

REVIEW

# Climate change in the uplands: a UK perspective on safeguarding regulatory ecosystem services

H. G. Orr<sup>1,\*</sup>, R. L. Wilby<sup>2</sup>, M. McKenzie Hedger<sup>3</sup>, I. Brown<sup>4</sup>

<sup>1</sup>Environment Agency, Environment Centre Wales, Deiniol Rd, Bangor LL57 2UW, UK

<sup>2</sup>Department of Geography, Lancaster University, Lancaster LA1 4YQ, UK

<sup>3</sup>Institute of Development Studies, University of Sussex, Sussex BN1 9RE, UK

<sup>4</sup>Macaulay Institute, Aberdeen AB15 8QH, UK

**ABSTRACT:** The UK uplands are highly sensitive and significant cultural landscapes that have been created by woodland clearance for agriculture and are at threat from fire, over-grazing, mineral extraction, land drainage, air pollution and recreation. Some of these activities increase upland sensitivity to climate change, contributing to increased flood risk, or soil carbon losses. Many distinct areas of public policy impinge on the uplands, but most have yet to integrate climate change protection within their objectives. Placed within the emerging ecosystems services perspective, policies could be modified to deliver land management services to secure soil carbon stocks, and to protect the goods, services and functions that uplands deliver. There are, therefore, both new opportunities and threats to tackle. The present paper outlines climate sensitivity and change in the uplands; reviews adaptation and mitigation options; and considers available policy, information and management tools. Within an ecosystems framework, emphasis is placed on safeguarding key regulatory services. We offer a research agenda to support adaptation and outline measures that could be developed within existing regulatory frameworks, or signal where policies may need revision. Research priorities include better quantification of carbon fluxes under different soils and land management practices, techniques for up-scaling local interventions to quantify landscape-scale benefits, and the evaluation of adaptive responses in the context of sustainable land use. Potential adaptation strategies include improved spatial planning for land and water, the creation of networked habitats to enable species migration, and practical guidance on appropriate locations for intensification and extensification of land use.

**KEY WORDS:** Climate change · Uplands · Carbon balance · Adaptation · Ecosystem services · Policy

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## 1. INTRODUCTION

No formal definition exists for 'uplands' because definitions vary according to local climate, topography and vegetation characteristics. However, elevations >200 m above sea level are generally accepted (Stuki et al. 2004), equating to roughly a quarter of the Earth's land surface (Kapos et al. 2000). Climate change presents a special set of challenges for upland regions, as well as new opportunities for their management. The present paper will: (1) summarise evidence of the climate sensitivity and related risks to dominant processes in upland environments, (2) cite examples of

mitigation and adaptation opportunities within existing institutional frameworks for UK uplands, (3) identify research needed to support practical adaptation responses and (4) explore where new regulation and governance could address specific risks.

### 1.1. Climate sensitivity and change in the uplands

The potential sensitivity of uplands to anthropogenically driven climatic variation and change have been discussed before (Beniston 2003, Bjornsen Gurung 2005). Although broad principles for adaptation have

\*Email: harriet.orr@environment-agency.gov.uk

been developed, few adaptation measures have yet been implemented (e.g. Smit et al. 1999, Aerts & Droogers 2004, Wilby et al. 2005, Smit & Wandel 2006, EEA 2007). What is lacking is regionally specific information with linked economic and environmental analysis of multiple benefit strategies (including greenhouse gas emissions) within a practical framework of environmental protection and sustainable development.

Uplands are highly heterogeneous meteorologically making them hard to characterise for the present, let alone future, climate (Beniston 2003, Gilles et al. 2006, Pepin & Kidd 2006). However, evidence of recent climate change comes from observations at high altitude sites across the globe. Winter rainfall and rainfall intensity have increased (e.g. Pepin & Losleben 2002, Barry 2003, Beniston 2003, Groisman et al. 2005, Malby et al. 2007), and temperatures are increasing more rapidly than at lowland sites, particularly through increases in minimum (nocturnal) temperatures (Bradley et al. 2006). These changes are sufficiently large to melt mountain glaciers (Beniston et al. 1997) and to contribute to sea level rise in the 21st century (Barry 2003, Raper & Braithwaite 2006).

Upland landscapes provide a wide range of climate-sensitive ecosystem goods and services (Millennium Ecosystem Assessment 2005), with consequences for water quantity and quality well beyond their own boundaries (Beniston 2006). Uplands are also unique ecological zones, often providing refuge habitats and nursery areas for species threatened by rising air and water temperatures (Conlan et al. 2007). Species' suitable climate space is already changing (Hickling et al. 2006), placing some vulnerable habitats and species at risk (e.g. Walmsley et al. 2007). Upland sensitivity to environmental change is widely recognised, as is their influence on downstream ecosystems and economies (Burt 2001, Werritty 2002). Hence, uplands could be regarded as sentinels of regional climate change that may pre-herald impacts elsewhere (Beniston et al. 1997). This review focuses in particular on safeguarding the environmental regulatory services that uplands provide, although by following an ecosystems approach it inevitably also includes supporting, provisioning, and cultural services within the larger-scale framework (Millennium Ecosystem Assessment 2005).

Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes,

particularly temperature increases (IPCC 2007). Change will continue over the next 50 yr (Christensen et al. 2007), so it is important to understand impacts and to implement timely adaptation responses. Developing improved predictive tools such as catchment-scale climate change scenarios and impact models represents an important step towards planning adaptive land management. This is because the hydrology, geomorphology, soils, ecosystems and socio-economic contexts of upland areas imply a characteristic set of location-specific, climate-driven risks (Table 1).

## 1.2. Special issues in UK uplands

The UK uplands are highly valued culturally. They are important assets for rural employment, tourism, recreation and contain most of the large-scale protected landscapes in the UK. They are mainly in private ownership, but have been protected for over 50 yr for their natural beauty, landscape and nature conservation characteristics. By global standards, the UK uplands are small in scale, with distinct land tenure and management issues, but, in common with others, they are remoter areas, with low population densities and land uses dominated by pastoral agriculture and forestry. Uplands are important for water supply (70% of UK resource) and biodiversity, and there have been long-running tensions arising from conflicting use of these areas for agriculture, forestry and conservation.

UK uplands are classified informally as land above the line of enclosure. This boundary is typically 200 to

Table 1. Climate-driven processes and associated impacts in the uplands

	Drivers	Impacts
Physical component	Changes to: duration, magnitude, frequency, suddenness	Changes to: resilience, vulnerability, flexibility, scale
Climate	Temperature, precipitation, wind, radiation	Snow melt/frost-free period, flooding, drought, soil moisture
Hydrology	Total runoff, flood, drought. Seasonal variation in runoff	Water quality and quantity Increased flood exposure Water supply reliability Wetland sustainability
Geomorphology	Weathering, erosion, landslides, debris flows, channel activity. Mobilisation of sediment	Sediment supply, transport Source channel connectivity Mobilisation of pollutants
Soils	Fertility, nutrient cycling Biophysical processes Erosion	Increased water pollution, Loss of soil function Loss of carbon
Ecology	Species migration Invasive species, extinction Ecological processes Primary productivity	Habitat loss and change, Loss of ecosystem services (e.g. buffering, filtering)

300 m above sea level, but has varied historically due to fluctuating rural population pressure and economic returns from marginal agricultural land. In addition, effective upland management requires recognition of all land uses within the landscape, from valley to hill-sides to summits. Nevertheless, if a broad representation of upland climate and vegetation 'types' is considered, then the uplands can be regarded as extending from the highest ground in SW England to sea level in cooler NW Scotland (Ratcliffe & Thompson 1988, Averis et al. 2004). Fig. 1 shows the uplands considered for the purpose of this review.

Many UK uplands are now exploited less for natural resources than for scenic amenity, leisure and tourism. A suite of national designations has emerged from the complex administrative framework (with control devolved to agencies in England, Wales, Scotland and Northern Ireland) and requirements of European Union (EU) directives. Hence, areas of high landscape quality, which are mainly in the uplands, are designated as National Parks, Areas of Outstanding Natural Beauty (AONB), or National Scenic Areas (NSAs) in Scotland. Similarly, areas of high biodiversity or geological value are designated as National Nature Reserves or Sites of Special Scientific Interest (SSSI), and some are incorporated in the European Natura 2000 network. Within National Parks, many residents

work on land-related employment, although agriculture now contributes <1% of the UK economy (Curry Report 2002), but, despite fewer people employed in farming, National Parks typically have higher rates of employment and in-migration compared with other rural areas (Park et al. 2004).

