underpinning spatial variations in habitats and biodiversity (Bardgett *et al*. 2011; Mace *et al*. 2011). It also recognises a limited contribution to cultural services in terms of the value of preserving rare and distinctive landforms and geological formations (Church *et al*. 2011). However, Mace *et al*. (2011, p. 16) sought to justify the limited treatment of geodiversity on the grounds that “direct intervention in ecosystems through changed management practices or polices is unlikely to have major impacts on geodiversity or the ability of the ecosystems involved to deliver services. Most processes influencing geodiversity operate on much longer timescales than those influencing biodiversity although direct changes by people to landforms can affect local geodiversity.” Such an approach reflects a commonly and wrongly held perception, and one reflected in environmental policy and decision frameworks, that geodiversity is not under threat. It also underestimates the dynamic role of short- and medium-term geomorphological processes in ecosystem development.

Although some components of geodiversity may appear to be robust, the above perceptions are misleading on several grounds. A common misconception is that geodiversity features do not require active management or planning. The pressures and threats facing geodiversity are many and varied, generated by development planning and land-use activities at both site and wider landscape scales (Prosser *et al*. 2006; Stace & Larwood 2006; Gordon & Barron 2011). Other impacts may arise from the effects of climate change and sea-level rise, and particularly the human responses (e.g. in the form of ‘hard’ flood protection and coastal defences), especially on dynamic systems (Prosser *et al*. 2010). The principal effects can be physical loss or damage, loss of visibility or access, fragmentation and disruption of relationships between features, interruption of natural processes (e.g. river flow regimes and sediment cycling) or loss of natural state (e.g. stabilisation of river meanders). Consequently, direct management intervention is essential to ensure that geodiversity continues to deliver or support vital ecosystem services (Table 1). Climate change and sea-level rise present particular management challenges that will require governments, planners, decision makers and local communities to collaborate to ensure sustainable management of geodiversity as part of wider, long-term adaptation strategies delivering protection of ecosystem services (Prosser *et al*. 2010; Rennie & Hansom 2011).

Second, human activities do not only affect local geodiversity. As a result of society’s dependence on the Earth’s resources for industrial manufacturing, food production, transport, building construction and waste disposal, human activities are now the dominant global geomorphological force in terms of material transport (Hooke 2000; Wilkinson 2005; Price *et al*. 2011). Humans have re-shaped the Earth’s surface by moving rock and soil, building cities, motorways and dams, fixing the coast through concrete barriers, and accelerating deforestation and soil erosion. Natural processes have been altered, often with adverse effects on floodplain, landslide and coastal processes, thus enhancing local and regional hazards. Consequently, many components of geodiversity are vulnerable to land use change and environmental change across a wide range of spatial scales.

Third, there is growing interest from ecologists in managing climate change adaptation through conservation of geodiversity – “conserving the arenas, not the actors” (Beier & Brost 2010). This reflects an emerging recognition of the links between biodiversity and particular ‘geo-physical’ settings (Anderson & Ferree 2010; Parks & Mulligan 2010; Hjort *et al*. 2012). Conservation of geodiverse, heterogeneous landscapes should help to underpin the development of robust ecological networks and managed adaptation strategies and/or relocations. In addition, the long-term perspectives available from palaeoenvironmental records should enable better understanding of ecosystem dynamics and trends in ecosystem services (Willis *et al*. 2007; Jackson & Hobbs 2009; Gray *et al*. in press), an acknowledged (and glaring) gap in the MA.

Fourth, it is important to understand the nature of the vulnerability and the management requirements for different types of geodiversity interests (Prosser *et al*. 2006; Kirkbride & Gordon 2010). Because many geological processes operate over long timescales, the resulting rock formations or landforms may effectively be relict features. In some cases, the interest is spatially extensive, so that new exposures can usually be created if existing ones are damaged or destroyed. In others, however, the interest comprises very specific features of limited extent (e.g. a fossiliferous bed or an esker) that, like extinctions of species, cannot be recreated if damaged or destroyed. Active geomorphological processes are particularly vulnerable to modification by human intervention both locally and over wider areas (e.g. through upstream changes in a catchment that affect river discharge and sediment throughputs), although, like some ecosystems, they also have the potential to recover through management unless limiting thresholds are crossed (Gordon *et al*. 1998).

Provisioning services

The principal contributions of geodiversity to ecosystem provisioning services are through the supply of fresh water, mineral resources, construction materials and renewable energy (Table 1). Other contributions to food, fibre, fuel, genetic resources and biochemicals are principally delivered indirectly through services provided by soils (Aspinall *et al*., 2011).

Fresh water

Geology provides the fabric for groundwater aquifers and supports surface water systems. Soils, subsurface geology and topography all influence surface water storage potential, while aquifer and aquiclude architecture controls groundwater storage and yield. Groundwater is an essential part of the environment and economy. It sustains river flow and plays an important role in maintaining many fragile wetland ecosystems, water quality and habitat availability; groundwater also provides high quality, reliable and inexpensive public and private water supplies and dilutes and removes many of society's contaminants.

