Review of the historical environmental changes in the UK uplands relevant to management and policy

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Summary

1. This review draws together information on the historical processes and drivers which underlie the current state of the uplands in order to illustrate the range of accumulated legacies which threaten or enhance the resilience of upland habitats and rural communities. The target audience for the review includes ecologists, conservationists (in research and practice), land managers and policy-makers.
2. *Why look back?* Short-term (annual to decadal) perspectives remain pre-eminent in policy and management, despite frequent mention of the role of the past in shaping current landscapes and values, and the time-implications underlying many ecological, conservation, restoration and policy issues.
    - A longer-term perspective (centuries to millennia) shows that the origins of many trends of current management importance lie well beyond the duration of observational records.
    - By providing a critical evidence-base for assessing naturalness, disentangling natural and cultural drivers, and establishing the limits of acceptable change underpinning ecological thresholds, a historical perspective can be used to test the applicability and sensitivity of baselines and targets derived from short-term knowledge. This provides a more scientifically and socially defensible and robust basis for making sustainable policy and management decisions.
3. *What are the barriers?* At present, inevitable constraints on time and funding, institutional and communication barriers, limits to the expertise of individuals, and the perceived limitations of long-term data limit the extent of information sharing and opportunities for discussion and collaboration with those involved in policy and ecology. This review is a first attempt to draw together relevant long-term information in order to raise awareness of the potential for collaboration in the context of the UK uplands.
4. *Why the uplands?* Upland environments are sensitive to change and are an important environmental, conservation, social and economic resource on national and global levels. The future of the UK uplands is uncertain owing to changes in agricultural production, energy provision and climate, pressures which need to be balanced with increased recreational use and growing conservation concern. It is therefore essential to foster long-term sustainable management strategies which reflect the full range of threats and uncertainties.
5. *Review structure & sources*: The review is structured around issues of current concern, derived from policy documents, journal articles and information on stakeholder views (especially land managers). The long-term information presented derives from published palaeoenvironmental and historical articles and reports relevant to upland environmental, habitat and management change. The review is divided into five main thematic sections, each beginning with a summary of the key implications for management and policy.
6. *Theme 1*: Farming in fluctuation - moorland management & dynamics
    - Baselines must be influenced by evidence that the intensity and cumulative impact of grazing and burning has increased to unprecedented levels over the course of the 19th and 20th centuries, in addition to erosion and pollution legacies. Over-reliance on 20th century baselines is thus often inappropriate.
    - Heather losses are far more prolonged than conventional ecological records suggest, with implications for restoration and biodiversity, although not all heather-dominated systems have a long history. Grasses are a natural part of many moorland systems, but a former grass/heath balance has been lost through management intensification over the last two centuries.

- More work is required to understand the extent of past variations in burning and grazing regimes and their effects on current moorland mosaics, floristic and faunal diversity.

7. *Theme 2*: Degraded lands & thresholds of stability
    - Some peat- and moorland sites may have crossed thresholds of stability as the current extent of erosion and pollution lies outside historic limits of variability.
    - The risk of drought damage and associated release of pollutants stored in organic soils and peats is particularly high in more marginal and damaged moors, and the likelihood of recovery is difficult to predict due to complex feedback mechanisms between climate, erosion and management. Novel strategies and alternative restoration targets need to be considered.
    - Sensitive management is critical for maintaining a favourable carbon balance and preventing the release of stored pollutants, although this is hampered by the shortage of data on the long-term effects of management on C balance.
8. *Theme 3*: Upland diversity – the legacy & role of management
    - Cultural legacies are so intrinsic to current upland values that 'good' agricultural management is essential for achieving biodiversity and restoration goals.
    - Policy has a key role since much attrition over the last c.250 years at least has been driven by market opportunity and subsidy.
    - Abandonment and 'wild land' are not logical alternatives to agricultural management or mismanagement, as the outcomes are inherently unpredictable and idealised in ecosystems shaped by centuries of human activity.
9. *Theme 4*: Resilience & restoration management
    - Misconceptions and value judgements detrimental to the resilience and conservation values of peat and woodland habitats are inherent in restoration. Management visions based on current appearances and narrow definitions of 'normal' conditions are restrictive and threaten the resilience of the habitats they seek to restore and maintain.
    - Uncertainties relating to future climatic impacts on peatlands and woodlands are not sufficiently integrated into current restoration strategies.
10. *Theme 5*: Climatic & economic change: rural risk & resilience
    - Analysis of past climatic risk to farming emphasises the extent to which economics outweighs climate as a driver of upland agriculture.
    - The reliance of agricultural communities on economic incentives and support mechanisms limits opportunities for local diversification and increases the vulnerability of rural communities.
11. *General conclusions*:
    - A longer-term perspective emphasises the extent to which 20th century baselines, and narrow targets and norms underestimate the extent of ecological change and the vulnerability of many upland habitats.
    - Due to the accumulated impacts of past management, climatic and pollution change, some habitats may already have crossed critical thresholds, and may not respond as expected to management, making it increasingly impractical to maintain or restore current values.
    - Management based on misguided views threatens the inherent adaptability and flexibility of upland ecosystems. Growing recognition of the need to manage for change requires more flexible definitions, and realistic targets which can accommodate change and distinguish between critical thresholds and acceptable limits of variability.

- Many positive attributes derive explicitly from cultural interactions, so management strategies (rather than mimicking natural processes) are essential for maintaining habitat continuity. This provides a positive foundation for incorporating conservation into agri-environmental schemes. By contrast, uncertainty is implicit in non-intervention and ‘naturalistic’ management strategies.
- Routine use of long-term sedimentary records in current management and policy regarding freshwater lakes provides a model for the wider integration of long-term sources to other environments.
- There is scope and impetus for better communication between long- and short-term sources of information: an informed approach requires evidence which spans diverse spatial and temporal scales, and this can only be achieved by combining the strengths of different disciplines and practical knowledge to minimise risks and uncertainties that face upland ecosystems, rural communities and the wider populace who rely on the products and ecosystem services derived from them.

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Aims and objectives of the review

- The primary objective of this review is to make existing information on the historical processes and drivers which underlie the current state of the uplands available to a wider audience, including ecologists and conservationists (in applied and research spheres), land managers and policy-makers. To best serve this wide target audience, each thematic section of the review begins with a summary of the key findings, before reviewing the underlying evidence.
- The review deals with interactions between environmental, ecological and management changes in the UK uplands over the last c.300-500 years. The uplands are readily acknowledged to be cultural landscapes, so the last few hundred years (rather than pre-anthropogenic, 'natural' ecosystems) are of most direct relevance to the current state of the UK moors and mountains. The review does not summarise the environmental history of the UK or of moorlands, for which readers are referred to other sources (*e.g.* Stevenson & Birks 1995, Smout 2000, Simmons 2001, 2003).
- Understanding the historical trajectories shaping current conditions is a secure starting point for responding to future change since the legacies of past human activities and climate change affect the status, sensitivity and resilience of current upland habitats, but the exact nature of these interactions is seldom used to inform policy or management decisions.
- The review also indicates gaps in our current understanding of how environmental change and land management, in particular, have shaped the uplands and the implications for management.

Why the uplands?

'*Behind the face of scenic beauty… the English uplands are suffering from economic crisis, social change and environmental degradation*' (English Nature 2001)

Upland environments and their future are important for environmental and socio-economic reasons: they are sensitive to environmental change and serve a wide range of values and uses (*e.g.* Bragg & Tallis 2001, Milne & Hartley 2001, Moore 2002). UK peat- and heathlands are an important environmental, conservation, social and economic resource on national and global levels (Thompson *et al*. 1995b, Tallis 1998, Moore 2002). As a result of increased recreational use and conservation concern, upland ecosystems are becoming more highly valued, but they and rural communities are also facing significant threats and uncertainties, associated with changes in agricultural production, energy provision and climate (*e.g.* Foresight 2008). It is therefore essential to minimise uncertainties involved in monitoring and managing future change, especially in view of the changes, instabilities and damage already evident in many upland areas. Numerous recent and ongoing reviews of upland policy and management are indicative of the pressing need to deal with these threats (*e.g.* Defra 2006, Land Use Consultants *et al*. 2006, Reid 2007, Royal Society for the Protection of Birds 2007, Royal Society of Edinburgh Inquiry 2007).