Uplands have a very long history of native woodland removal and agricultural intensification leading to the loss of semi-natural habitats (e.g. Simmons 2003). Afforestation with conifer plantations has not replaced the area of native woodland lost. Heather moorland has decreased by about 23% since the 1940s, having been replaced by new conifer plantations or converted to grazing land. Recent population growth and economic development have added new pressures, particularly through greater demands on infrastructure and on the landscape due to tourism. Uplands are also cultural landscapes shaped in the past, present and future by multiple land uses such as farming and grouse management (Defra 2006, Holden et al. 2007). Uplands are increasingly being viewed in terms of the ecosystem services they provide, with new ways of seeing and capturing value in biodiversity. However, the full benefits and costs of upland goods and services may not be reflected in the local economy. For example, headwaters draining unmodified peat moorlands may yield cost savings for downstream water users compared to modified moorlands; modifications include draining, burning and heavy grazing. In short, upland economies in the UK remain highly dependent on primary sectors (e.g. agriculture, forestry, sporting estates) together with tourism, and water resource management (water supply and hydro-electric power), all of which are exposed sectors in terms of climate change risks (HM Government 2006). This implies that adaptation via land management and spatial planning will require upland farmers and land managers to both recognise, and potentially be rewarded for, the less tangible products and wider public benefits that they provide (Defra 2006, Piper et al. 2006). We may not be able to rely on plentiful, clean water from the uplands indefinitely at such a very low cost (Millennium Ecosystem Assessment 2005).

The cool-wet climate of UK uplands has a strong influence on natural processes and land use (Manley 1951). In the future, the UK climate is projected to have wetter milder winters, hotter drier summers and a greater frequency of extreme precipitation events in all seasons (Hulme et al. 2002). Some of these patterns are beginning to emerge from a background of considerable natural variability (e.g. Osborn & Hulme 2002, Karoly & Stott 2006). For example, winter precipitation has shown large changes—in parts of western Scotland totals have increased by 60 to 100% since 1960 (Barnett et al. 2006). There is evidence of more

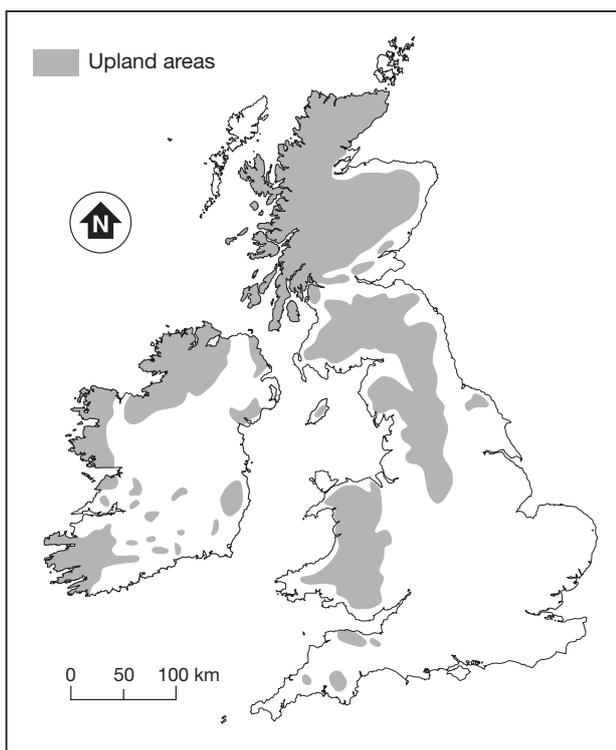


Fig. 1. Uplands of the British Isles (modified from Averis et al. 2004)

rapid warming (Holden & Adamson 2002) and more marked precipitation changes in uplands (Malby et al. 2007). Winter rainfall intensity has increased over high ground (Fowler & Kilsby 2007), and rain shadows may have weakened leading to greater risk of local flooding over recent decades (Malby et al. 2007). Intense orographic rainfall events are prominent amongst the dozen occasions on which precipitation totals exceeding 200 mm in 24 h have been reliably recorded in the British Isles (Burt 2005). Although there are too few such events for trend analysis, overall, mean winter rainfall and river flows have increased in western parts of upland Britain since the 1960s (Wade et al. 2005, Dixon et al. 2006, SEPA 2006, Wilby 2006). There is also tentative evidence of long-term changes in snow cover and persistence in UK uplands (e.g. Harrison et al. 2001, Watson et al. 2004, Johnson 2005). However, the attribution of rainfall-runoff trends to climate change is not yet possible at the scale of the UK, not least because of the confounding effect of multi-decadal variability linked to the North Atlantic Oscillation (Wilby 2006).

The climate change mitigation agenda could place further demands on some upland areas. Recent research has focused on the contribution made by upland environments to the global carbon balance (e.g. Worrall et al. 2004). In the UK, the greatest soil carbon density is found beneath woodland and semi-natural land uses (Bradley et al. 2005). Peatland and upland soils contain at least 50% of the soil carbon in Britain (Milne & Brown 1997). Organic soils in Scotland and Wales contain approximately 3000 Mt C (Scottish Executive 2007). In comparison, the UK contributes 150 Mt C yr<sup>-1</sup> to total global carbon emissions of 6000 Mt C. Historically these soils have been regarded as carbon sinks, but there is growing concern about a possible long-term transition to a carbon source, driven by a combination of climate change, over-grazing, fire and land drainage (e.g. Worrall et al. 2007). Furthermore, the use of uplands for forestry and renewable energy (notably wind energy) has been given prominence in the policy agenda, sometimes to the detriment of adaptation.

## 2. VULNERABILITY OF UK UPLANDS

Uplands have specific vulnerabilities described in the following sections on hydrology, geomorphology, soils, ecology and land use. Evidence of recent and projected environmental change is considered alongside associated risks and opportunities. Gaps in knowledge are identified with particular focus on where these could constrain mitigation and adaptation options.

### 2.1. Hydrology and hydrochemistry

Climate-driven changes in hydrological regimes directly impact water resource management, ecosystem health, flood risk and hazard management (Fowler & Kilsby 2003, Jasper et al. 2004). Climate projections are particularly problematic for upland river catchments because of the complex terrain and climate feedbacks (Gilles et al. 2006, Christensen et al. 2007). In addition, runoff from upland environments has a very high range of natural variability over daily and interannual timescales, making climate change detection in discharge records particularly challenging for these areas (Wilby 2006).

Although national analyses of runoff do not show sustained trends in UK river flows (Robson 2002, Hannaford & Marsh 2006, Wilby et al. 2007), regional changes in flood frequency, flow duration and flow variability have been observed over recent decades, such as a shift to greater winter flows in western Britain (Black & Burns 2002, Wade et al. 2005, Orr & Carling 2006, SEPA 2006, Wade & Vidal 2006). This is associated with trends in the North Atlantic Oscillation over the same period, resulting in a greater prevalence of westerly airflows in winter and increased precipitation on western upslopes (Barker et al. 2004). However, lack of systematic quantitative data on land cover changes makes the separation of land use and climate signals in runoff trends very difficult for most UK catchments (O'Connell et al. 2004).

Costs from future flooding in the UK are expected to rise by between 2 and 20 times the present values by 2080 (Evans et al. 2004). High flows, those exceeded <5% of the time are projected to increase in magnitude by up to 25%, particularly at high elevation catchments, providing an increased risk of flooding during winter months (Fowler & Kilsby 2007). Rivers fed by upland systems are expected to mobilise greater sediment, potentially exacerbating flood levels (e.g. Lane et al. 2007) and channel migration (Werritty & Leys 2001). Ongoing work is examining regional variations in UK flood risk under climate change, taking into account the influence of underlying catchment properties and changes in snowmelt regime (Crooks 2006).

Increasing drought frequency driven by lower summer rainfall could impact adversely on upland ecosystems and water supply. Indeed, significant changes in low flows in southern England are expected as early as the 2020s (Arnell 2003, Wade et al. 2005, Fowler & Kilsby 2007). Small single-season upland reservoirs of NW England could be particularly vulnerable to future droughts (Wade & Vidal 2006), whereas larger reservoirs that can contain more winter storage may be less sensitive (Fowler & Kilsby 2007). Summer rainfall scenarios are even less certain for northern Britain than

southern areas, with considerable variation between climate models, meaning that assessment of adaptation options is rather less advanced (e.g. Werritty 2002).

There are a large number of indirect chemical impacts associated with hydrological change in the uplands. For example, subtle changes in acid deposition and activation of ephemeral hydrological pathways during heavy rainfall are expected to delay the recovery of acidified catchments (Wilby 1996, Evans et al. 2001, Monteith & Evans 2005). There are also high levels of nitrogen deposition in upland areas and potential for leaching nitrate to freshwaters (Curtis et al. 2005, Helliwell et al. 2007). In particular, high altitude catchments dominated by mineral rather than peat soils may be more susceptible to nitrate leaching (Helliwell et al. 2007). There may be selective contamination by other anthropogenically derived pollutants, such as mercury and lead, related to past mining activity (Battarbee et al. 2005). Dissolved organic carbon (DOC) is also increasing and may be related to climate change. Repeated droughts may result in long-term loss of carbon from organic-rich soils (Sowerby et al. 2008). In addition, drought conditions increase nitrogen mineralisation and sulphur oxidation, leading to the release of nitrate and sulphate into surface waters (Miller et al. 2001). In lowlands, post-drought 'flushing' by intense winter rainfall enhances nutrient delivery (Whitehead et al. 2006). It is unclear how important this mechanism could become in the uplands, where nutrient levels are generally low, but receiving waters may be particularly sensitive to even small increased inputs. Rising water temperatures further increase the rate of dissolution and precipitation reactions during low flows (Langan et al. 2001).