Groundwater can also play a significant role in annual runoff in river catchments (Soulsby *et al*. 2005). In Scotland, groundwater forms the basis of the mineral water industry and gives Scotch whiskies some of their local characteristics and diversity of taste and appearance. However, despite the obvious importance of groundwater, it is often undervalued and overlooked as a national asset, probably because of a perception of adequate surface water resources driven by high rainfall amounts.

Mineral resources and construction materials

Minerals are essential to maintaining a modern economy and lifestyle. They are the basic raw materials for manufacturing, construction, infrastructure, energy and agriculture. Scotland’s geodiversity provides significant useful mineral resources such as brick clay, coal, igneous rock, limestone, sand and gravel, sandstone, silica sand and peat for local, regional, national and international needs (Bide *et al*. 2011). Scottish quarries supply around 50% of Great Britain’s igneous rock, and many produce key high specification aggregates. Excluding oil and gas, the total value of minerals produced in Scotland was approximately £610 million in 2009 (Bide *et al*. 2011). As well as indigenous mineral production, the economy also gains from the consumption of these raw materials in high-value downstream industries, such as chemicals manufacture, construction and energy production. However, the Scottish economy, like the rest of the UK, is heavily reliant on imported minerals. With increasing global demand driven by growth in emerging economies, concern is growing over the long-term availability and security of supply of many of these minerals. The European Commission compiled a list of economically important raw materials (European Commission 2011c) and the British Geological Survey maintains a risk list of elements and element groups of economic value (British Geological Survey 2012). A review of raw materials critical to the Scottish economy (SNIFFER 2011) indicated that certain mineral resources are under threat and that their availability and market price in the medium to long term is uncertain. For example, rare earth elements are required to build high technology products that are required in renewable and low carbon technologies. Also included was phosphate rock, essential in fertiliser production for Scotland’s important agricultural sector.

Geodiversity also provides essential energy resources. Hydrocarbons have contributed significantly to the UK economy since the mid 1970s; oil and gas in the UK were valued at £24.8Bn in 2009 (at 2006 prices) (Bide *et al*. 2011). Onshore, coal produced in the UK in 2009 was valued at £906M (at 2006 prices), with Scotland producing 35% of this total (Bide *et al*. 2011). Minerals are also important for employment in Scotland. Around 1500 direct and over 4000 indirect jobs are provided by onshore mineral extraction (excluding coal) in Scotland (Department for Communities and Local Government 2011). Offshore, of the 440,000 jobs supported from activity on the UK Continental Shelf, 196,000 are estimated to be based in Scotland (Scottish Government 2012b).

Active and disused quarries can play an important role in enhancing both geodiversity and biodiversity. With careful planning through the operational life and restoration of a quarry, opportunities for geodiversity, biodiversity and recreation can be maximised (Bate *et al*. 1998; Davies 2006; Scott *et al*. 2008). Where nationally important fossils beds, sequences of rocks, geological structures or Quaternary features are exposed by quarrying, the best examples may be preserved in Sites of Special Scientific Interest whilst others may be incorporated in Local Geodiversity Sites, enhancing local geodiversity. Finished faces in sand and gravel pits left at a steep angle encourage bank-nesting birds, such as sand martins, and invertebrates (Whitehouse 2008). Deposits worked out below the water table can be modelled to promote wildlife establishment if the pits are to be restored to wetlands. Hard rock quarries are often worked in benches, which may provide a habitat for cliff-nesting birds and plant species. Inclusion of geoconservation in the restoration of mineral workings can also provide opportunities for interpreting industrial heritage (Fig. 2) or for recreation, such as rock climbing.

Renewable energy

During the ‘Power from the Glens’ campaign of the 1940s and 1950s, many of Scotland’s glens were dammed to provide a head of water to drive hydro-electric generating stations. Although hydro-power’s once-rapid growth has slowed, several new major prospects have been identified, and there is scope for many more smaller ‘run-of-river’ schemes due to the suitability of the terrain (elevation drop) and natural flows. Today, around 6.5% of Scotland’s electricity is generated by hydro-electric power (Department for Energy and Climate Change 2011). While hydro-power may be considered a low priority in terms of its additional contribution to national targets in comparison with wind-generation schemes, it is nevertheless important economically for rural diversification and local energy security, with significant potential for local job creation (Forrest & Wallace 2009; Scottish Government 2009).

The development of renewables has become one of the Scottish Government’s highest priorities, with a target of generating the equivalent of 50% of Scotland’s electricity demand from renewable sources by 2015 and 100% by 2020. Geodiversity provides the topography for the optimum location for onshore wind farms, while the coastal and submarine topography is a key factor in site selection and development of offshore wind farms and tidal stream and wave schemes. For example, the tidal race within the Pentland Firth alone is expected to generate 800 MW by 2020 through both wave and tidal devices.

Regulating services

The principal contributions of geodiversity to ecosystem regulating services are through climate regulation, water regulation, water purification and waste treatment, disease regulation and the regulation of erosion and natural hazards (Table 1). Other contributions to air quality regulation and disease and pest regulation are principally delivered indirectly through soil processes (Aspinall *et al*. 2011).