In ecological terms, the uplands are generally defined as the areas lying above the upper limits of improved or enclosed agricultural ground. However, this belies the importance and extent of hill management and the diversity contributed by adjacent and interspersed farmland, particularly in northern Britain, where the higher latitude compresses altitudinal effects, lowering the upper limits of many upland communities. In addition, rural communities and land management are integral to the origin, character and value of these areas and, for the purposes of this report, relatively unimproved hill ground and upland farms are therefore included in the definition of the uplands.

Why look back?

‘*Management of our environment must be informed by past, present, and predicted change*.’ (Scottish Natural Heritage 2002a)

Policy and conservation documents frequently acknowledge the role of past land management in altering and shaping our current landscapes and conservation values, but detailed knowledge of these past legacies is seldom used to inform current policy or set appropriate baselines, beyond the sphere of built heritage. Longer-term evidence indicates that the origins of many trends of current management importance lie well beyond the duration of observational records and over-reliance on shorter-term views can generate a ‘shifting baseline syndrome’: the progressive change in standards as each new generation bases their expectations on their own experience (Pauly 1995), or on the prevailing political situation. In addition to the uncertainties present in ecology and the value judgements and myths inherent in conservation (Sutherland *et al*. 2004), this imposes the very real risk of generating inappropriate targets or insensitive monitoring standards which may bias future policy and management, and even the future sustainability or resilience of upland ecosystems. In this context, short-term is defined as ranging from seasonal to the last c.60 years.

With the need to meet targets and adapt to climatic changes, the speed and magnitude of which are unparalleled in our history or that of most upland systems (Tallis 1998, Huntley & Baxter 2002), we do not have the luxury of being able to learn from mistakes or manage changes as they occur.

- A long-term view (defined as ranging from 100-10000 years) can allow the benefits of hindsight to be incorporated into upland management as the past effectively forms a series of ‘natural experiments’, which provide more opportunities to test hypotheses and received wisdom regarding ecological responses to change than is possible through adaptive or experimental management (cf. Sutherland *et al*. 2004, Sutherland 2006).
- Long-term perspectives can help assess naturalness, the vulnerability and resilience of current habitats or ecosystems, the status of endangered and invasive species, and can indicate processes of change, including forcing and feedback mechanisms (*e.g.* Birks 1996, Bragg & Tallis 2001, Ellis & Tallis 2001, Gillson & Willis 2004, Dearing *et al*. 2006, Holden *et al*. 2007a). They also help define relevant timescales and disentangle natural or ‘normal’ variability from climatic and cultural trends, both of which are impossible using short-term data, and establish the processes and limits of acceptable change underpinning ecological resilience and thresholds of concern (Swetnam *et al*. 1999, Parr *et al*. 2003, Willis *et al*. 2005, Willis & Birks 2006).
- A historical perspective can thus be used to test the applicability and sensitivity of currently accepted baselines, indicators and targets derived from short-term knowledge, and provide a greater appreciation of the extent of natural and human-induced variability, in space and time (Huntley 1991, Willis *et al*. 2005).
- This approach can provide a more scientifically and socially defensible and robust basis for making decisions about sustainable development, land management, economic viability, conservation and restoration (Barber 1993, Birks 1996, Charman 1997, Chambers *et al*. 2006, Willis *et al*. 2007b), so helping to reduce uncertainties and providing a tool for understanding vulnerability, predicting

responses to change and validating ecosystem modelling (*e.g.* Swetnam *et al*. 1999, Anderson *et al*. 2006, Dearing *et al*. 2006).

- While acknowledging that there may be no past analogues for many current environmental and socio-economic issues, all of these concepts provide valuable insights and guidance for future sustainability.
- Longer perspectives can also provide a forum for debate about best practice, providing an opportunity to involve a wider stakeholder audience. Land managers, for example, which frequently feel excluded and frustrated by the emphasis on science in conservation, yet are also the vehicle for carrying out conservation management (Johnston & Soulsby 2006).

What are the obstacles?
There is a sizeable and growing literature advocating the importance and value of incorporating longer-term palaeoecological perspectives into ecology, but this has yet to become commonplace in conservation and sustainable management (*e.g.* Foster *et al*. 1990, Birks 1996, Parr *et al*. 2003, Dearing *et al*. 2006, Willis & Birks 2006, Willis *et al*. 2007a). This stems from a combination of the disjunctions between policy, research and practice (including communication), inevitable constraints on time and funding, limits to the expertise of individuals (which is usually confined to a single discipline) and the perceived imprecision and limitations of information on the past (Swetnam *et al*. 1999, Willis *et al*. 2005, 2007a). Developments in palaeoenvironmental techniques and the growth of environmental history as a field of research to study the mutual interactions between people and their environment through time (Simmons 1993) provide scope for more productive collaborations across disciplinary and institutional boundaries, particularly with the growth of interest in ecosystem goods and services. A framework for communication and networks of exchange are thus required to build collaborative bridges between policy, applied management, ecology, environmental economics, and fields of historical and long-term research. This review is a first attempt to draw together relevant long-term information in order to increase awareness of the potential for such collaboration regarding the UK uplands.

Structure of the review
To ensure that the relevance of environmental history for upland management and policy-making is clear, the review is structured around issues of current concern, and emphasises the linkages between the patterns and drivers of change. These themes were derived from policy documents, journal articles and the limited number of published sources which detail the views of stakeholders (land owners, managers and residents). Some themes, such as the impacts of climate change and management, recur throughout the review.

The review is divided into five main thematic sections, each of which begins with a summary of the key implications for management and policy, and current research gaps. The first section deals with farming in fluctuation, particularly as regards the dynamics of heather moorland, with which upland farming long has been closely associated. This is followed by an examination of extent of ‘degradation’ and the fragility of the uplands due to legacies of climate change, exploitation and atmospheric pollution. Then evidence for the benefits of active management are presented, firstly by contrasting the role of agriculture in supporting biodiversity with abandonment and ‘wild land’ values, and then by presenting long-term insights into habitat restoration and resilience, focusing on peatland and woods. The fifth section examines human resilience, particularly in the face of climatic and economic change. Several case studies are presented to illustrate selected themes. The review ends with general conclusions and a list of references can be found in the appendix.

Data sources

The information in this review is derived primarily from published literature of relevance to upland environmental, habitat and management change, and from unpublished reports and surveys commissioned by stakeholder organisations. Data derive largely from palaeoenvironmental sciences, using written evidence to understand the socio-economic and management drivers behind ecological and environmental change. The palaeoenvironmental data relate primarily to plant ecology and atmospheric chemistry, rather than faunal communities which are harder to study and for which less detailed information is available.

1. Moorland management & dynamics: farming in fluctuation

'*[H]eath landscapes were 'cultural' not only in their origins but also because in time they often became associated with a distinctive way of life for those who lived and worked in them*' (Gimingham 1995)

- Heaths and moorlands are readily acknowledged to be cultural landscapes, created and maintained by land managers (Thompson *et al*. 1995a, Smout 2000, Simmons 2003), although the frequent emphasis on 'naturalness' in upland conservation creates tensions with land managers (*e.g.* Johnston & Soulsby 2006).
- The value of 'traditional' agriculture is also frequently commented on in conservation and policy documents, but is seldom clearly defined (*e.g.* Land Use Consultants *et al*. 2006, Scotland Rural Development Programme 2008, cf. Sutherland *et al*. 2006). With a continuing move towards integrated agri-environment schemes, it is essential that we understand the long-term ecological impacts of different farming systems to shape best practice in balancing conservation and production.
- Furthermore, unless the impacts of mid-20th century agricultural change are assessed relative to mid-19th century intensification we risk promoting unsustainable and impoverished moorland ecosystems in agricultural, conservation and restoration management.

Key findings & uncertainties:

- Baselines based on 20th century data may be set at levels that are not sustainable in the long-term since the intensity of grazing and burning has increased to unprecedented levels over the course of the 19th and 20th centuries.
- While heather losses are far more prolonged than conventional ecological records suggest, with implications for the feasibility of restoring *Calluna* and associated biodiversity, it is essential to recognise that grasses are a natural and not wholly invasive part of many moorland systems, and that not all heather-dominated systems have a long history.
- More work is required to understand the extent of variation in burning regimes and how this has affected moorland mosaics and biodiversity, including plants and invertebrate faunas since this has implications for many bird populations.