As noted above, uplands can be important for seasonal water storage in the form of snow and ice, or as soil moisture in thick peat deposits. Predicted reductions in snow cover leading to earlier runoff, lower soil moisture and drier vegetation in spring increase the risk of fire and droughts (McEvoy et al. 2006). A number of land management practices with detrimental environmental impacts may be exacerbated by climate change. For example, high-density grazing and poor forestry practices can modify soil structure and vegetation cover in ways that increase the rate and volume of runoff (Stott & Mount 2004, Orr & Carling 2006). Conversely, practices that promote localised soil water retention include increasing soil organic matter and reducing compaction (Bragg 2002, Tollan 2002, Carroll et al. 2004, Ellis et al. 2006). However, to what extent these can influence flood and drought reduction at river catchment scales is uncertain; the local response may be shown, but regional outcomes are less clear and require further research (Wheater 2002, O'Connell et al. 2004).

Demand for upland water resources is expected to increase under climate change as there are moves towards greater use of renewable sources of energy (hydro-electric power) and water generally. Whilst upland areas have large reservoirs for water supply, they also contain numerous small, often private, supplies that may be particularly vulnerable to droughts. Coupled to this are the large number of private sewerage treatments that may have an increasing impact on water quality through reduced dilution and, hence, indirect effects on upland ecosystems.

## 2.2. Geomorphology

Climate is the major driver of landform evolution in tectonically inactive areas; thus, climate change could modify geomorphic processes and disturb landscape stability. For example, more intense precipitation could accelerate landscape evolution through mass movements, debris flows, soil erosion, transport of hillslope-derived sediments, and channel change. Although it is difficult to monitor trends in the frequency of extreme events in remote places, increased geomorphic activity is expected with a shift in climate regime (Jones 1993a,b, Rumsby & Macklin 1994, Macklin et al. 2005, Chiverrell et al. 2007). However, the response to increased rainfall can be complex as sediment derived in headwaters is transferred through river catchments via intermediate sediment stores and downstream propagation of landform instability (Dadson & Church 2005).

Uplands are amongst the most geomorphologically active areas in the UK, because slope-channel connectivity is high and there are significant areas of bare ground. Furthermore, land-use pressures are presently causing vegetation removal, which is expanding the areas of eroded topsoil and potentially increasing the risk of accelerated soil loss under climate change. For example, the area of eroded topsoil in a 350 km<sup>2</sup> catchment of the English Lake District increased from 4% in the 1970s and 1980s to 8% in 2000 (H. Orr unpubl. data). Erosion of topsoil represents a carbon loss and has importance for upland conservation status by adversely affecting sensitive ecosystems, particularly upland water bodies. Some land-use changes increase landscape sensitivity (Thomas 2001); for example, periods of active hillside gully erosion in NW England are only evident in the later part of the Holocene following significant woodland clearance and introduction of sheep (Chiverrell et al. 2007).

Steep upland channels are capable of delivering very large amounts of coarse sediment during floods, which can accumulate behind obstacles and impede flows (Johnson & Warburton 2002, Burt 2005, Golding

et al. 2005). Traditional management strategies include gravel traps, but these are often overtopped and represent unwelcome habitat modification for some species such as crayfish. Alternative measures include reducing hillslope-channel coupling through woodland buffer strips on steep upland tributaries. Recent modelling studies suggest that up to 80% reduction in sediment delivery can be realised by these methods (Lane et al. 2008). An important source of fine sediment in river catchments is often riverbank erosion or, indirectly, channel engineering (e.g. Hatfield & Maher 2008). Increased stream power and changing flood frequency could lead to more rapid and extensive bank erosion. However, careful riparian management, such as stock exclusion, helps reduce sediment losses from sites that are not experiencing very active planform change through meander migration.

Uplands are also subject to hazards such as landslides, debris flows, bog bursts and sediment mobilisation from floodplains (Jones & Lee 1994, Warburton et al. 2004). These events pose severe risks to local communities and infrastructure, and trigger sediment accumulation/bed morphology changes downstream (Johnson & Warburton 2002). Sediment-related problems often occur in rivers that have lost natural deposition areas as a result of embankments, revetments and artificial channelisation. This limits space for channel adjustment following large floods and can lead to sediment deposition in undesirable locations, exacerbating conditions for river management (e.g. Sear et al. 1995). Recent policy initiatives are beginning to acknowledge these issues and develop schemes to 'make space' for water and surplus sediment by restoring floodplains and multiple river channels (Defra 2005a).

### 2.3. Soils

Soils provide a wide range of ecosystem goods and services and act as the buffer between atmospheric and aquatic processes. Recent warming and changes in rainfall patterns may help explain recently altered biogeochemical processes in upland soils with potentially profound effects. Since the industrial revolution, uplands in the UK have been subject to high levels of atmospheric deposition of pollutants, leading to acidification and, in recent decades, to the export of terrestrial carbon. The carbon loss from the terrestrial biosphere has been manifested, in part, by increased DOC in stream water (Freeman et al. 2001a, Worrall & Burt 2004, Worrall et al. 2004) and by carbon reduction in soils (Bellamy et al. 2005). Northern upland peatland systems have become the focus of attention because they are major carbon sinks and major sources of water

supply. Even a relatively small imbalance between production and decay of carbon in these systems can cause peatlands to shift from carbon sinks to sources (cf. Laiho 2006). This has raised concern that these losses may constitute a positive feedback to global warming by increasing terrestrial carbon release (Cox et al. 2000).

Peat and peaty soils cover only 14% of the UK, yet contain more than half of the soil carbon (Milne & Brown 1997, Dawson & Smith 2008). Much of this soil carbon is in deep Scottish blanket peat (2735 Mt C; Scottish Executive 2007). In England and Wales stagnogleys, brown earth and raw peat soils contain most carbon, predominantly in the uplands (Milne & Brown 1997, Dawson & Smith 2008).

The distribution of observed increases in DOC across the Northern Hemisphere and for a variety of land uses (Driscoll et al. 2003, Hejzlar et al. 2003) indicates a large-scale driving mechanism, currently the subject of intense research efforts and speculation (cf. Roulet & Moore 2006). The dominant competing hypotheses are recovery from acidification (Evans & Monteith 2001, Evans et al. 2006, Monteith et al. 2007), elevated temperature and CO<sub>2</sub> effects on soil primary production and rates of organic matter decomposition (Freeman et al. 2001b, 2004, Worrall et al. 2006) and climate-driven changes in hydrological processes and drought (Sowerby et al. 2008). The first is supported by correlation and metadata analysis, but a full explanation of the process is not yet available; the latter 2 are supported by field and laboratory studies, but at small scales.

Local conditions regulate DOC flux so the trend is not always upwards, as is presently occurring in SW England (although these areas have been less impacted by acidification). Some soil carbon losses are explained by agricultural extension over the last 20 to 30 yr, particularly land drainage leading to soil erosion (Evans & Monteith 2001, Janssens et al. 2003), increased productivity in crop yields and less use of animal manure (Smith et al. 2007b). Direct temperature rises explain 12% of the DOC increase in an intact upland peat bog in the Pennines (northern England); repeated droughts and an enzyme latch mechanism may account for the remainder (Worrall et al. 2006). This is because enzymes are switched on by water table drawdown, but not switched off after water table recovery, effectively increasing peat decay and carbon loss (Freeman et al. 2001b, Wallage et al. 2006, Worrall et al. 2006).

Over longer time scales, persistent lowering of peatland water tables as a result of drought does not always result in a reduced carbon store (Laiho 2006). The carbon flux depends on vegetation composition, organic matter input and substrate availability to enzymes

(Davidson & Janssens 2006, Laiho 2006). Older peat formations can only decay, but decomposition and carbon release from newer peat layers may be offset by rates of new peat growth (Worrall & Burt 2005). Furthermore, fluvial export of carbon as undissolved particulate organic carbon (POC) is secondary to losses through gaseous exchange in eroding peatlands and at least equivalent to the net gaseous flux from intact peatlands (Worrall et al. 2003, Evans et al. 2006b). The fate of POC is not well understood except that much may be deposited within fluvial environments either at the base of slopes or on floodplains. Questions surround how readily POC is oxidised and released as carbon to the atmosphere.