Climate regulation

At a global scale, climate is modulated by a range of natural processes and perturbations, including variations in the Earth’s orbital parameters and geological processes such as plate tectonics that determine the distributions of continents and mountains. Variations in topography also affect climate at global to local scales. For example, at a local scale, the combination of relief, wind exposure, precipitation gradients and other climatic factors produce strong local changes in climate (e.g. between valley bottoms and mountain tops), which in turn are reflected in the diversity of hydrology, soils and habitats (Gordon *et al*. 1998).

Geological processes are a key influence on the carbon cycle and atmospheric greenhouse gas regulation over different timescales. Sedimentary rocks in the lithosphere are the dominant global carbon reservoir, while tectonic and volcanic processes, chemical weathering of silicate rocks and burial of organic carbon in sediments regulate carbon cycling over long timescales. Over shorter timescales, the oceans are the key global carbon reservoir, sequestering an estimated 30% of anthropogenic CO_2 emissions (Denman *et al*. 2007), but the process is finite and limited by the relatively slow release of cations from rock weathering (Falkowski *et al*. 2000).

Ecosystems also regulate climate through biogeochemical and biophysical effects (Smith *et al*. 2011, 2012). Scotland’s organic soils play a major role as a terrestrial sink of carbon and are a key consideration in climate change mitigation and adaptation (Bardgett *et al*. 2011; Smith *et al*. 2011). They are estimated to contain approximately 11,800 Mt CO_2e, more than half of the UK soil carbon stock (Chapman *et al*. 2009; Dobbie *et al*. 2011), which compares with a total of approximately 433 Mt CO_2e in the surface vegetation of the UK (Milne & Brown 1997; Cruickshank *et al*. 2000). Protecting and managing these important soils to maintain and enhance carbon sequestration is crucial (Ostle *et al*. 2009; Dobbie *et al*. 2011); for example, the loss of only 1% of the carbon in Scottish soils would equate to over double the total annual emission of greenhouse gases in Scotland (55.7 Mt CO_2e in 2010 – Scottish Government 2012c). Similarly, it is estimated that a loss of only 5% of the UK’s peatland carbon would equate to the total annual UK anthropogenic greenhouse gas emissions (Bain *et al*. 2011).

Water regulation, water purification and waste treatment

Catchment geology, topography, soils and hydrological pathways are important in water regulation, while river channel geomorphology, sedimentary properties and flow characteristics fundamentally influence water quality and habitat availability (Tetzlaff *et al*. 2007). For example in the Cairngorms, detailed studies have demonstrated critical links between geology, groundwater and surface water chemistry, the influence of catchment characteristics (particularly soil types) on groundwater residence times and contributions to runoff, groundwater-surface water interactions and the influence of groundwater on surface water chemistry and ecology, and stream and surface water acidification (Soulsby *et al*. 2001, 2006). Soils in particular play an important part in protecting water quality through pollutant sequestration, breakdown of organic pollutants, acidity buffering and denitrification (Smith *et al*. 2011). By preventing pollutants from reaching watercourses (e.g. through nitrate retention), they can help mitigate subsequent eutrophication of freshwater and coastal systems.

Disease regulation

Geological factors impact both beneficially and detrimentally on human and animal health through the composition of rocks, soil and water and their influence on soil, water and air quality. For example, soils are an important source of trace elements that can act both as micronutrients and contaminants (Kabata-Pendias & Mukherjee 2007). Geological factors also influence the epidemiology of diseases: polluted rivers and streams can transmit diseases and carry poisonous substances, while groundwater may contain soluble natural chemicals such as nitrate or sulphate, which are a health risk at certain levels. The interdisciplinary field of medical geology (geomedicine) is increasingly important in helping to alleviate health problems and to understand the role of environmental factors on their geographical distributions (Selinus *et al*. 2005; Bunnell *et al*. 2007). For example, geochemical mapping can help to locate sources of hazards and inform assessment of risks or exposure to harmful substances (e.g. from urban soil pollution) (Broadway *et al*. 2010). Soil chemical analyses have also revealed how past manuring practices have contaminated soils in remote rural areas (Meharg *et al*. 2006; Davidson *et al*. 2007). Other issues include increased contaminant mobility resulting from extreme weather events such as flooding.

Erosion and natural hazard regulation

Geodiversity contributes through coastal protection, soil erosion and landslide protection, and flood protection (Smith *et al*. 2011). Coastal and fluvial flooding, land instability, soil erosion and sediment deposition are all natural geomorphological processes that can be perturbed by natural causes, such as extreme weather events, but are also disrupted by human changes to the environment, such as urbanisation, afforestation, deforestation, river and coastal engineering, floodplain development and mineral extraction. They frequently impinge on human activity, with consequent economic and social costs (Winter *et al*. 2008). Management responses often result in locally engineered solutions such as riverbank and coastal protection measures that may alleviate in the short term but are unsuccessful in the longer term, or simply transfer the problem elsewhere and consequently have adverse ecosystem impacts. Typically, management timeframes are based on human experience and are not informed sufficiently by a longer-term geological perspective that is vital in assessing natural hazards and implementing sustainable management of natural resources (Fig. 3). Earth scientists therefore have a key role, particularly in “improving our understanding of the physical processes responsible for natural disasters and for providing reliable data on the frequency and magnitude of past events” (Clague 2008, p. 204).