1.1 *Moorland management legacies: intensity of use*

- Grazing and burning are the primary drivers responsible for the creation and maintenance of many moorland landscapes, and debate continues as to the merits of differing regimes for managing and maintaining productive, diverse and high conservation value upland habitats, and best practice for controlling erosion, carbon loss and the spread of trees, grasses and bracken (Thompson *et al*. 1995b, Holden *et al*. 2007b).

1.1.1 *'Traditional' grazing*

- Written sources question numerous stereotypes and supply some of the details missing from often vague definitions of 'traditional' agriculture and also contribute to debates over the value and future of grazing for maintaining upland values.
- Foremost is the very different scale and impacts of pre-19th century upland livestock systems compared with modern hill grazing regimes. Stocking densities were well below modern rates (although calculations must be treated with caution as they are based on non-standardised data).

  - *E.g.* In 9 Perthshire townships, stocking densities rose from 0.0625-0.125 livestock units [LU]/ha, from 1727-c.1870s, taking into account smaller livestock sizes, rising to 0.3-0.6 LU/ha by the 1870s (Dodgshon 2004).
  - *E.g.* In N Wales, medieval monastic holdings of c.0.12-0.59 ewe units/ha and 0.07 cattle units/ha had shifted to 0.35 ewe units/ha and 0.17 cattle units/ha by the 16th century, before rising to 3.7 ewe units/ha by 1867 (Hughes *et al*. 1973).
- Before the 19th century, most hill grazing was neither year-round nor systematic relative to the full extent of available hill ground (Winchester 2000, Dodgshon & Olsson 2006). Consequently, vegetational impacts were more limited, potentially within the limits of resilience of the system, and most complaints about degradation begin in the 19th century, under sheep-dominated systems, although some upland soils were sensitive to even relatively light grazing pressures (Case study 1: Heather: stability & spread and 2.1 Erosion).

1.1.2 *Regulated burning*

'[W]e do not sufficiently know enough about the historical burning practices that have produced different vegetation communities. This can make it difficult to establish modern 'good management practice'.' (Holden *et al*. 2007a)

- The large extent of rotationally burned heather is unique to UK and Ireland, and the long-term effects contribute to current heathland composition (Hobbs & Gimingham 1987, Thompson *et al*. 1995b, Holden *et al*. 2007b). However, there is a lack of information on the extent, history and effects of burning practices, particularly serial, rotational burning, to make informed management decisions on upland burning (Stewart *et al*. 2005, Yallop *et al*. 2006).
- Charcoal in peat profiles indicates that recurrent fires have been a long-term characteristic on blanket and raised mires over centuries and millennia, although it is difficult to distinguish between natural and deliberate causes, and to quantify the frequency and intensity of burning (*e.g.* Tallis & Livett 1994, Edwards *et al*. 2000, Stevenson & Rhodes 2000).
- Regulated burning extends back at least into the medieval period, challenging the notion that regular burning regimes arose during 19th century intensive sheep grazing and grouse management (*e.g.* Yallop *et al*. 2006, Holden *et al*. 2007b). References to 'muirburn' occur as early as 1400 in an Act of Scottish Parliament and similar strictures were restated into the 17th century, stipulating no moor burning from March until September/harvest to manage heather and grass, and to protect trees (Smout 2000, Dodgshon & Olsson 2006).
- Similarly, patch burning was clearly known before the 1911 government enquiry into fluctuating grouse populations, which has been put forward as the origin of this practise (*e.g.* Holden *et al*. 2007b). For example, strip/patch burning systems on a minimum 10 year rotation were stipulated in 1895 on the Sutherland Estate (National Archives of Scotland Acc10853/427).
- In combination with other stresses, increased burning over recent centuries has contributed to unprecedented impacts on moorland vegetation, erosion (Sections 1.2 & 2.1) and C storage (Section 2.3).

1.1.3 *Implications & gaps: traditions of grazing & burning*

- Current concerns over the potential impacts of falling stocking levels must take into account the centuries of lower grazing pressures pre *c*.1850 and the unprecedented stocking levels that have become the norm over the last *c*.100-250 years (Sections 1.2 & 3.0).

- While data from recent decades indicate that upland burning has intensified since the 1970s in some areas (*e.g*. Yallop et al. 2006), longer-term data show that this represents the most recent phase of intensification in a much more prolonged series of changes. In many cases, burning has increased over the last *c*.100-250 years, with a further rise at some sites around 1900, due to agricultural intensification (Rhodes & Stevenson 1997). The 1970s thus represent a midpoint and not a baseline for monitoring the extent or impacts of burning in the uplands, with variations across the UK even on a 20th century scale (*e.g.* Hester & Sydes 1992). This emphasises the limitations to current management and conservation approaches for setting limits to burning.
- This long-term and historic information needs to be linked with detailed experimental and written records which record different intensities, frequencies and seasons of burning, to inform practical management.

1.2 *Management & moorland dynamics*

- A longer-term perspective can establish whether 20th century changes in the relative abundance of heather and grasses lie within the acceptable limits of change for moorlands or whether they have reached thresholds of concern.

Case study 1: Calluna decline

- The loss of distinctive heather moorland communities and spread of grassland are significant concerns for the conservation status, biodiversity, productivity and landscape value of UK heather moorlands (Thompson *et al*. 1995b). The loss of heather is known from observation over the last c.50-100 years (Anderson & Yalden 1981, Thompson *et al*. 1995b, Tudor & Mackey 1995).
- However, a 1940s benchmark for restoration is inadequate as many heaths had been depauperate for at least 100 years by this time as the origins of heather contraction range from pre-1700 into the 20th century, with a concentration during the later 18-19th centuries (Stevenson & Thompson 1993, Tallantire 1997, Chambers *et al*. 1999, 2007, Tipping 2000, Hendon & Charman 2004, Yeloff *et al*. 2006, Davies & Dixon 2007).
- While is no single cause can be recognised at a national level, grazing practices are most strongly implicated: with the intensification in farming around c.1750-1850, the body size, hardiness and number of sheep rose, as did the grazing burden on higher ground, particularly during winter, since grazing became year-round rather than seasonal and low-lying farmland was saved for wintering or fodder crops (Hughes *et al*. 1973, Whyte 1981, Stevenson & Thompson 1993, Tipping 2000, Dodgshon & Olsson 2006; 1.1 Moorland management legacies). This also increased pressure in largely unfenced upland woods, which provided winter shelter for livestock and deer (Mitchell & Kirby 1990).
  - Within c.50-100 years of these changes in stocking, heather was in decline, dry grassy heaths were converted to species-impoverished grassland (possibly the *Nardus* communities present now) (Tipping 2000, Davies & Dixon 2007), and blanket peats were increasingly affected by the spread of grasses like *Molinia* (Stevenson & Thompson 1993, Chambers *et al*. 1999, 2001, 2006, 2007; Case study 3: Grasses on mires & moors).
- The long-term impacts of burning on heather are no more clear-cut in the past than in the present: moor-burning ceased on dry heaths in the Cheviots as *Calluna* was

replaced by species-impoverished grassland (Tipping 1998a, 2000, Davies & Dixon 2007), whereas increased burning contributed to some heather losses on blanket peat, acting in combination with grazing, air pollution and climate change (Stevenson & Rhodes 2000), as has occurred due to severe moorland fires in the 20th century, where burning has also contributed to peat erosion (Maltby *et al*. 1990, Mackay & Tallis 1996, Yeloff *et al*. 2006).

- Most heather losses post-date the period of increased climatic variability around 1100-1800, which caused peat and soil erosion (2.1 Erosion). In combination with sheep grazing, atmospheric N deposition may be continuing to exacerbate losses, favouring grasses (Chambers *et al*. 1979, 1999, Holden *et al*. 2007a, b, Hughes *et al*. 2007).