It is clear that many upland peatlands, particularly in England and Wales, are 'damaged' to some extent by land-use practices and atmospheric pollution. Restoration of these areas would help to protect existing carbon stores and wider ecosystem functions. For example, the organic content of soils is an important determinant of water-holding capacity and propensity to erosion (Bragg & Tallis 2001). More research is needed on carbon flux mechanisms at plot to landscape scales (e.g. Janzen 2006, Sowerby et al. 2008) and on the sensitivity of different soil types to climate change (Laiho 2006). Although the main pathways of carbon in its various forms are broadly understood, the relative importance of some pathways is less clear (Fig. 2). As noted previously, the management of eroding peatlands is best achieved by measures that reduce connectivity between slope and channel, thus reducing sediment loss (Evans et al. 2006b).

Drier summers could increase the risk of fires in upland peatlands (see also Defra 2004), with greater

consequences for soil carbon loss than biotic responses (Davidson & Janssens 2006). A study of moorland fire frequency in the Pennines showed a high incidence during the hot dry summer of 1976 and dry spring of 2003, and the greatest frequency of fires tended to be on eroded bare peat (McMorrow et al. 2006). Water treatment plants downstream of blanket bogs can incur increased costs when DOC emissions rise following upland fires (Worrall & Burt 2005). A further complicating factor is that some moorland is regularly burnt as part of a deliberate management strategy to encourage new vegetation growth for game birds.

Although some water bodies are presently showing recovery from acidification following reduced sulphur emissions (Monteith & Evans 2005, Wright et al. 2005), soils represent significant stores of pollutants that may be remobilised under climate change, thereby delaying long-term recovery (Battarbee et al. 2005). Furthermore, high nitrogen deposition has increased substrate fertility and has been linked to a shift in species composition in upland vegetation (Smart et al. 2003).

Agricultural soils are, in some (mainly lowland) catchments, a major source of phosphorus contamination of surface waters (Defra 2000, McDowell et al. 2001) and cause of freshwater eutrophication (Vollenweider 1968, Sharpley 2000). It is generally assumed that phosphorus delivery to upland waters is low. However, given the greater sensitivity of nutrient-poor upland rivers and lakes, even small additions from diffuse sources can result in nutrient enrichment and loss of some species. Unfortunately, there has been limited research to date on phosphorus budgets and export from upland soils, or on potential implications of changes in land use.

## 2.4. Ecology

Climate influences the distribution of species and fundamental ecological processes such as photosynthetic capacity and trophic interactions. Large-scale meta-analyses indicate a consistent signal among species and taxa expressed as alterations to plant and animal populations across the globe (Parmesan & Yohe 2003, Root et al. 2003). Range shifts polewards and upwards (Klanderud & Birks 2003, Hickling et al. 2006) are consistent with palaeoecological studies showing that the key response by species to climate change is range adjustment (Huntley & Webb 1989). However, ecological adjustment over the last 20 000 yr was not

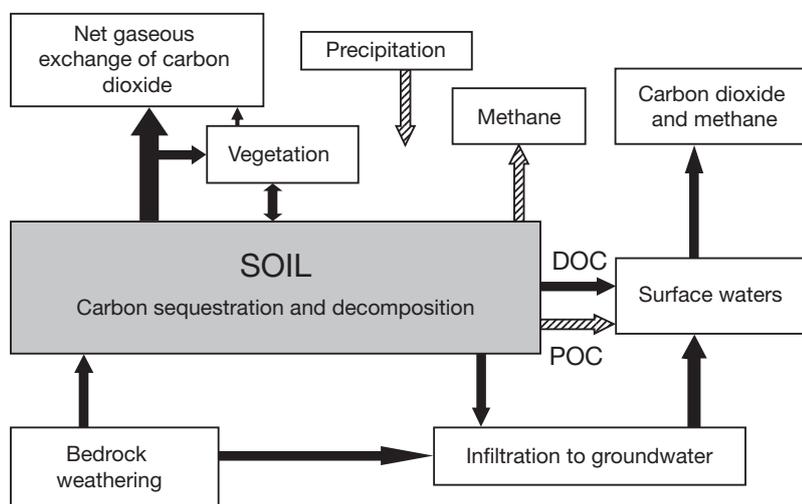


Fig. 2. Simplified carbon flux pathways from soil (after Worrall et al. 2003). Hatched arrows represent fluxes about which we have uncertain knowledge

faced with such rapid rates of temperature change as those predicted for the next 100 yr, nor with the degree of habitat fragmentation and modification of post-industrial times (Root & Schneider 2006). Climate changes may thus be too rapid for some species to migrate or adapt to a changing food supply, so extinctions and a loss of biodiversity are likely (Thomas et al. 2004, Hannah et al. 2005, Malcolm et al. 2006).

Recent changes in UK species' phenology have been reported (Collinson & Sparks 2003, Sparks & Collinson 2006). Upland habitats are already under pressure from grazing livestock and atmospheric pollution and may be particularly sensitive to climate change impacts (Hossell et al. 2000). In addition, genetic diversity, and hence the adaptive capacity of some Arctic-alpine plant populations, such as the Snowdon lily, is low (Jones & Gliddon 1999). Reduction in snow cover affects snow buntings, which rely on insects in snow patches for food, and also some bryophyte species, which require snow as insulation against low winter temperature or as a source of moisture in spring (Hill et al. 1999).

Because key bioclimatic variables have a dominant influence, either directly as constraints or more usually indirectly by controlling food supply and breeding success, it is possible to classify and map bioclimatic zones. Bioclimate envelope modelling has been used to predict potential species' responses across Britain and Ireland (Berry et al. 2003, Dockerty et al. 2003, Araújo et al. 2005). This methodology clearly shows that the areas of greatest bioclimatic heterogeneity are in the uplands, corresponding to a wide variety of habitats (Hossell et al. 2003). In addition to projected range changes, these models show potential loss of important montane species due to reductions in suitable climate space (e.g. Black grouse, Capercaillie and Arctic-alpine plants such as Norwegian mugwort and twinflower) (Walmsley et al. 2007). Some rare species have 'nowhere to go', such as Snowdon lily, northern dart and icy rock moss, simply because they are already in isolated positions at their limit, and the possibility of more suitable, northerly/higher altitude locations does not exist (Hossell et al. 2000). Few studies report changes in ecosystem processes as a result of species loss and movement, although attention has been focussed on indicators of ecosystem response, notably keystone or focal species (e.g. Simberloff 1998). Similarly, questions remain about the potential for species to colonise new niches and the impact of invasive alien species.

Uplands include many 'open', semi-natural habitats found above the upper limits of agricultural enclosures, such as heaths, bogs, rough grasslands, and rocky habitats on screes, ledges and mountain slopes. These habitats have important interfaces with native woodlands and freshwaters, and support a wide range

of species. Climate change may affect disturbance regimes due to fire, pest outbreaks and severe storms. These influence species adaptation rates or succession processes, favouring some less-specialist invasive species so novel ecosystems should be expected (Hobbs et al. 2006). In addition, changes in the upland climate may result in asynchrony of breeding cycles and availability of food, as already noted for important bird species (Moss et al. 2001, Pearce-Higgins et al. 2005, Beale et al. 2006). Change is inevitable and may be non-linear; therefore, the challenge is to determine how to maintain essential and/or desired ecosystem functions (Hulme 2005). Change may also be sudden as loss of ecosystem resilience usually paves the way to catastrophic change (Scheffer et al. 2001).

Understanding climate-driven changes in freshwaters is particularly complex because ecological processes are affected by local meteorological, hydrological and nutrient regimes, as well as by indirect terrestrial impacts (Conlan et al. 2005). Upland freshwater flow regimes are often more highly variable, making detection of individual pressures more difficult, and, in general, they are less well served by monitoring data. Species population data are generally spatially limited and of short duration (e.g. Monk et al. 2006), except for high-profile species such as salmon. These data show declining upland salmon populations linked to climatic changes, affecting ability to grow and survival during time in the sea, as well as freshwater pollution (including acidification), habitat degradation, overexploitation and excess predation (e.g. Mills 2003, Davidson & Hazelwood 2005). Climate signals have also been found in the physical, chemical and biological characteristics of lakes (George et al. 2004), and in the abundance and community composition of invertebrate populations (Durance & Ormerod 2007; Fig. 3).

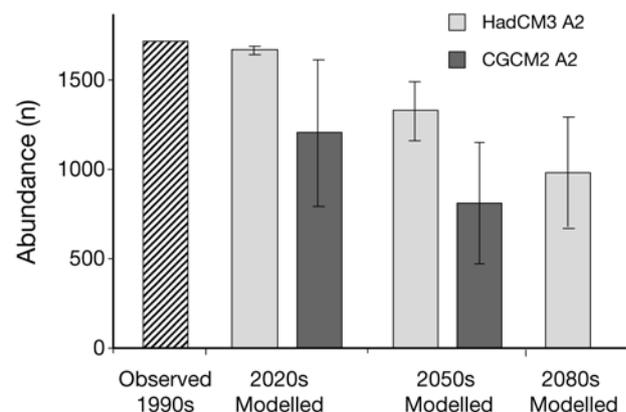


Fig. 3. Changes in abundance of freshwater invertebrates for upland Welsh streams using 2 General Circulation Models (GCMs) and 1 medium-high emission scenario (A2, UKCIP02) (adapted from Conlan et al. 2007). Error bars:  $\pm$ SE

Higher temperatures and reduced flows/lake volumes could increase eutrophication and exacerbate the effects of acid pollution (Schindler 2001). Nonetheless, distinguishing the range of natural variability in freshwater populations from human-induced trajectories of change driven by climate is of critical importance to the delivery of 'good ecological status' under the EU Water Framework and Habitats Directives (Wilby et al. 2006). Homogeneous records of species-level freshwater invertebrate data have improved understanding of ecological responses to changes in flow regime, but such data are relatively rare (Jackson & Füreder 2006, Monk et al. 2006). Monitoring systems will need to be reviewed as species adapt to new regional climatic gradients, flow regimes and water body status (Monk et al. 2006).