The MA Policy Responses report stressed the importance of sustainable solutions that involve non-structural measures and working in harmony with natural processes in order to avoid detrimental impacts on ecosystems and the services they provide (Mirza *et al*. 2005). Such solutions depend on the effective application of geoscience knowledge as part of the development of more integrated process-based approaches, such as managed realignment and the maintenance of sediment transport at the coast or natural flow regimes and floodplain reconnection in rivers (Hooke 1999; Orford & Pethick 2006; Opperman *et al*. 2009; Beechie *et al*. 2010; Brazier *et al*. 2012). For example, the natural coast functions as an important form of coastal defence. Although hard coasts are likely to remain resilient to accelerations in sea-level rise, soft coasts are likely to be more dynamic, with implications for the land uses behind them (Hansom 2001). The internal reorganisation of sediment within coastal cells is critical to the health of the soft coast. Any intervention that locks-up or restricts sediment movement is likely to propagate erosion on down-drift stretches of coast. Good sediment husbandry informed by coastal sediment budgets is therefore essential to managing these dynamic landforms (Hansom 2001; Pethick 2001; Orford & Pethick 2006). Understanding the natural evolution and dynamics of the coastline will become increasingly important in the future, as the significant costs and limited life expectancy of traditional coastal defence will mean that adaptation becomes the sustainable approach to managing and avoiding the impacts of sea-level rise in many locations (Cooper & McKenna 2008; Delta Committee 2008).

Cultural services

The principal contributions of geodiversity to ecosystem cultural services are through educational values and knowledge capital, artistic inspiration, aesthetic values, landscape character and sense of place, cultural heritage, and recreation and ecotourism (Table 1). Scotland’s geodiversity is the foundation of our scenery and has the potential to contribute increasingly to economic development through tourism-based activities in Geoparks and elsewhere that link geology, landscape and cultural interests. Although such activities are usually associated with sustainable rural development, urban geodiversity also offers opportunities for raising public awareness of geoheritage, for example through exploration of the links between geology, use of building and paving stones and architectural heritage and industrial archaeology.

Educational values and knowledge capital

Scotland’s geodiversity includes an exceptional record of long-term landscape evolution extending back over much of the Earth’s history (Trewin 2002). As demonstrated in the volumes of the Geological Conservation Review (Ellis 2011), many of the features are of outstanding importance on a world scale and have significant value for scientific research. Scotland’s geology and geologists have also played a vital part in the development of many of the principal concepts in geoscience (Gordon & Barron 2011).

In its strategic framework for science, the Scottish Government recognises that science is vital to underpin sustainable economic growth and to deliver its Strategic Objectives (Scottish Government 2008). Geoscience can make a significant contribution in the following areas, as identified at workshops on ‘Earth Sciences in the 21st Century’ coordinated by the Geological Society of London, the British Geological Survey and the Natural Environment Research Council and held in London and Edinburgh in 2010 (see http://www.bgs.ac.uk/ukgeoscience/):

- Earth and environmental sensitivity: enabling prediction and adaptation for the future;

- Resource security (including the diversity of energy production (enhanced recovery of oil & gas; unconventional hydrocarbons such as coal-bed methane, shale-gas, hydrates; nuclear); economic minerals; water);
- Waste management (including containment of rad-waste, other toxins, carbon capture and storage);
- Hazards (understanding risk and uncertainty including hazards of tectonic origin and those related to climate change and sea-level rise);
- Development of holistic Earth models for climate change;
- Forcing, fluxes & feedbacks: the Deep Earth - surface interactions;
- Origins of the Earth's atmosphere, oceans, continents, core and life itself, and their influence on each other.

Science and education encompass schools, life-long learning and wider public awareness of geological processes and how they affect society. There is a responsibility to future generations to ensure that the best sites and features are protected as an essential resource for field education, training, life-long learning and interpretation of geoheritage.

Society benefits from knowledge of the Earth's physical properties, materials, processes and history in many ways. This knowledge includes records of past climate and environmental changes preserved in a variety of sedimentary archives (e.g. ice cores, ocean sediments, landforms, peat bogs and lake sediments). These provide a longer-term perspective on Earth system processes and ecosystem dynamics, status, trends, rates of change and human interactions, as well as baselines for environmental monitoring. The MA highlighted the importance of understanding the direction and speed of change. It acknowledged that "[p]rojected changes in climate during the twenty-first century are very likely to be without precedent during at least the past 10,000 years and, combined with land use change and the spread of exotic or alien species, are likely to limit both the capability of species to migrate and the ability of species to persist in fragmented habitats" (p. 79). It also noted that "[d]ifferent categories of ecosystem services tend to change over different time scales, making it difficult for managers to evaluate trade-offs fully" (p. 88), and that changes may be non-linear. Proxy data from sedimentary archives can help fill these gaps in understanding, validate models and inform future trajectories of drivers and changes in services (Dearing *et al*. 2012; Gray *et al*. in press). This is well exemplified for climate change: "[t]he geological record contains abundant evidence of the ways in which Earth's climate has changed in the past. That evidence is highly relevant to understanding how it may change in the future" (Geological Society of London 2010). Details of climate change over timescales from annual to millions of years are preserved in a variety of geological records (Jansen *et al*. 2007). While there are unlikely to be any exact geological analogues for a future warmer world (Haywood *et al*. 2011), Earth system science can help in planning for the future by revealing levels of natural variability and rates of change and providing the understanding and data for testing possible scenarios for change and trends over different temporal and spatial scales - in effect “learning from the past” (Anderson *et al*. 2006; Dearing *et al*. 2006; Edwards *et al*. 2007; McCarroll 2010).