Case study 2: Heather stability & spread

- In view of the evidence in Case study 1, past land-uses which favour diverse heather moorland, including conditions which maintain a balance between grasses and heaths, are relevant to current moorland management.
- Grazing was the main mechanism for encouraging and maintaining heather prior to the 19th century. This is clearest on better-drained soils around the Cheviot (SE Scotland & Northumberland): heather was only a minor component until it spread in species-rich grassland (possibly an *Agrostis-Festuca*-type community) under sheep and cattle rearing regimes around the 12-14th centuries. More systematic, possibly seasonal grazing is thought to have been causal. Stocking densities were undoubtedly lower than in recent centuries (1.1.1 'Traditional' grazing) and so species-richness remained high (Tipping 1998a, 2000, Davies & Dixon 2007). Grassland may have been burnt to encourage the spread of heather or to manage pastures after the grass-heath formed. On some blanket peats cattle-dominated grazing regimes may have contributed to the expansion of heather until the mid-1800s, when declines set in, although this is less well understood (Stevenson & Birks 1995).
- It is important to recognise that, at the same time as better known 19th century declines (Case study 1), *Calluna* spread on some blanket mires in the North York Moors and North Pennines, and has risen to unprecedented levels in South Wales during the 20th century. These occurred as a result of burning and erosion, at the expense of grasses, sedges and, in some cases, *Sphagnum* (Atherden 2004, Chambers *et al*. 2006, 2007), while in other cases, lower sheep densities may be responsible, alone, as part of grouse moor management or in combination with erosion or drainage, as occurred on some cotton grass moors in the Peak District between 1913 and the 1970s (Anderson & Yalden 1981).

Case study 3: Grasses on mires & moors: dynamic cycles to invasions

- The spread of *Molinia* and *Nardus* in moorland habitats has negative impacts on grazing and conservation values (Welch 1986, Chambers *et al*. 1999, Marrs *et al*. 2004, Milligan *et al*. 2004, Littlewood *et al*. 2006a). However, grasses have long been part of the moorland vegetation. *Molinia*, for instance, has been present for hundreds of years and, on blanket mires in Exmoor and Wales composition fluctuated between Callunetum and grass moor (Chambers *et al*. 1999, 2001, 2007). Similarly, between the 12-14th and later 18th centuries, grass-heaths grew on drier soils around the Cheviot (Case study 2: Heather: stability & spread).
- It was not until the late 18-20th centuries that the competitive balance altered, allowing grasses to achieve dominance, replacing *Calluna*, *Sphagnum*, and, in

some cases, *Eriophorum*, on blanket and raised mires, and dry heaths (Yeloff *et al*. 2006, Chambers *et al*. 1999, 2001, 2007). As in the present, this process was driven by combinations of anthropogenic factors, with similar end results: burning, grazing (higher stocking densities and sheep dominance), increased nutrient inputs (through more intensive stocking or atmospheric deposition), pollution and drainage (including peat-cutting) (Yeloff *et al*. 2006, Chambers *et al*. 1999, 2007, Hughes *et al*. 2007).

1.2.1 *Implications & research gaps: heather & grass dynamics*

- With current concerns over heather loss, examples of expansion may be considered desirable, but the significance attached to *Calluna* must be tempered by the knowledge that its current dominance may have no long history at some sites and is due to conditions which are damaging the resilience of the habitat (*e.g.* erosion, *Sphagnum* loss) and occur at the expense of other valued habitats. This must be considered in the context of climate change, which may increase the extent of heather cover as some bogs become drier (4.1 Peatland resilience & restoration management)
- As a result of the cumulative impacts of grazing, burning and more recent atmospheric deposition, some heather moors retain only the most resistant species, and heather abundance or (floristic) diversity may thus have become relatively insensitive stress indicators. See 3 Upland diversity for further aspects of the role of management in diversity change, including agricultural abandonment.
  - The loss of *Calluna*-dominated moorland threatens the floristic diversity of the sub-montane zone as well as many rare and threatened bird species.
  - The extent and antiquity of species losses in some areas means that (1) focusing on a single dominant taxon, like heather, may be a poor means of restoring the wider ecosystem unless it is considered a keystone species for the community in question (Littlewood *et al*. 2006b), and (2) reduced stocking alone is insufficient to restore diversity, particularly with additional competitive pressures caused by atmospheric N inputs. This reinforces the need to move away from single species to consider associated habitat changes and interactions (cf. Hulme 2005).
- Where *Molinia* has risen to unprecedented levels in the recent past (20th century), conservation management efforts to reduce *Molinia* dominance are justifiable and success may be more likely as management does not have to combat long-established dominance (Chambers *et al*. 2001, 2007).
  - However, long-term grass-heather dynamism and the loss of equally endangered species-rich acid grasslands in the formation of dry grass-heaths highlights the range of possible restoration targets for moorland and valid alternatives to *Calluna*-domination (cf. Anderson *et al*. 1997).
  - Consequently, reference to history can broaden management vision and restoration targets where rigid adherence to contemporary vegetation classifications for setting management targets, which ignore historic precedent, may exclude potentially relevant assemblages which contribute to habitat resilience (Chambers *et al*. 1999, cf. Wilkinson 2001).
  - As experiments show, reductions in grazing pressure alone are likely to be ineffectual in controlling the spread of grasses in moorlands since this is not the sole cause (cf. Thompson 2002, Marrs *et al*. 2004), emphasising the potentially fragile state of heaths.

- The contrasting ecological footprints of medieval, pre- and post-19th century stocking regimes suggest that agri-environmental schemes for moorland conservation would be best served by relatively low stocking densities, using modified grazing regimes (less sheep, with lighter cattle grazing), which are seasonally controlled, in combination with reduced burning and more intensive shepherding to actively maintain heterogeneity (at landscape and community levels) (cf. Thompson *et al*. 1995b, Littlewood *et al*. 2006b). This requires the expertise present in rural agricultural communities, but must also be combined with reduced atmospheric pollution and efforts to reduce gullying to maintain hydrological integrity and so help regulate the competition balance between grasses and other mire taxa (Chambers *et al*. 2007).
- There are insufficient data to understand the relationships between local grazing, burning and pollution histories and their effects on the composition, biodiversity and productivity of different moorland habitats (Shaw *et al*. 1996, Yallop *et al*. 2006, Holden *et al*. 2007a, 2007b).
- Data on relationships between the history and current status of many moorland ecological groups other than plants are scarce. For example, work on invertebrates in lowland peat environments has shown significant habitat-related changes which have shaped the current diversity of invertebrate faunas (*e.g.* Whitehouse 2006) but very little is known regarding upland faunas (*e.g.* Clark 2003, cf. Littlewood *et al*. 2006a).

2. Degraded lands & thresholds of stability

'Overgrazing is perceived to be a major cause of blanket mire degradation in all parts of Britain' (Tallis 1998)

'*Climate change is a principal driver of many degradation processes*' (Holden *et al*. 2007a, p.20)

- Upland deterioration has been a recurrent theme since the later 19th century and is often associated with declining diversity or carrying capacity on hill grazings, the spread of moorland grasses, pollution and erosion damage (Holden *et al*. 2007b). This concern is also reflected in the drive to halt biodiversity losses by 2010 (3 Upland diversity).

Key findings & uncertainties:
- The present state of some peat- and moorland sites is outside all historic limits of change, suggesting that they have crossed thresholds of stability. Consequently, the risk of drought damage and associated release of stored pollutants is particularly high in more marginal and damaged moors and peatlands.
- The complex interactions and feedback mechanisms between climate, management, hydrology, erosion and pollutants and the unprecedented severity of erosion in some areas makes it difficult to predict recovery, and suggests high costs, long timeframes and a need to consider novel strategies or alternative 'restoration' targets.
- Management is critical for maintaining a favourable carbon balance, as well as preventing the release of pollutants stored in organic soils and peats, since abrupt vegetation shifts have strong impacts on C stocks and climatic impacts will initially occur via changes in near-surface hydrology and vegetation.
- However, further research is required as there is a shortage of data on the impacts of anthropogenic activities on C balance and interacting factors needed to extrapolate from site-specific studies to landscape-scale management implications.