Hydrological process modelling suggests that UK upland freshwater ecosystems are particularly sensitive habitats (Conlan et al. 2007, Durance & Ormerod 2007). Climate change impacts have been explored in terms of fish growth rates (Davidson & Hazelwood 2005), loss of fish habitat due to rising water temperatures (Rahel et al. 1996), low flows (Conlan et al. 2007) and changing hydromorphology (Orr & Walsh 2006). It is also recognised that upland populations may be affected by changes in other (remote) habitats as well as *in situ* conditions. For example, rising ocean temperatures affect salmonid survival (Davidson & Hazelwood 2005), and upland stream temperature changes at critical points in the juvenile salmon life cycle have been associated with earlier out-migration (Langan et al. 2001). Questions remain about the relative importance of climate stressors compared with other pressures such as habitat degradation and diffuse pollution.

### 2.5. Land-use change

The UK uplands tend to be relatively sparsely populated, except where there is a legacy or ongoing use of natural resources, or where landscapes of high scenic value are accessed. Land use is therefore strongly related to socio-economic drivers, especially in agriculture and forestry, but also in some areas through grouse and deer management. Traditional use of land to provide food, fibre, wood, or other fuels is also increasingly combined with conservation or cultural landscape functions (recreational, aesthetic, or educational) that support a growing tourism industry. However, land use is also constrained by biophysical limitations, notably from the prevailing climate. By influencing land-use patterns, a changing climate can therefore indirectly affect hydrological, ecological, soil and geomorphological functions. As a consequence, exploration of land-use scenarios in conjunction with

climate scenarios can become an important component when considering upland vulnerability and adaptation options (Audsley et al. 2006). Land-use scenarios are conventionally developed from generic socio-economic scenarios, such as the IPCC (Intergovernmental Panel on Climate Change) special report on emissions scenarios (IPCC 2000, Rounsevell et al. 2005). Some modelling environments can integrate different land-use scenarios (e.g. afforestation or new crops), and these can be used to explore sensitivities to future change (e.g. Holman et al. 2005); these may be particularly useful when developing catchment-based programmes of measures under the Water Framework Directive (WFD).

Both UK and European uplands are expected to be affected by recent reforms of the Common Agricultural Policy (CAP), which may lead to reductions in overgrazing, but in the long term there is large uncertainty. The UK foot and mouth crisis in 2001 has had an impact on the numbers of grazing animals in the uplands. For example, sheep in the largely upland county of Cumbria were at 2.6 million in 2000, 1.2 million were then culled in 2001, but numbers had returned to 2 million by 2006; this is still a high grazing intensity. Approximately 8% of the total UK sheep flock were culled (Defra 2007a). Market developments are likely to be a more significant driver of agricultural land-use change than climate variation (Holman et al. 2005, Rounsevell et al. 2005), although water stress in southern Europe may lead to indirect climate advantages for agriculture in the UK (e.g. Edwards-Jones et al. 2007). Amelioration of the upland climate could provide new opportunities in some areas that are currently 'marginal', especially if they are close to urban markets, and can thus reduce 'food miles'. Similarly, the growth of 'carbon offsetting' schemes is encouraging further planting of forests in British uplands, and, in Scotland, there is a strategic aim to increase forestry coverage to 25% of the country. Conversely, if market opportunities decline, land 'abandonment' could become an increasingly realistic scenario.

Climate change is expected to stimulate upland tourism and hence the need for investment in the protection of vulnerable sites (McEvoy et al. 2006), although the potential for winter sports has notably declined (Harrison et al. 2001). Visitor access to 'unimproved' land has also been formalised as a legal right. Recent growth in the economic importance of tourism has not necessarily translated into economic gains for land managers or facilitated the achievement of conservation objectives. Indeed, declining employment in agriculture and natural resource management could constrain future conservation potential (Scottish Agricultural College 2002, English Nature 2003, HM Government 2006).

To alleviate these pressures, many UK uplands have stakeholder partnerships linked with planning authorities for National Parks or AONBs. Many of the partnerships are developing innovative schemes promoting long-term strategic planning for the future. However, large areas of uplands fall outside current statutory designations (including NSAs in Scotland) and are therefore neglected, sometimes because they are deemed to have insufficient biodiversity value or landscape quality, despite the presence of significant semi-natural habitat, organic soils and services to downstream areas. Furthermore, the stakeholder model for partnerships often excludes individuals or small communities who do not have a specific well-defined interest, aside from living or working in the area.

New economic niches can also drive land-use change. For instance, European policy promotes the use of biomass in order to achieve a doubling of renewable energy supply across the EU, providing wood fuel energy as well as carbon sequestration. The Community Biomass Action Plan (European Commission 2005) aims to increase total biomass production by 2010 to >40% of 2001 levels. This is likely to drive significant land-use change (e.g. Andersen et al. 2005) and possible displacement of pastoral agricultural activities, as areas most likely to be affected are marginal zones fringing the uplands where biomass could prove more economic than conventional agriculture. Uplands therefore have an emerging economic role in carbon sequestration and control of emissions through soil, vegetation and landscape management. Options include: (1) preserving healthy or restoring degraded peatlands, (2) improving soil cover and hence reducing erosion, (3) extending afforestation on marginal agricultural land and managing existing woodland to ensure a mixed age structure of trees, and (4) growing renewable crops for bio-energy or product replacement (such as construction grade timber, e.g. Gustavsson et al. 2006). There is, however, debate about how the production of energy crops could affect air quality, soils, water use and biodiversity (e.g. Heaton et al. 1999, House of Lords EU Committee 2006, Wiesenthal et al. 2006, Eriksson & Berg 2007). In particular, there is concern that reduced carbon emissions could be negated by rises in other greenhouse gases such as nitrous oxide and methane.

### 3. CURRENT POLICY AND EMERGING ISSUES

#### 3.1. Overview

Changes in temperature and precipitation will have a range of physical impacts on upland areas, with some potential benefits to growing seasons and opportuni-

ties for agriculture. However, these changes have a propensity to adversely affect the regulating ecosystem services uplands currently deliver; furthermore, changes in the frequency and intensity of extreme events could be outside the range of previous experience and overcome the resilience of ecosystems and damage their capacity to recover. Additional pressures could arise as a result of strategies to handle climate change, for example, increased demands for carbon and water storage. The uplands have always presented a particular set of policy challenges, for which some specific responses connected with economic development and conservation have been devised in the past. It is now time to look afresh at the policy agenda. This section considers the existing policy frameworks, how they can be used, and where they need strengthening to improve mitigation of climate change by the reduction of carbon emissions through land management and, secondly, to ameliorate the projected consequences of unavoidable climate change, such as floods and droughts. But there are limits. High rates of temperature change may exceed the adaptive capacity of natural or human systems in the uplands and could result in irreversible impacts: for example, loss of some protected montane habitats and potential loss of carbon storage facility in the soil. Facing the worst, were the ice sheets to melt, the uplands could constitute refuges for displaced people.

#### 3.2. Current upland policy strategy

Opportunities for policy interventions are often limited because the UK uplands, and even National Parks, are not state or communally owned. Ultimately, land management is a function of actions taken by land managers, and these are often related to land tenure. Although some water companies and private interest groups concerned with conservation are land owners, purchase of land for environmental management is rare. Land ownership is clearly an important factor when evaluating policy options, given that 70% of the UK's 24 million ha belongs to just 1% of the population. The largest institutional landowners are the Forestry Commission (1 million ha), followed by the Ministry of Defence (300 000 ha), the National Trust (222 000 ha), the Crown Estate (162 000 ha), and the Church of England (55 000 ha). Private estates are also significant landholders, with the largest owning 110 000 ha (Cahill 2001). A significant proportion of land is bought, not for its economic development potential, but for its status or investment value, reducing intervention opportunities still further. Land ownership in the uplands is hard to establish, although 50% of common land is in these areas, held mainly in

private ownership and with multiple grazing rights. The National Trust owns 150 000 ha in the uplands that is managed by tenants under essentially the same market pressures as other farmers in agriculturally marginal areas.