Quaternary studies have a vital role to play in this respect (Walker & Lowe 2007; Clague 2008), particularly proxy records for the Holocene which are generally more detailed, better dated and show greater resolution than those for earlier time periods. Such records should enable observed or projected changes in both the geomorphological (Higgitt & Lee 2001; Hansom 2001; Wohl & Rathburn 2013) and ecological (Willis *et al*. 2007, 2010; Froyd & Willis 2008; Davies & Bunting 2010) components of ecosystems to be evaluated in the context of past environmental variability. By revealing the interactions of past human activity and environmental change and their effects in ‘sensitising’ the landscape through changes in geomorphological processes, soils, habitats, species and vegetation communities (Tipping *et al*. 1999; Dearing *et al*. 2006; Chiverell *et al*. 2007; Lewin 2013), they can help to inform future management interventions. From a nature conservation perspective, palaeoenvironmental records also show that maintaining the *status quo* is not an option, requiring a shift in focus from short-term preservation to actively managing change in the longer term to enable adaptation through working with natural processes. This will require consideration of evolutionary processes to ensure sustainable ecosystem functioning, rather than attempting restoration back to some unattainable historical condition (Pressey *et al*. 2007; Mawdsley *et al*. 2009).

Some of the more pronounced effects of climate change are likely to be in coastal areas. Records of Holocene sea-level are a critical source of data to help inform future sea-level rise scenarios, particularly to test and validate glacio-isostatic adjustment models (e.g. Gehrels 2010; Shennan *et al*. 2012). Comparisons between Holocene, recent and present rates of sea-level change can also provide an important context. Recent tidal observations (since 1992) at Scottish ports indicate that all are experiencing relative sea-level rise between 2 and 6 mm/yr (Rennie & Hansom 2011). If such rates continue into the future then they will have matched the latest projections from UKCP09 which show an expected net regional sea-level rise of between 5 and 7mm/yr in Scotland over in the next few decades, outstripping rates seen in the last 7000 years (Rennie & Hansom 2011). The resulting effects are likely to be exacerbated by continued sediment deficit (Hansom 2001), coastal steepening (Taylor *et al*. 2004), fluctuating levels of storminess and the presence of ‘hard’ coastal defences.

Cultural diversity, inspiration and aesthetic values

In Scotland, as elsewhere, the landscape and its geological features have long been a source of inspiration for art, sculpture, music and literature (Carter & Badman 1994; Stanley 2004; Gordon 2012a, b). The radical change in perception of the Scottish Highlands, from an inhospitable wilderness to an awe-inspiring place to be experienced, was encouraged by Romantic writers, painters and travellers in the late 18th and early 19th centuries (Holloway & Errington 1978; Campbell 1993). The creative influence of geodiversity is continued in later landscape art (e.g. in the influence of the west coast landscapes on the Scottish Colourists) and literature (e.g. in the poetry of Hugh MacDiarmid, Norman MacCaig and Sorley MacLean). Modern land art installations, too, involve a strong sense of connection with nature, geology and landscape: such art forms can “open new doors” for people to connect with geodiversity through different forms of personal experience (Gordon 2012b).

Landscape character, sense of place and cultural heritage

Scotland’s varied landscapes result from the interaction of both natural and human influences. For example, the influence of geodiversity on the landscape character of the North West Highlands is apparent in the topographic expression of the main geological elements - Lewisian gneiss plateau surfaces, isolated Torridonian sandstone mountains and the Moine Thrust Zone. The action of geological and geomorphological processes over long timescales has emphasised geological weaknesses, giving a strong ‘grain’ to the landscape, evident in the orientation of the main sea lochs and the fjord-like coast. Weathering and erosion have also acted on the bedrock to shape the distinctive character of individual mountains. Successive Quaternary glaciations and postglacial processes, including the formation of extensive peatbogs, have left an equally distinctive imprint. The range of habitats also corresponds with the geodiversity: a complex of wet heath, blanket mire and open water bodies on ice-scoured Lewisian plateaux, grass and moss heaths on drier Torridonian mountains and calcareous plant communities on Durness Limestone. The human element in the landscape is predominantly in the last 5000 years, but the impact on landscape character has been significant, especially in terms of patterns of woodland clearance, landuse and settlement, although these too are influenced by the underlying geodiversity. Similar relationships elsewhere are revealed in landscape character assessment surveys (Hughes & Buchan 1999).