2.1 *Erosion*

- Upland peat and soil erosion are widespread (*e.g.* Grieve *et al*. 1995, Tallis *et al*. 1997, Tallis 1998, Higgitt *et al*. 2001) and pose a serious threat to the large carbon stores in upland sediments and thus to climate change (Bellamy *et al*. 2005, Dawson & Smith 2007, Holden *et al*. 2007a). This is in addition to threats from historic legacies (*e.g.* pollution deposition; 2.2 Pollution), current land management and climate change. The impacts extend beyond terrestrial habitats, adversely affecting upland aquatic systems and water quality (*e.g.* Rose *et al*. 2004, Evans *et al*. 2006, Shotbolt *et al*. 2006, Rothwell *et al*. 2007a).
- As the carbon cycle has a long equilibrium time, the wider impacts of erosion are unknown as yet, but the consequences of actions taken now will persist for many centuries (Scholes 1999, cited in Dawson & Smith 2006) and policies and management regimes must therefore be carefully considered.
- Observational data on the extent of erosion are largely descriptive and of insufficient time-depth to provide secure insights into the origins, frequency and potential timescales of erosion, while written sources often describe only more extreme or obvious changes at a limited number of sites (Tallis 1985, Bragg & Tallis 2001, Higgitt *et al*. 2001). Current appearances may be misleading as re-vegetation can mask the severity, extent and timescale of erosion processes, giving the landscape a less degraded appearance, while the reactivation of erosion scars

may give an exaggerated view of current processes (Burt *et al*. 2002, Grieve *et al*. 1995, Higgitt *et al*. 2001).

- Despite the shortage of detailed long-term studies, the difficulties of dating eroded sediments, and separating climatic and anthropogenic drivers (Tallis 1987, Ballantyne 1991, Higgitt *et al*. 2001), long-term records indicate that degraded bogs and eroded soils are multi-causal and that much current upland erosion is the result of nearly 1000 years of climatic and management impacts (*e.g.* Figure 7.1 in Higgitt *et al*. 2001). This contrasts with more isolated evidence for peat and soil erosion in prehistory (*e.g.* Bradshaw & McGee 1988, Stevenson *et al*. 1990, Edwards & Whittington 2001, Chiverrell 2006, Leira *et al*. 2007, Chiverrell *et al*. 2008, Foster *et al*. 2008).
- While current efforts to halt erosion may provide a temporary stop-gap, immediately pre-industrial targets are not sufficient to restore peatland integrity and a longer perspective warns of the financial and practical feasibility and timeframes required to sustain or achieve current targets for halting and repairing erosion.
- The main drivers of upland erosion/instability in the past, which are also likely to be influential in the future, are: natural (internal) factors, intensified grazing and burning, deforestation and afforestation, drainage, atmospheric pollution and climate change. Interactions between these factors can be especially damaging; this increases the difficulty of predicting erosion and the need for diverse monitoring protocols.

2.1.1 *Drivers of erosion*

- While bog bursts may be natural (see below), the evidence for erosion as a natural feature of upland peatlands is limited, although it may have been more significant in locations which are climatically marginal for peat growth, such as the Pennines, where the formation of a naturally unstable peat mass led to the formation of drainage gullies by the 11th century (Tallis 1985, 1998, Tallis & Livett 1994).
- Increased climatic variability on regional to global scales characterised the period c.800-1850 (popularly, but misleadingly, known as the ‘Medieval Warm Period’ and the ‘Little Ice Age’). An increased incidence of peat and soil erosion from northern Scotland to the southern Pennines is linked with more extreme climatic/weather events during this period.
    - *Drier conditions*: In the southern Pennines, peat desiccation around 1100-1300 caused permanent damage to the bog ecosystem by changing peat growth patterns on exposed ridges and summits and peat margins, possibly leading to gullying (Tallis 1997). This sensitised the ecosystem to subsequent perturbations, making it more susceptible to even short-term desiccation (Tallis 1995, 1997). This pattern continues since climatically-induced drought has contributed to damaging wildfires, especially in the 20th century when high sheep numbers have further limited regeneration and exacerbated peat erosion (Mackay & Tallis 1996, Yeloff *et al*. 2006).
    - *Wetter, stormier conditions*: Increased peat and soil erosion around 1500-1700 is attributed to climatic wetness, especially increased storminess and extreme rainfall events, both of which may increase in frequency in the future (Stevenson *et al*. 1990, Ballantyne 1991, Rhodes & Stevenson 1997, Curry 2000, Higgitt *et al* 2001, Chiverrell *et al*. 2008). On high plateaux, increased wind stress and prolonged snow-lie may have caused the formation of deflation surfaces in NW Scotland around 1550-1700 (Ballantyne & Morrocco

2006, Morrocco *et al*. 2007). Intense rainstorms, possibly coupled with anthropogenic disturbance, have triggered an increased incidence of landslides (peat slides and bog bursts) over the last c.150-200 years, again, especially during the late 20th century (Higgitt *et al*. 2001, Foster *et al*. 2008, Hatfield *et al.* 2008, Hatfield & Maher 2009, Mills & Warburton unpublished, cited in Holden *et al*. 2007a).

- Climate may have triggered erosion, but human activity is the critical factor which pushed these systems towards erosive thresholds (Chiverrell *et al*. 2008, Foster *et al*. 2008, Hatfield & Maher 2009). Activities such as the removal of hillslope woods and mining (Chiverrell 2006, Hatfield et al. 2008) affected some catchments, but agricultural intensification is a main factor. Grazing (especially of sheep) has been a significant driver of upland soil and peat erosion and vegetation change over the last 1000 years, particularly in combination with other factors.
    - This applies even before widely documented land-use intensification in both the late 18-19th and 20th centuries; medieval grazing practices instigated or exacerbated peat and soil erosion, gullying and slope instability, especially during periods of climatic instability (Harvey *et al*. 1981, Harvey & Renwick 1987, Brazier *et al*. 1988, Curry 2000, Ellis & Tallis 2001, Reid & Thomas 2004, Chiverrell 2006, Morrocco *et al*. 2007). In some instances, this may be the result more systematic, year-round grazing regimes (*e.g.* Tipping 2000, Davies & Dixon 2007; 1.2 Management & moorland dynamics).
- The effects of burning on erosion are less well researched. Burning and grazing do not necessarily cause instability since evidence for peat stabilisation in some upland lake catchments coincided with increased burning and rising grazing pressures around 1850-1950 (Rhodes & Stevenson 1997). However, damaging wildfires during periods of climatic dryness have contributed to damaging erosion, particularly in combination with grazing (Tallis 1994, Mackay & Tallis 1996, Yeloff *et al*. 2006). Higher charcoal quantities suggest that eroded peats pose an increased fire risk over the long-term (Tallis 1987).
- Similar to modern experience of erosion caused by ploughing in advance of conifer afforestation (Battarbee *et al*. 1985), deforestation on hillslopes has in the past contributed to slope instability, particularly in combination with grazing and burning (Curry 2000, Ellis & Tallis 2001, Chiverrell 2006, Hatfield *et al*. 2008). Careful slope management will be required in the felling and planting of conifers and new native woods. Chiverrell (2006) suggests that major changes in land cover, such as woodland loss, may have been more significant than climate in causing slope destabilisation; such destabilising land-uses persist today.
- The extent, ecological impacts and contribution of peat-cutting and extensive moorland drainage systems to erosion are poorly understood and often go unrecognised (Holden *et al*. 2007a). For example, domestic peat-cutting has removed an estimated 40-50% of blanket peat surface areas in parts of the south Pennines (Ardron *et al*. 1996, Rotherham *et al*. 2004). It is likely that these modified and artificial drainage networks accelerated peat erosion by developing into larger gullies and promoted fluvial incision on hillslopes (Tallis 1998, Foster *et al*. 2008).
- The loss of *Sphagnum* from upland bogs due to atmospheric pollution post-dates the establishment of most current erosion patterns, but may have enhanced erosion by limiting the recolonisation of bare peat, further exacerbated by high stocking levels (Tallis 1985, 1987, Mackay & Tallis 1996; 2.2.2 Atmospheric pollution in terrestrial systems).