Public policy does have important entry points and levers through providing financial incentives, particularly the CAP, and also through regulation and control of water abstraction and discharge. Many significant policy frameworks that have an impact on upland land management are a function of separate policies in England, Scotland, Wales and Northern Ireland, although increasingly linked by the same external drivers (Table 2). These include the EU Water Framework Directive and the Floods Directive, the Habitats Directive, and international conventions, such as RAMSAR, or UNESCO's World Heritage Site designation (as proposed for the English Lake District). But these are not all yet 'climate proofed', that is, that the impacts of climate change or reduce greenhouse gas emissions have been reduced. At national levels, current public policy affecting uplands fall under sectoral policies for the

water cycle (management of existing droughts and floods), spatial planning (regional spatial strategies and local development frameworks), biodiversity (SSSIs and other designated sites), landscape conservation (National Parks and protected areas), agriculture and forestry. Several of these policy levers are discussed below in terms of the level of 'climate proofing' they provide.

### 3.3. Biodiversity policy

After the Second World War, public policy focused on improving economic productivity of the uplands through intensification of forestry and agricultural activities and conifer plantations, acid grasslands and so-called 'improved' hill pastures replaced many of the more natural upland habitats (Mackey et al. 1998). Major policy reversal started in the early 1990s; for example, Habitat Action Plans have been published as part of the UK Biodiversity Action Plan to reverse these trends and to re-establish healthy and biodiverse up-

Table 2. Existing policy tools for climate change adaptation in the uplands. CFMP: Catchment Flood Management Plan; CAMS: Catchment Abstraction Management Strategies; WFD: Water Framework Directive; SSSI: Sites of Special Scientific Interest; SAC: Special Areas of Conservation; SPA: Special Protection Areas; RAMSAR: International Convention on Wetlands; RD: Rural Development; RDR: Rural Development Regulation

Policy tool	Spatial scale	Horizon (review cycle)	Relevance to uplands
CFMP	Catchment	Continuous (6 yr)	Yes
CAMS	Catchment	Continuous (6 yr)	Yes
Water Resource Strategy	Region	25 yr (5 yr)	Yes
WFD	River Basin Management Plan (catchment and water body)	18 yr (6 yr)	Yes
Making space for water	Catchment	Continuous	Yes
Habitats and Birds Directive (SAC, SPA)	Full species range	6 yr	Yes
Biodiversity action plans	Full species range	3–5 yr	Yes
SSSI	Site based (10–15% of Britain)	No statutory requirement but target dates (2010)	Yes
RAMSAR wetland sites	Large sites	Continuous	Mainly Scotland
Areas of Outstanding Natural Beauty (E&W, National Scenic Areas) (Scotland) — similar to National Parks	Large sites	Continuous (5 yr)	Limited number
Forestry and woodland grants (RDR)	Field — catchment	Long-term	Yes
National Nature Reserves	Site, often designated SSSI	Continuous (6 yr)	Limited area
Agri-environment and associated schemes	Farm scale	~10 yr	Yes
Proposed uplands reward scheme (RDR)	Farm scale	2007–2013	Yes
National Parks	Most of uplands of England and Wales (2 in Scotland)	Continuous (5 yr)	Yes
Regional spatial strategy (not National Parks)	Regions	10–20 yr	Yes
National Nature Reserves	Site, often designated SSSI	Continuous (6 yr)	Limited
Strategic environmental assessment (EU Directive)	Limited to some larger developments	Continuous	Limited

lands — the UK Government's target is 95 % in favourable condition by 2010 (English Nature 2003). But there is a long way to go. A report on the status of SSSI sites in England found that 42 % are in unfavourable condition, and most of these are in the uplands (English Nature 2003, Williams 2006). Primary reasons cited for poor condition were overgrazing (45 %), inappropriate burning (24 %) and drainage (9 %). It was also acknowledged that the effects of atmospheric pollution, particularly on bogs, are not fully understood. Nearly 20 % of English SSSIs are on common land, where multiple ownership and grazing rights make land management agreements particularly difficult to coordinate — common land accounts for 35 % of 'moorland' and only 20 % of such areas have joined agri-environment schemes (Defra 2001).

Most uplands in England and Wales are covered by designations, but these have had mixed success as evidenced by the status of SSSIs. National Parks have acted to limit development in rural areas, but have had less impact on land conservation and resource management, despite having jurisdiction over much of the uplands and being well placed to implement more integrated adaptation strategies. Ensuring that all conservation-designated sites are in the best possible condition is most likely to improve ecosystem resilience and enhance adaptive capacity. Efforts to reduce overgrazing by co-ordinated agreements are being made, but are likely to take several years to have a discernable impact on biodiversity and may be threatened by greater economic returns from agriculture in the future. Other interventions such as protection and restoration of peatlands by drain blocking have been targeted at schemes and will require additional resources to become more widespread.

Guiding principles for conserving biodiversity in a changing climate have been identified (Hopkins et al. 2007), but resources to enact change are currently very limited, particularly for enhancing biodiversity as opposed to preventing deterioration (Piper et al. 2006). Concerns about migration potential and habitat fragmentation have led to calls for landscape approaches to habitat restoration, but the cost effectiveness and biodiversity gains of site-based conservation versus countrywide initiatives has yet to be established. This is partly due to a lack of systematic recording and availability of data from site-based conservation in the UK (Gaston et al. 2006) and evidence of 'what works' (Sutherland 2006). Upland habitats are in poor condition and are, by definition, isolated, but generally less fragmented than lowland habitats with the exception of native woodland (English Nature 2003). Undertaking defragmentation by connecting existing habitats along climatic and species migration axes could involve the creation of networks of protected areas and

land in agri-environment schemes (e.g. Latham et al. 2004, Latham 2006), particularly where these exploit natural gradients (Hulme 2005) or landscape units (Table 3). Habitat creation is already a statutory requirement for major flood defence schemes in the UK and provides an additional opportunity.

The impact of climate change on freshwater ecosystems is highly uncertain and the subject of ongoing research (e.g. Conlan et al. 2007). The most effective adaptation option may be to enhance ecosystem resilience by reducing the impact of other co-stressors (Tables 3 and 4). However, we currently lack a full inventory of freshwater habitat extent and condition. Maps are available for terrestrial habitats at a range of spatial scales and levels of accuracy (e.g. landcover map [Fuller et al. 2002], habitat survey of Wales [Howe et al. 2005]). Although similar data are not available for freshwaters, site information is held for approximately 5000 sites from river habitat surveys (Raven et al. 1998), but these data need to be integrated with physical channel typologies to allow wider inferences to be made (Orr & Walsh 2006).

Although a large number of species are likely to become extinct through loss of climate space, in many areas, a greater number continue to be threatened by land-use practices (Hannah et al. 2005). Conversely, other species may potentially gain from an expansion of their climate space, depending on suitable habitat being available (Walmsley et al. 2007). Thus, adaptation measures might include removal of physical barriers to migration, assisted natural recovery from overgrazing or channelisation, or reductions in diffuse pollution. However, the long-term conservation of key species such as salmon will depend on whether suitable climate space will be available; loss of lowland habitats may make upland sites even more valuable. Other measures can represent 'no regrets' options, for example, increasing the amount of riparian woodland, particularly in headwater streams could help buffer the effects of increasing water temperatures (Langan et al. 2001, Caissie 2006) and reduce sediment delivery (Lane et al. 2008). River restoration activities, particularly those that promote reconnection of channels with floodplains, can increase sediment deposition on floodplains, enhance storage of eroded soil and nutrients, reduce downstream flooding, improve in-channel habitats, and re-create sustainable floodplain wetlands (e.g. Shankman & Pugh 1992, Erskine et al. 1999, Tockner et al. 1999). Creation of floodplain woodlands may also increase medium and long-term carbon sequestration (Robertson et al. 1999) and provide habitat to enable ecological migration as well as economic land uses where other types of crop production may be constrained (for example, by more frequent flooding). In some cases, conservation objectives might conflict

Table 3. Landscape units linked to land management options

Landscape unit	Land uses	Pressures	Potential options
Uplands	All	All	Improve condition
Fell tops	Grazing, recreation	Overgrazing and trampling leading to erosion	Reduce grazing, repair footpaths
Upland gullies	Grazing, woodland	Erosion	Exclude stock, plant woodland
Hillslopes	Grazing, woodland, forestry	Drainage, grazing	Block drainage, plant woodland
Upland confined floodplains	Grazing	Drainage	Block drainage
Blanket peat	Grazing, forestry, moorland sports	Grazing, footpath erosion, fire	Reduce or remove grazing, block gullies and drains, manage fire risk
Gorges	Grazing, woodland		Retain, manage and extend woodland
Enclosed land	Grazing	Sub-surface drainage, diffuse pollution	Field-scale soil and runoff management (buffer strips, small wetlands, ditch management, location of livestock facilities)
Floodplains	Grazing, silage, limited crops	Embankments, revetments, drainage, intensive agriculture	Channel restoration, floodplain reconnection, floodplain woodland, wetland creation
Riparian zones	Mixed	Stock damage to banks, diffuse pollution	Create buffer zones, riparian woodland, floodplain woodland, floodplain meadows
River channels		Channelisation, abstraction, pollution	Disconnect drains, maintain flow levels
Urban/settlement/tourist facilities		Sewerage, abstraction, runoff, visitor pressure	Management of private sewerage treatment, composting toilets, ban on phosphate detergents, encourage better water use
Mines and quarries		Abandoned, unstable and contaminated sediment and runoff	Stabilisation or removal of contaminated and mobile sediment sources, management of contaminated mine runoff

with climate change-related opportunities, for example, where intensive agricultural activities expand into the upland fringe due to a longer growing season or longer access period when soils are in workable condition (e.g. Carter & Parry 1994). Resources for river restoration are currently limited and are largely available through capital works aimed at reducing flood risk; thus, being captured under water policy.