In a country often referred to as a ‘land of stone’, geodiversity forms a key part of Scotland’s built heritage. Natural stone is the principal construction material of the pre-1919 building stock, with different materials and architectural styles in buildings and monuments reflecting the variations in geology across the country (Wilson 2005; Hyslop *et al*. 2006; Gordon & Barron 2011). Archaeological records, in the form of Neolithic and later stone monuments, burial sites and historic settlements, also demonstrate the inter-connections between people, place and geological landscapes through time (Edwards & Ralston 2003). A growing awareness of ‘sense of place’ and ‘local distinctiveness’ has increased the importance of stone to the nation’s cultural identity and a resurgence in appreciation of indigenous natural stone for modern buildings has revived the stone industry in several parts of Scotland.

Recreation and ecotourism

Geodiversity forms the basis for the landscapes and scenery of Scotland that are so highly valued by visitors and the tourism industry and it represents an asset for a variety of recreation and leisure activities. Geotourism is a growing component of the tourism industry, both globally and in Scotland, as recognised by community-led action to develop Geoparks and to provide interpretation of local geological landscapes and landmarks (McKirdy *et al*. 2001; Dowling & Newsome 2010; Newsome & Dowling 2010). Scotland’s three Geoparks in the North West Highlands, Lochaber and Shetland provide opportunities for communities to benefit from their geological heritage through awareness raising and educational initiatives, tourism-based activities, and opportunities for niche branding of local products and services (Hambrey Consulting 2007). They can also help to promote more holistic awareness of Earth heritage, biodiversity, land use, landscape history, archaeology, the built landscapes and local culture, while supporting sustainable economic development (Eder & Patzak 2004; Morrison & MacPhail 2009; McKeever *et al*. 2010). Geotourism in a broad sense is not a recent phenomenon and the development of tourism in Scotland in the mid-18th century was closely linked to the landscape, its geological features and how 'wonders of nature' were portrayed in contemporary literature, art and travelogues (Hose 2010; Gordon 2012a).

Scotland's natural heritage makes an important contribution to people's physical and mental health and well-being. This can be delivered through participation in outdoor recreation, volunteering and outdoor learning, and support for the provision of local greenspace, path networks and attractive landscapes (Scottish Natural Heritage 2009). Geological trails provide opportunities for health benefits through encouraging walking in the outdoors (e.g. British Geological Survey 2004; Scottish Natural Heritage 2004). There is also significant potential for geointerpretation to add value to existing long- and short-distance trails and to the many annual walking festivals in Scotland, and in doing so, to help enhance the promotion of Scotland as a walking destination based on its natural landscapes and geoheritage.

Supporting services

The principal contributions of geodiversity to ecosystem supporting services are habitat creation and maintenance, particularly through soil formation, biogeochemical (nutrient) cycling and water cycling, and the availability of suitable localities for waste disposal and water storage and land for building and infrastructure (Table 1).

Habitat support

Geodiversity provides the essential physical framework that strongly influences the spatial distribution and diversity of a range of habitats and species both at a landscape and a local scale (Ferreira 1959; Thompson *et al*. 2001; Cottle 2004). Geomorphological and biogeochemical processes also maintain dynamic habitats and ecosystems through sediment movement, nutrient cycling and hydrology (e.g. in coastal sand dune/machair systems and the gravel-bed rivers that provide spawning grounds for Atlantic salmon) (Hansom & Angus 2001; Moir *et al*. 2004; Aspinall *et al*. 2011). In the marine environment, geodiversity supports important biodiversity interests (Baxter *et al*. 2011), and many key fishing grounds are associated with submarine features (e.g. the Wee Bankie, Rockall and Southern Trench areas). Biodiversity, and the services it provides, depends on the continued existence of these links with geodiversity, and it is now recognised that conservation management of the non-living parts of the natural world helps to sustain living species and habitats and is therefore crucial for the conservation management of the living parts (Hopkins *et al*. 2007). This requires a more integrated approach to nature conservation and the management of sites and landscapes than has been seen thus far, based on an understanding of their geological and geomorphological contexts and current process dynamics.

Traditional approaches in conservation management have focused on species and protected areas, often neglecting wider ecosystem functions and links. Geodiversity and biodiversity have been treated separately, and there has generally been a lack of integration based on knowledge of the geomorphological processes and the soil and substrate properties and conditions that help to maintain dynamic habitats, ecosystems and landscapes. The temporal dimension is also important; ecosystems are not fixed and stable but are continually adapting to changes in geomorphological processes over centennial, millennial and longer timescales in response to a range of natural and human drivers (Dearing *et al*. 2010). To understand how ecosystems respond to change, it is therefore crucial to consider how geomorphological processes operate over both space and time (Fig. 4). Thus, the present landscape is an intricate blend of current process activity superimposed upon a longer-term legacy of landscape evolution (Thomas 2012). This evolution is conditioned by antecedent conditions and processes during the Late Devensian and Holocene, to which the landscapes may still be adjusting (Chiverell *et al*. 2007; Ballantyne 2008). It is essential that these links are adequately understood in developing effective management responses to human pressures and climate change. For example, responses to disturbance in linked geomorphological-ecological systems may occur in complex, non-linear ways (Viles *et al*. 2008), involving irreversible or step-change 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 (Werritty & Leys 2001; Harvey 2001; Church 2002; Jonasson *et al*. 2005). In some cases, recovery may occur over much longer timescales than that of the disturbance event (e.g. where soil cover is stripped through erosion) and may never be fully attained before the next event; where extrinsic thresholds are crossed, a different process regime may initiated. Thus, whereas some areas may be characterised by geomorphological instability, others may be geomorphologically stable. Such variations in themselves may be important in maintaining biodiversity through the heterogeneity of the physical environment (Nichols *et al*. 1998; Mace *et al*. 2011).