2.1.2 *Implications: erosion*

- The erosive degradation of moorland is a result of numerous episodic processes and interacting factors, leading to pulses of enhanced erosion (*e.g.* Grieve *et al*. 1995, Rhodes & Stevenson 1997, Tallis 1998, Reid & Thomas 2004). Past legacies (*e.g.* grazing, pollution damage) cannot be ignored even in managing major catastrophic events since short periods of disturbance, extreme events and unpredictable combinations of events can have disproportionate impacts, especially where habitats have been sensitised by a history of erosion (Tallis 1987, Mackay & Tallis 1996, Anderson *et al*. 1997, Ballantyne & Whittington 1999, Higgitt *et al*. 2001, Yeloff *et al*. 2006).
- Many past causal factors have intensified over the 20th century and are predicted to increase further under global warming scenarios. This includes the incidence of wildfires, intense rainfall events, more severe droughts and lowered water-tables (Charman 1997, Mackay 1997, Tallis 1998, Chiverrell 2006, Worrall *et al*. 2006b, Yeloff *et al*. 2006, Malby *et al*. 2007). This is particularly relevant near the margins for blanket peat formation, where climatic impacts are likely to be more intense and management impacts more severe.
- Owing to the combined destabilising effects of climate and land management, it is unlikely that controlling single causal factors will be adequate to halt, limit or repair erosion damage. For example, hydrological impacts are unlikely to be reversed by drain blocking alone, which may take many decades to restore favourable hydrological conditions, even before climate change pressures are factored in (cf. Charman 1997, Hendon & Charman 2004).
- Long-term accumulated erosion damage may be so severe and/or extensive that some peatlands may have crossed thresholds of resilience, especially in more southerly and easterly blanket peats in the UK. This reinforces the need to understand long-term site histories to establish appropriate management strategies and predict the impacts of future perturbation, particularly from climate change.
- It may be necessary to assess whether some sites have undergone such serious, long-term erosion damage that it is no longer possible to restore functioning peatland habitats and alternative stabilisation mechanisms and management targets may need to be considered, as is already occurring in some areas (*e.g.* south Pennines, see http://www.moorsforthefuture.org.uk/mftf/main/Home.htm).
- This may include re-evaluating the value of tree growth on peat since it may become increasingly hard to prevent tree or scrub colonisation without further damaging eroded and drying organic sediments (Chambers 1997, 2001, Mackay 1997). The potentially stabilising effects of tree growth may need to be balanced with a desire to prevent their drying effects and maintain current agricultural, sporting, aesthetic and leisure values associated with open moorland.
- In serious cases, the long-term practical and financial costs of implementing restoration, and the reduced likelihood of final success will need to be balanced with environmental costs to water quality and carbon emissions from continued erosion, and the diversion of financial support from protecting other sensitive, but less severely damaged sites.

2.2 ***Pollution***

- Due to past and continuing atmospheric pollution and the enhanced deposition of atmospheric pollutants at higher altitudes, freshwater systems, in particular, have undergone acidification and eutrophication, while organic sediments act as reservoirs for nitrogen, heavy metals and persistent organic pollutants. Existing and future damage to the integrity of these storage systems poses serious challenges for upland management since the release of stored sources may negate or even counteract atmospheric reductions in pollutants and conservation or restoration initiatives (Dawson & Smith 2006, Holden *et al*. 2007a).

2.2.1 *Lake acidification*

- Strengthened by the Water Framework Directive, palaeoenvironmental records of water quality are one area where long-term ecology is an established part of policy and management, since it is recognised that many freshwater systems have been acidified since mid-19th century industrialisation, thus requiring alternative sources to define pre-industrial hydrological baseline conditions.
- Before the mid-19th century, some lakes show early acidification owing to natural soil impoverishment through leaching soils derived from nutrient-poor geologies, but others show pH stability, despite long-term leaching and the development of extensive blanket peat in the surrounding catchments (Battarbee *et al*. 1988). In these cases, natural acidification is unlikely to have reduced the buffering capacity of lakes or increased their susceptibility to acid deposition.
- Surface water acidification has occurred in upland lakes due to increased sulphur (S) deposition, which has caused reductions in pH of around 0.5 units over the period c.1800-1850 (Flower *et al*. 1987, Battarbee *et al*. 1988, 1989, 1996, Jones *et al*. 1989, Birks *et al*. 1990). Lakes in closer in proximity to industrial areas have been more strongly affected, but even remote lakes have been acidified (Battarbee & Allott 1994, Fowler & Battarbee 2005).
- There is little evidence that changes in moorland grazing, burning or afforestation were causal (*e.g.* Battarbee *et al*. 1988, 1989, Kreiser *et al*. 1990), in contrast with the evident sensitivity of terrestrial habitats to land-use intensification during this period (1.2 Management & moorland dynamics and 2.1 Erosion).
- In addition to contaminating water with lead, zinc, fossil fuel-derived soot particles and persistent organic pollutants, water acidification has caused a shift to an acid-tolerant diatom flora, a decline in aquatic insects and increased concentrations of toxic inorganic aluminium. This deterioration in water quality has, in some instances, adversely affected fish stocks and fish reproduction, with implications for higher predators, including humans (Birks *et al*. 1990, Kernan *et al*. 2005; 4.3 River management & restoration).
- In some lakes, increases in pH and the recovery of algae and invertebrates, acid-sensitive plants and mosses, and fish populations following the 1970s reduction in atmospheric SO_2 emissions suggests that acidification is reversible (Allott *et al*. 1992, Battarbee *et al*. 1988, 2005, Juggins *et al*. 1996, Ferrier *et al*. 2001).
    - However, recovery is by no means universal and is being offset or slowed due to the erosive influx of pollutants stored in catchment soils and increased N deposition, while predicted climate changes may exacerbate damage by enhancing decomposition, erosion and leaching over future decades (Jones *et al*. 1989, Ferrier *et al*. 2001, Rose *et al*. 2004, Battarbee *et al*. 2005, Fowler & Battarbee 2005, Kernan *et al*. 2005).
    - In addition, climatic conditions which favour reduced nitrate inputs from catchment sources may enhance dissolved organic carbon (DOC) influx, thus offsetting recovery from acidification (Rose *et al*. 2004).

  - The nature of surrounding vegetation could affect recovery, since proximity to plantations may slow recovery due to the acid scavenging behaviour of conifers (Juggins *et al*. 1996, Harriman *et al*. 2003).
  - Direct rehabilitation techniques such as liming may help neutralise lake acidity, but the resulting algal flora is often unlike anything known in the past and may induce the invasion of new species, rather than restoring the pre-acidification ecosystem (Flower *et al*. 1990).

2.2.2 *Atmospheric pollution in terrestrial systems*

- Organic soils form a reservoir for pollution-derived nitrogen and heavy metals, but evidence for the ecological impacts of atmospheric deposition on terrestrial systems is more equivocal than aquatic systems (Woodin 1988, Lee *et al*. 1988, Thompson & Badderley 1991, Tallis 1998). This reflects the differential sensitivities of various taxa and the difficulties involved in distinguishing atmospheric-scale influences from local (*e.g.* biotic) factors (*e.g.* Lee 1991, Thompson & Badderley 1991, Caporn 1997, Tallis 1998, Rosen & Dumayne-Peaty 2001).
- Two examples illustrate the importance of understanding the impacts of historical pollution on upland resilience and the potential threats arising from a decline in ecosystem integrity: the loss of *Sphagnum* and the role of peat as a repository of heavy metals. These warn against any attempts to decouple atmospheric deposition from management and climatic factors (cf. Thompson 2002).