### 3.4. Land-use policy

The main land-use driver in the EU is the CAP, with its objectives to increase agricultural productivity, to ensure a fair standard of living for rural communities and to stabilise markets. Financial support for farmers is based on 2 'pillars', which influence production decisions. Pillar 1 covers market related subsidies; Pillar 2 covers rural development and sustainable use of resources in rural areas, providing assistance to difficult farming areas. Member states can select from a range of options in order to target specific needs (Dworak et al. 2005).

Current European policy on climate change takes into account the role of agriculture for climate change mitigation and recognises that the agricultural sector

will have to adapt to secure food production and sustain the livelihoods of rural areas. Despite the lack of explicit references to adaptation in the current framework of the CAP, adaptation concerns might yet be integrated and supported through existing instruments. Before CAP reform, Pillar 1 was used to support change through product-related (coupled) payments without necessarily considering climatic or other environmental conditions. By introducing 'decoupling' as part of the 2003 CAP reform, market-based incentives became more relevant. Income support is still provided to the agricultural community, but its influence on production decisions is reduced, which leads to a larger role for the market in the determination of prices.

The new (2005) European Rural Development Regulation (RDR) also provides opportunities to strengthen the contribution of the CAP in combating climate change and supporting adaptation through Pillar 2. Climate change mitigation and adaptation are acknowledged as community priorities in the strategic guidelines for rural development, and member states are encouraged to incorporate appropriate actions in rural development (RD) programmes to address these priorities. Measures include: (1) direct support of new equipment needed for adaptation (e.g. Article 26 RDR modernisation of agricultural holdings); (2) support for the development of

Table 4. Range of benefits of adaptive measures. DOC: dissolved organic carbon; HD: Habitats and Birds Directive; HLS: Higher Level agri-environment Scheme; other abbreviations, see Table 2

Action	Mitigation		Adaptation				Policy tools WFD, HD	
	Reduce soil C loss	Improve sequestration	Improve water holding capacity of soil	Reduce erosion	Reduce runoff	Improve ecological adaptive capacity		Reduce diffuse pollution
Grip blocking	Probably (DOC reduction 60–70%)	Yes	Yes	Yes	Yes	Yes	Yes	SSSI, SAC, stewardship, HLS
Woodland	Not initially but gains in biomass, soil stability	Yes	Yes	Yes	Yes	Yes	Yes	Woodland grant scheme and Forestry Commission
Destocking uplands	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Land purchase, Common Land agreements, HLS stewardship
Changes in burning practice	Unclear	Unclear	No	A bit	On steep slopes	Possibly	Maybe	Stakeholder partnerships and best practice guidance, code of practice
Revegetation of bare peat	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Remove stock, may need land purchase, repair footpaths
Reduced fertiliser application	Unclear	No	–	–	–	Yes	Yes	Stakeholder partnerships and best practice guidance
Wetland creation (from grassland, arable)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Agri-env. schemes, HLS, making space for water
Mine waste removal or stabilisation	–	–	Yes	–	–	Yes	Yes	Ownership may be in question, forthcoming EU Minewaters Directive (2007/2008)

new products, processes and technologies in the agricultural, food and forestry sector (Article 29 RDR); and (3) educational measures (e.g. Article 22 RDR and Article 58 RDR). In addition, the 2007 to 2013 RDR provides an opportunity to set up measures that aim to restore agricultural production damaged by 'natural' disasters (e.g. flooding) and introducing appropriate prevention actions (Article 20 [b] [Vi] RDR). The commission has also developed possibilities to introduce new risk and crisis management measures into the menu of rural development policy. It suggests instruments such as financial contributions to premiums paid by farmers for insurance against natural disaster, support for mutual funds in the agricultural sector, and a generalised approach to respond to income crises. Awareness of risk exposure to climate change through the increasing frequencies of extreme events might provide an additional stimulus to further pursue such approaches.

Depending on the priorities set by the member states, measures provided by the new RDR can therefore be used to encourage the adaptation process. It is important to note that the total share of CAP funding spent on Pillar 2 is still small compared to the sums available under Pillar 1. This should be considered when assessing the potential options to adapt to climate change in the agricultural sector.

The UK has provided support to upland areas since 1975 through the EU Less Favoured Areas Support Scheme to support farming where production conditions are difficult. Most of this land is used for either rough or improved grazing. New schemes are now being introduced with a broader suite of environmental considerations that could include adaptation and mitigation responses by supporting high water quality, reducing flood risk, ameliorating droughts, encouraging carbon sequestration and supporting wildlife. They may need to be sufficiently flexible to enable targeting and to take local conditions into account (e.g. Tables 3 & 4). A range of options are available (Fig. 4) with obvious cost implications, some of which may become more 'justified' or cost effective under future climate change.

Ultimately, socio-economic factors will dictate the recognition of priority measures at the regional/local level. It is therefore imperative that climate change responses are directly included within these deliberations and therefore targeted within that regional/local land-use context, rather than implemented as generic or separate schemes. Evidence from implementation of agri-environmental schemes has shown that neglecting this cultural context tends to result in limited success (e.g. Burton et al. 2008).

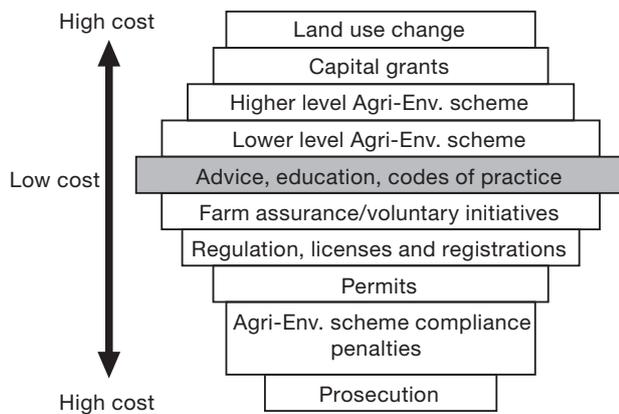


Fig. 4. Toolkit for change in the agricultural sector (source: H. Wakeham, Environment Agency, pers. comm.)

Increasingly, land use is likely to be affected by policies aimed at mitigating climate change. Carbon, methane and nitrous oxide emissions from land use are receiving greater attention both globally and in the UK (HM Government 2006, Stern 2006). Work is underway in the UK and EU to see whether market mechanisms such as a trading scheme can be used within the agricultural sector. Best practice guidance could be established, for example, through Carbon Aware Land Management (CALM) and the use of simple farm-scale carbon accounting tools (e.g. Viner et al. 2006). However, verification of soil carbon sequestration within the context of the national targets set within the United Nations Framework Convention on Climate Change (UNFCCC) is not straightforward (Dawson & Smith 2008), and controlling methane or nitrous oxide emissions is extremely difficult with so many sources involved (Smith et al. 2007a). Nonetheless, the opportunities for generating revenue from carbon management should not be ignored. Globally, there is increased pressure for land-use stocks to be brought within a post-2012 climate deal. The estimated environmental cost of soil organic carbon loss in 1996 was £106 million (Pretty et al. 2000). Overall, there is limited scope to enhance the sequestration potential of uplands. Two possibilities include the growing of biofuel and biomass crops on the upland fringe, assuming sufficient water availability, and woodland or forestry planting and management. Wood production may provide the best carbon savings when used as a substitute for more CO<sub>2</sub> intensive material manufacture. Perhaps more critical is to ensure steps are taken to protect existing carbon stores by stopping bad practice such as over-grazing, drainage, or burning. Furthermore, within the clear imperative of emission-reduction targets, there is also an over-riding need that mitigation schemes do not significantly hinder effective adaptation strategies, for example, that areas of new woodland are also integrated with biodiversity and water resource objectives.

### 3.5. Water policy

In England and Wales water abstraction is granted under licence and is regulated through Catchment Abstraction Management Strategies (CAMS). These are reviewed every 5 yr within a larger Water Resource Strategy, which looks 25 yr ahead and is a mechanism for climate change adaptation. At the current time the majority of licence abstractions are granted indefinitely, although the Environment Agency has powers to revoke these. This may become particularly significant in upland areas that are key water resource zones and often have small water supplies that may be unsustainable under both future climate change and the new requirement to achieve good ecological status (GES) in all water bodies under the EU WFD.