Understanding the links between geodiversity and biodiversity is particularly important in dynamic environments, where natural processes (e.g. floods, erosion and deposition) maintain habitat diversity and ecological functions. Thus Hopkins *et al*. (2007) recommend that: “allowing natural processes to shape the ecology and structure of whole landscapes, will create the best possible chance for conserving the greatest amount of biodiversity” (p. 14); and in relation to site conservation, “there is a need to move from management largely focused on selected species and habitats towards much greater emphasis on the underlying physical processes that are essential to the maintenance of biodiversity on the site” (p. 22). In a changing climate, protecting geodiversity and making space for natural processes is fundamental to maintaining mosaics of physical environments (with appropriate geology, landforms, soils, drainage and flows of water, sediments and nutrients) to enable habitats and species to be maintained, adapt, relocate or be restored (Brazier *et al*. 2012).

Soil formation

The weathering of rocks and other soil parent materials is a key factor influencing the formation of soils and the availability of the main types of nutrients and trace elements (Bardgett *et al*. 2011). The combination of geology, climate, topography and the accumulation of organic materials has given rise to a wide range of soil types and properties that have formed over many millennia since the end of the last glaciation (Langan *et al*. 1996; Lilly *et al*. 2012). Because of the strongly maritime climate with cool temperatures and rocks which are generally resistant to weathering and deficient in base cations, Scottish soils are in general more organic, more leached and wetter than those of most other European countries (Towers *et al*. 2006). Also, the Midland Valley is dominated by mineral soils, whereas the Highlands and Southern Uplands are dominated by peaty soils (peat, peaty gleys and peaty podzols), especially in the west. Mineral soils generally underpin most of Scotland's agricultural production; organic soils support many nationally and internationally important habitats and forest production, and they store the major part of the UK's terrestrial carbon (Chapman *et al*. 2009).

CONCLUSIONS

The MA noted that "both the supply and resilience of ecosystem services are affected by changes in biodiversity" (Millennium Ecosystem Assessment 2005, p. 46). The same may equally be argued for changes in geodiversity. As a key policy driver in the UK, the ecosystem approach now provides a framework for developing much better integration of geodiversity, biodiversity and landscape management, as well as a means of realising the wider values and benefits of geodiversity through its contribution and functionality in delivering ecosystem services. Such an approach underpins Scotland's Geodiversity Charter (Scottish Geodiversity Forum 2012) and opens up opportunities for interdisciplinary geoscience research and its practical applications in environmental geology, both in terrestrial and marine environments. The challenge is for the geodiversity and biodiversity communities to break down barriers between disciplines and to work more closely together to achieve that integration through more holistic Earth system science. In terms of ecosystem assessment, there are challenges to analyse and evaluate geodiversity's contribution in both monetary and non-monetary terms to ensure that natural capital is not undervalued through its omission, and to demonstrate and communicate how investment in the natural environment can result in enhanced service provision and benefits for society (Gordon *et al*. 2012). In terms of ecosystem management, it means developing better understanding of the functional links between geodiversity and biodiversity (Bruneau *et al*. 2011) and applying that understanding to improve the management of protected areas as parts of wider functioning ecosystems (Scottish Government 2012a) and setting management objectives based on physical templates (Hopkins *et al*. 2007; Hagerman *et al*. 2010). Where practical, it also means 'allowing space for nature' to enable coasts, floodplains and slopes to evolve dynamically with minimal human intervention, rather than implementing static 'fix and control' measures (Brazier *et al*. 2012). This requires integrating the understanding of natural processes as part of managing the capacity of natural systems to absorb change in the short term through awareness of their interlinked ecological and geomorphological resilience, but at the same time accepting the inevitability of natural change and ecosystem evolution in the longer term. Knowledge of geodiversity can inform ecosystem adaptation, for example, through spatial analysis and scenario modelling of the impacts of geomorphological changes on habitats, species and ecosystems and through assessment of how realistic biodiversity targets are, taking account of geodiversity factors and the likely magnitude and speed of their changes. Palaeoenvironmental records also have an important part to play through providing a longer-time perspective on ecosystem dynamics as well as trends in ecosystem services (Gray *et al*. in press). Soils, too, are a key area that can help bridge the gap between gesoscience and ecology, where knowledge of biogeochemical processes and landscape history is essential to understanding the functional links between below-ground and above-ground components of terrestrial ecosystems (Frossard *et al*. 2006). In addition, progressing conservation of geodiversity should help to ensure the availability of mosaics of environments to facilitate the adaptation or restoration of habitats and species. Geodiversity-informed management strategies will therefore be a vital part of future-proofing biodiversity and ecosystems where that is practically possible (Brazier *et al*. 2012; Gray *et al*. in press).