Case study 4: the loss of <u>Sphagnum</u>

- The sensitivity of *Sphagnum* (especially *S. austinii* [formerly *S. imbricatum*]) to S and N pollution is well documented and the decline or disappearance of *Sphagnum* in peatlands is the most-cited example of historical pollution damage to British and Irish peatlands, although *Sphagnum* was not the only taxon affected: *Racomitrium* growth may have been reduced in areas of high pollution, for example (Tallis 1994, 1995).
- Major *Sphagnum* losses have been driven by 19th century increases in atmospheric pollution, but this is not the only cause. Of particular relevance for future monitoring is evidence that interactions between climate and disturbance (*e.g.* drainage, peat-cutting, burning and grazing) determine when local thresholds for *Sphagnum* regeneration are crossed (Mauquoy *et al*. 2002, Yeloff *et al*. 2006).
  - For example, periods of climatically-induced wetness or desiccation combined with competition and disturbance caused asynchronous local extinctions in *S. imbricatum* between the 10th and 15th centuries (Tallis 1994, Mauquoy & Barber 1999, Mauquoy *et al*. 2002, Coulson *et al*. 2005, Langdon & Barber 2005, McClymont *et al*. 2008). Drier climatic conditions coupled with disturbance are implicated in 19th and 20th century *Sphagnum* losses (Mackay & Tallis 1996, Chambers *et al*. 2001, 2007, Coulson *et al*. 2005, Yeloff *et al*. 2006).
  - Although most major *Sphagnum* declines post-date the start of peat erosion, this has contributed to the failure of re-vegetation on peat, especially in conjunction with high stocking levels (Tallis 1985, 1987, Mackay & Tallis 1996). Palaeoecological records show that *S. austinii* has re-established itself during phases of reduced human activity but it is difficult to envisage this happening in the near future (Hughes *et al*. 2008).

Case study 5: heavy (trace) metal storage

- In addition to causing freshwater acidification, industrialisation has also left a potentially harmful legacy due to the affinity of organic matter for heavy metals (Lee & Tallis 1973, Rosen & Dumayne-Peaty 2001, Coulson *et al*. 2005). This is in addition to enhanced soil concentrations of lead and zinc around former arable land in rural locations due to past manuring practices (Davidson *et al*. 2007).
- While this affinity has the beneficial effect of reducing pollutant concentrations in runoff and water reaching lakes and reservoirs, peats may become future pollution sources (Yang *et al*. 2001, Kernan *et al*. 2005, Rothwell *et al*. 2005). This is already occurring near heavily industrialised areas, such as the southern Pennines, where lead inputs to reservoirs derive mainly from past deposition via erosion and leaching, with potential ecotoxicological effects (Shotbolt *et al*. 2006, Rothwell *et al*. 2007a).
- Peat acidification and climate change may exacerbate the release of heavy metals by increasing mobilisation and leaching or erosion, thus restricting or delaying recovery from pollution (Yang *et al*. 2001, Rose *et al*. 2004, Kernan *et al*. 2005, Rothwell *et al*. 2005, 2007b).

2.2.3 *Eutrophication*

- Despite the relatively recent history of eutrophication, the impacts are already becoming detectable in longer-term records, emphasising the sensitivity of upland ecosystems to atmospheric pollution (Curtis & Simpson 2007, cf. Britton *et al*. 2005).
  - Eutrophication is affecting even large water bodies such as Loch Ness, where major changes in the diatom flora around 1970 are attributed to nutrient enrichment (Battarbee & Allott 1994, Jones *et al*. 1997).
  - Nutrient loading by nitrogen (N) deposition may be contributing to the recent ousting of *Calluna* by *Molinia* on moorland (Chambers *et al*. 1999; Case study 1: *Calluna* decline and Case study 3: Grasses on mires & moors).
- Like heavy metal sequestration, the storage of N in peats may provide a future threat, particularly to carbon storage (2.3 Carbon sequestration).

2.2.4 *Implications & research gaps: pollution*

- Managing individual contributory factors may slow erosion and pollution impacts, but holistic approaches are essential for predicting the likely long-term impacts on upland ecosystem integrity due to feedback mechanisms between climatic and anthropogenic processes.
- Reducing current levels of atmospheric pollutants will not necessarily reverse the damage to upland resilience since the store of historically-deposited pollutants in organic soils will remain a threat into the future, preventing recovery or even exacerbating acidification in freshwater systems.
- Similarly, in terrestrial systems, reducing grazing levels will not offset the increase in nutrient deposition from current atmospheric deposition or erosion inputs from historic pollutant accumulations.
- It is not yet clear whether pH recovery will restore the feedback mechanisms which maintained stable pHs prior to industrialisation or even exactly what these mechanisms were.

2.3 *Carbon sequestration*

- Carbon (C) storage has become a primary policy and management concern, but the evidence-base required to shape effective policy remains limited (Holden *et al*. 2007a). In addition to threats posed by erosion and pollution, future climatic warming is predicted to lead to the enhanced release of C from organic sediment stores, particularly from drying peatlands and organic soils. The impacts on water quality are already recognised (*e.g.* Evans *et al*. 2006, Worrall *et al*. 2007), but surprisingly little is known about the effects of anthropogenic activities on peatland C balance (Garnett *et al*. 2000).
- Since emissions from organic substrates derive from both recent and old C, two aspects of C storage need to be considered to manage and reduce emissions: (1) the processes of long-term C sequestration in organic sediments, and (2) the response of existing C stores to perturbations, i.e. their potential to become sources (Anderson 2002). This includes managing hydrology and vegetation, to effect continued C incorporation, as well as considering the impacts of temperature and instability on existing C accumulations (Anderson 2002, Charman 2002, Belyea & Malmer 2004, Malmer & Wallen 2004, Holden *et al*. 2007a).
- Abrupt vegetation shifts have a strong impact on C sequestration, as they alter productivity and decomposition rates (Belyea & Malmer 2004). Management has a key role in managing C stocks and water quality since vegetation composition is largely controlled by management (whether for conservation or production) (Worrall *et al*. 2007).
- Low intensity sheep grazing had no significant effect on C mass (or vegetation biomass) over a 30 year period at Moor House NNR, but fires may cause a positive feedback by attracting sheep to recently burnt areas, so intensifying C losses by direct removal of biomass and indirectly affecting rates of net primary production (NPP), decomposition, hydrological change and compaction via trampling (Garnett *et al*. 2000, Worrall *et al*. 2007).
- Rotational burning every 10 years can lead to reduced C accumulation rates on blanket peat, but it is unclear whether this acts by directly reducing C stores in burnt layers, by reducing or halting the rate of peat accumulation or by changing vegetation composition (Garnett *et al*. 2000, Worrall *et al*. 2007).
- The relationship between C sequestration, peatland hydrology, and climate change is complex, and predictions thus vary. The potential impacts of future temperature and precipitation change are particularly important (Wieder 2001).
    - Climate change may force a system over thresholds, but is an indirect driver since C sequestration responses are mediated by changes in surface structure and developmental topography (by producing more litter or enhancing decay) (Belyea & Malmer 2004). This emphasises the need to better understand the mechanisms of change to predict future responses and manage ecosystem vulnerability (Worrall *et al*. 2007).
    - C loss is likely to be greater under a combination of warmer and drier conditions, with potentially marked impacts arising from summer droughts and severe fires (Moore 2002). Under this scenario, evidence that some peatlands are no longer resilient to drought has severe implications for C storage (Worrall *et al*. 2006b; 4.1 Peatland resilience & restoration management). However, warmer/drier conditions could also delay the switch from C sink to C source by increasing NPP relative to increased decay at depth.

  - Increased precipitation in oceanic regions is predicted to cause the expansion of hollows in patterned peatlands, inhibiting peat formation and C sequestration, while enhancing CH_4 emission (Belyea & Malmer 2004). In the past, wetter/colder climatic conditions have reduced C accumulation either by reducing NPP or through the rapid decay of aquatic Sphagna (Mauquoy *et al*. 2002, 2004).
- In addition to climate, grazing and burning impacts on NPP, it is unclear whether increased atmospheric N deposition will (1) lead to higher rates of C and N accumulation in bogs through enhanced NPP, or (2) whether reduced C:N ratios and increased N concentrations will increase decomposition rates, thus releasing carbon from organic soils and peats (Turunen *et al*. 2002, Malmer & Wallen 2004, Dawson & Smith 2007, Holden *et al*. 2007a).