The main policy tool for flood risk management in England and Wales is now the Catchment Flood Management Plan (CFMP). This flexible framework will identify broad policies for sustainable flood risk management that make sense in the context of a whole catchment and for the long term (50 to 100 yr). Climate and land-use changes can be built into considerations of how flood risk may change within the catchment. Both CAMS and CFMP will be used in River Basin District Plans (RBMPs) to implement the WFD and collectively present a significant opportunity to consider climate change adaptation measures at a range of spatial scales.

Abstraction licensing and strategic flood risk management have not formed part of the policy framework in Scotland prior to implementation of the WFD. New regulation has been established specifically aimed at delivery of the WFD (Water Environment [Controlled Activities] Regulations 2005 [CAR] and the forthcoming Floods Bill). Historically, voluntary Flood Appraisal Groups (now called Flood Liaison and Advice Groups) influenced flood policies and decision making via local government authorities, but their powers were non-statutory and they did not usually extend to non-agricultural land or whole catchments (Scottish Executive 2004).

In the UK, cross sectoral 'Making Space for Water' policies advocate catchment-wide management as an alternative to hard engineering solutions for local flood risk management (Defra 2005a). More research is needed on the costs and benefits of land management as a tool for reducing flooding. Consideration needs to be given to the landscape and catchment-scale effectiveness of local interventions (e.g. Lane et al. 2003, Defra 2005b). Cost-benefit analysis should consider the full range of environmental gains from actions aimed primarily at ameliorating flood impacts (Table 4).

### 3.6. Integrating policy challenges

Protecting the ecosystem services provided by the uplands will require adaptation planning at national and strategic levels, whilst implementation of adaptive measures needs to be undertaken at more local scales, but in an integrated way. This requires: (1) improved scientific information, for example, validated impact/adaptation models and downscaled climate change scenarios; (2) scoping of adaptation options and integrated assessment of outcomes; and (3) guidance for environmental managers and delivery mechanisms for achieving positive adaptation.

No single agency has responsibility for climate change adaptation, and integrated delivery may best be achieved through existing stakeholder partnerships (including rural development agencies) and new ways of working (e.g. Edwards Jones et al. 2007). The greatest opportunities through existing mechanisms, in terms of scope and area are perhaps through WFD and National Parks (see Table 2), because these have an integrated agenda and strong links with spatial planning frameworks. The WFD options appraisal stage will enable assessment of the socio-economic implications of adopting particular measures and the risks of 'doing nothing'.

The WFD RBMPs may provide a structure for inter-disciplinary and inter-agency working (Wilby et al. 2006), but need to be supported by information on climate change impacts at regional and catchment scales. Organisations such as river trusts are now widespread in the UK (see [www.associationofrivertrusts.org.uk](http://www.associationofrivertrusts.org.uk)), and are well placed to effect changes at catchment scales, because many already have active stakeholder partnerships based upon a shared 'vision' of the future and direct influence over land management. Community involvement in such initiatives is also critical and can lead to greater awareness and acceptance of change (e.g. [www.lake-district.gov.uk/bassenthwaite/](http://www.lake-district.gov.uk/bassenthwaite/) for the Bassenthwaite Restoration Programme).

Key challenges include reducing the number of grazing animals, addressing concerns and perceptions about the invasion of scrub vegetation and limited resources for biodiversity, habitat conservation and river restoration. Some issues could be addressed by research that identifies the benefits of upland management to other sectors such as water colour treatment likely to become increasingly expensive and difficult under climate change (Worrall & Burt 2005). Voluntary and subsidised agri-environment schemes may be limited in terms of scale of effectiveness unless there is scope for land purchase or other economic returns from managing land just for the water resource for example. There are currently few policy tools that link terrestrial and freshwater processes (Tables 2 & 3); the

WFD is largely aspirational with respect to land use, but is likely to be strengthened by the EU Thematic Strategy for Soil Protection (adopted in 2006), which includes a Soils Directive.

The water industry in England and Wales is tightly regulated and, whilst traditionally focussed on 'end of pipe solutions', there is increasingly a move towards 'catchment solutions' to long-term water-quality problems. However, the mechanisms for paying for catchment solutions would require significant change for these to become widespread.

Ultimately, water management is heavily regulated, but land management is not. Climate-driven risks to the largely free or cheap services uplands deliver may require new economic instruments to provide these services in the future.

## 4. RESEARCH PRIORITIES

Development of robust, evidence-based, best practice and guidance on climate change adaptation in the uplands will be aided by addressing knowledge gaps in: (1) soil carbon biophysical properties, carbon fluxes, climate and land-use drivers; (2) the effectiveness of land management in reducing hazards such as flooding, drought and erosion; and (3) the impacts of climate change on freshwater ecosystems. These themes should further address how and where adaptive measures will have the greatest impact on reducing vulnerability to climate change (e.g. Lane et al. 2003) and how we can ensure that climate change impacts are 'detectable' and that gains from land management intervention can be demonstrated. In addition to monitoring and modelling of current processes, future projections of change, e.g. using scenario analysis (climate and land use), are important for developing anticipatory adaptation responses. Demonstration projects may help to investigate resilience, communicate best practice and manage for uncertainty.

The carbon gains, losses and sequestration potential of land-use types are broadly understood (Table 5), although better quantification is needed (Bellamy et al. 2005, Kuzyakov 2006, Lund 2006). There could be substantial economic gains for land managers if carbon sequestration can be verified. Tools are needed to scale up field- and farm-scale sequestration to landscape and catchment scales. The carbon uptake also needs to be durable. Changes in management may only retard carbon loss from peatlands in the short term (Cleary et al. 2005), particularly if long-term changes in climate lead to peatland degradation. However, improving the condition and preventing further degradation of existing peatlands may secure the present carbon stock and favour other ecosystem services.

Table 5. Carbon sequestration and storage potential from different land use, land-use conversion and management changes (all data from a variety of sources reported in Dawson & Smith [2008], large uncertainties are attached to these). -: soil C loss; +: soil C gain

Land use	Carbon ( $10^3 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ )
<b>Storage potential</b>	
Native vegetation grassland	0.35
Peatland cultivation	-2.2 to -5.4
Moorland to grassland	-0.9 to -1.1
Grassland to afforestation	0.1
Wetland restoration	0.1–1.0
Revegetation on wetlands from grassland	0.8–3.9
Grassland to arable	-1.0 to -1.7
Forestry to grassland	-0.1
<b>Sequestration potential</b>	
UK peatland, natural accumulation (undrained)	0.2–0.5 (long-term may be 0.7)
Short rotation coppice	0.091–0.180
Marginal crop to forest	0.033–0.119
Increasing growth of construction timber	0.138–0.190
Intensification of nutrient-poor grassland	-0.9 to 1.1

Verification and economic analysis of multiple benefits could strengthen incentives to protect uplands.

In addition to research on soil biophysical processes, continuous measurements of DOC and POC are needed to monitor soil erosion and the outcomes of land management decisions. Integrating phosphorus and carbon monitoring would also be beneficial for assessing compliance with WFD, the Habitats Directive and the forthcoming Soils Directive. There may be opportunities here to link with monitoring under Defra's catchment sensitive farming (CSF) initiative. This could provide more data on the impact of land use as there are currently large uncertainties associated with the methodology for measuring carbon loss by *in situ* soil sampling. In addition, more research is required on the loss of carbon from mineral soils (Quinton et al. 2006), as these may be under-represented in Defra's database (Bellamy et al. 2005).

UK uplands have a high proportion of sites designated for conservation and special protection; more focussed monitoring could help assess biodiversity and ecological response to climate under constant management regimes in a cost-effective way (Sutherland 2006). The data could help produce climate-sensitive landscape ecology models to indicate where habitat networks could be improved. Data on freshwater ecology, temperature, water quality, hydrology and physical habitat could be integrated for climate-sensitivity testing. But there is also a need to scale up understanding of climate change impacts on freshwaters in order to make national and regional strategic assessments and ensure resources are effectively targeted.

## 5. CONCLUDING REMARKS

The present condition of many UK uplands and the increasing pressures expected under climate change are cause for concern. The present review highlights the need for better management, particularly with regard to the linkages between terrestrial and freshwater environments. Constraints and opportunities for doing so within existing policy frameworks and research priorities have been discussed. Some of the wider limitations to effective climate change mitigation and adaptation in the uplands include a lack of spatial planning in the rural environment, regulatory control of land use and management, recognition for services delivered by uplands to downstream areas and viable economic incentives to protect these areas that are also consistent with their cultural contexts. A general policy

framework to integrate and tackle these issues in the UK has recently been proposed through an Ecosystems Services Action Plan (Defra 2007b). Coupled with development of climate change policy on both mitigation and adaptation, incentivised through the Climate Change Bill, there is scope for a major re-framing of upland strategies. This opportunity should be taken.

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