Given the inter-connectedness of the biotic and abiotic components of ecosystems, it is essential that robust applications of the ecosystem approach involve multidisciplinary analysis, including appropriate geoscience input, to maintain and enhance the delivery of benefits for society. Human impacts on the landscape have become global and it is crucial that the links between the different drivers of change are understood at a landscape/ecosystem scale.

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Figure captions

FIG. 1. The contributions of geodiversity to a range of ecosystem services are exemplified by the beach, dune and machair landsystem of South Uist. This provides a foundation for valued habitats and crofting land use, a natural form of coast protection and assets for tourism, recreation and inspiration. (Photo: P. & A. Macdonald/SNH).

FIG. 2. Ballachulish Slate Quarries opened in the late-17th century and continued to operate until 1955. Today the area is enjoyed by the local community and visitors, with a prepared path and information boards interpreting the geology and industrial heritage. (Photo: John Gordon).

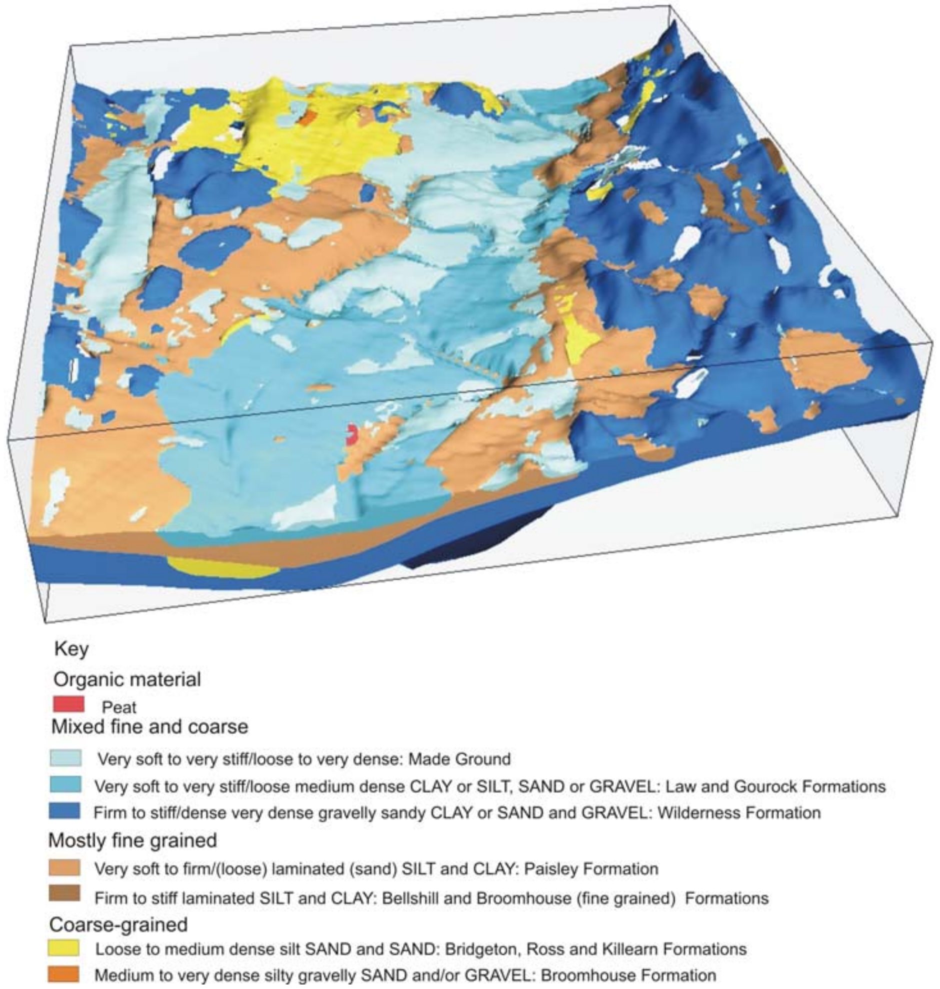

FIG. 3. A 3D engineering geology model of the superficial deposits of the Clyde Valley through the eastern part of Glasgow constructed with modelling software interrogating thousands of borehole records and field data. Suspended from a digital terrain model, it provides developers and planners with better understanding of near-surface ground conditions, physical and lithological properties of sediments, groundwater flow pathways and surface drainage. Such models can also assist in identifying ground which is prone to flooding and can be linked to other spatial datasets. (Reproduced with the permission of the British Geological Survey ©NERC. All rights Reserved).

FIG. 4. Upland habitats are frequently of high value for nature conservation but are dynamic and often fragile, as on the Torridonian sandstone plateau of Ben More Coigach in NW Scotland. This dynamism and fragility result from the properties of the regolith, soils and vegetation combined with the past and present geomorphological processes and harsh climate. Landscape sensitivity and thresholds for change (e.g. acceleration of soil erosion and consequent loss of habitats) depend on the interactions of these factors and human pressures. (Photo: John Gordon).