2.3.1 *Implications & gaps: C sequestration*

- Maintaining functioning surface vegetation is essential for C storage as only 10-13% of the C from the upper peat (the acrotelm) will be incorporated into long-term storage in the underlying waterlogged layers (Malmer 1992, cited in Anderson 2002) and responses to climate change are (at least initially) likely to occur in the acrotelm.
- While climatic impacts on C sequestration are likely to increase, there is a strong role for management in maintaining C stores in organic-rich upland sediments since vegetation and surface structure are the main controls on C sequestration, and both are largely controlled by management. This is now being incorporated into agri-environmental subsidies.
  - Continued review of burning practices is important as the predicted increase in fire risk with climate warming will exacerbate the release of CO_2 and loss of peat (Garnett *et al*. 2000, cf. Maltby *et al*. 1990, Kuhry 1994, Pitkanen *et al*. 1999).
- There is an urgent need to understand how surface structure and vegetation interact with climate and developmental changes in peatland hydrology (Belyea & Malmer 2004). It is also necessary to understand decomposition processes, especially acrotelm interactions and the movement of C into the lower, waterlogged peat; until such processes are understood at the micro-scale, predictions at the macro-level will lack precision (Moore 2002).
  - Modelled C budgets for representative catchments must be underpinned by a secure understanding of the hydrological and ecological mechanisms controlling peatland carbon accumulation responses; these are central for predicting potential feedbacks and identifying appropriate management responses (Belyea & Malmer 2004, Anderson *et al*. 2006, cf. Holden *et al*. 2007a).
  - This requires the development of integrated models to predict future carbon flux from organic sediment under a range of climatic and management conditions, using data covering a range of spatial and temporal scales (cf. Anderson *et al*. 2006, Holden *et al*. 2007a).

3. Upland diversity: the legacy & role of management

'*The uplands, although a landscape shaped by centuries of human activity, are the nearest that England has to wilderness*' (English Nature 2001)

- Preceding sections detail the cumulative impacts of land management and climate change over recent centuries, and the threats that they pose for the future ecological and socio-economic sustainability of the uplands.
- Since biodiversity has become an indicator of the 'health' of species and habitats, as well as a key target, and intervention or changes in management are required to meet these targets, this section draws together evidence for the impacts of land management – both adverse and beneficial – and the implications for future integration of conservation aims with agricultural land management and the potential impacts of abandonment and the cessation of management, and 'wild land' values.

Key findings & uncertainties:
- 20th century baselines for biodiversity loss due to intensification underestimate the extent of many species losses or declines.
- Policy has a key role since much attrition over the last c.250 years has been driven by market opportunity and subsidy.
- A retrospective view also reinforces the need to support 'good' agricultural management to achieve biodiversity and restoration goals.
- The environmental, social and economic implications of abandonment need to be jointly considered to address current debate over changing patterns of upland land management, especially the likelihood of adverse ecological impacts associated with abandonment and 'wild land'.
- 'Wild land' is not a logical alternative to management or mismanagement, as the outcomes are inherently unpredictable and idealised in upland ecosystems shaped by centuries of human activity.
- More detailed information is required on the processes and timescales of species loss across the full range of upland habitats.

3.1 *The attrition of diversity and heterogeneity*

- Concerns over degradation are reflected in the drive to halt biodiversity loss and improve the condition of designated sites by 2010 under the Convention on Biodiversity, implemented through UK Biodiversity Action Plans. These must be underpinned by evidence for the full extent and timescale of losses in each habitat, since these are often more severe or protracted than is known from observation over the course of the 20th century.
- After the development of extensive peat cover and extensive woodland losses in prehistory, the most significant changes to the upland landscape began around 1750 in areas with a longer history of intensive land-use, and intensified in most areas during the 19th century, when written sources record concerns over degradation (Mather 1978, Innes 1983, Smout 2000, Dodgshon & Olsson 2006). Similar concerns were repeated 100 years later, illustrating how short-term views can lower baselines (*e.g*. Darling & Boyd 1955, Pearsall 1971). As detailed above, intensified grazing, burning and, in some cases, atmospheric pollution and climate change/weather events emerge as common causes.
- Known losses include:
    - o the transition from diverse *Calluna*-grass communities to species-poor grassland in the Cheviots between 1750-1900 due to intensified sheep grazing,

    leaving only the most grazing-tolerant taxa (Tipping 2000, Davies & Dixon 2007; Case study 1: *Calluna* decline);
  - reduced plant diversity on blanket mires in northern England since the late 19th century and in Wales through the 19-20th centuries, including the unprecedented dominance of *Molinia* on some sites and *Calluna* on others, and the loss of such species as *Sphagnum* (especially *S. imbricatum*), *Myrica gale*, *Drosera intermedia*, *Andromeda polifolia* and *Rhynchospora alba* (Tallis 1964, 1998, Chambers *et al*. 2001, 2006, 2007; 1.2 Management & moorland dynamics);
  - significant changes in the composition and demography of many faunal populations, especially predatory birds and their prey (Smout 2000, Lovegrove 2007).
- High altitude montane communities are limited in the UK and face even greater threats from climatic change, disturbance and atmospheric pollution (Thompson *et al*. 2001, 2005). Although very limited, long-term data emphasise their vulnerability and the need for a historical context to establish where critical thresholds lie and the relative legacies of natural and cultural drivers, and so avoid implementing management strategies which reduce resilience by misinterpreting such sensitivities (Thompson *et al*. 2001).
  - *E.g*. Intensified grazing over last *c*.200 years has markedly restricted grazing-sensitive montane taxa to more inaccessible locations at Caenlochan NNR (Cairngorms, NE Scotland). This includes the contraction of fern-rich and tall-herb grassland and *Salix* scrub from grassland habitats above the tree-line and former niches within the woods, while less accessible fern-rich screes survived and grasses expanded (Huntley 1981). By contrast, the Morrone Birkwoods NNR (Deeside, NE Scotland) currently retains a diversity of arctic-alpine and montane taxa (Huntley 1994, Birks 1997).

3.2 *Agricultural abandonment & wild land*

- There is growing interest in 'wild land' in the uplands, through conservation interest in enhancing 'naturalness', the lesser degree of perceived human influence, the attrition of values through mismanagement and development over the last c.100 years and growing pressures on green spaces (*e.g.* Scottish Natural Heritage 2002c, Carver & Wrightham 2003, McMorran *et al*. 2006). With potentially similar social and agricultural implications, abandonment represents one extreme of the potential range of future scenarios for the uplands if there is a continued shift away from production.
- This is seen by some as an opportunity for 'rewilding'. However, wild land supporters may underplay the extent of human influence in 'semi-natural' habitats and promote exaggerated views of past over-exploitation (Breeze 1997, Chambers 1997, Smout 1997; 4.2 Woodland management & creation in the uplands), while abandonment poses a significant threat to valued habitats, including bird and invertebrate populations, and the character of the uplands, as well as exacerbating the loss of local knowledge, skills and rural populations (*e.g.* Burton 2004, Land Use Consultants *et al*. 2006). Furthermore, in many instances, there is a lack of ecological evidence to support decision-making, especially on the potential long-term impacts of reduced grazing pressures, while most supposed ecological benefits of 'rewilding' or reinstating 'natural processes' are, by their very nature, uncertain (*e.g.* Mitchell & Kirby 1990, Tallis 1998, Luxmoore & Fenton 2004, Hodder *et al*. 2005, cf. Sutherland *et al*. 2006; 3.3 Managing biodiversity).

- Although there are relatively few well-documented examples of complete historical long-term abandonment (of both settlement and land management), the impacts of reduced labour forces and extensification during the 19th and 20th centuries illustrate some possible future impacts.
    - The replacement of numerous small townships, practicing mixed arable/grazing regimes, to depopulated landscapes focussed on sheep grazing resulted in the 'degradation' of 'green lands' (the former infield), where less palatable grasses and mire replaced areas of species-rich improved grasslands in northern Scotland (Mather 1993, Smout 2000, Davies *et al*. 2006, Dodgshon & Olsson 2006). This has occurred even in areas where sheep farming declined by the end of the 19th century.
    - Twentieth century mechanisation and the decline in upland hay-making, for example, and the ongoing contraction of small-scale farming systems, like crofting, are repeating and exacerbating this loss of culturally-defined biodiversity and landscape character, in addition to having profound social impacts (Macdonald 1998, Brown 2006). Due to the duration and extent of long-term cultural influences, promoting natural processes through 'rewilding' is likely to cause similar changes in many upland landscapes.
- Scrub and woodland expansion/invasion are seen as a potential outcome of reduced grazing pressures and abandonment, and concerns have been voiced about potential impacts on the productive and aesthetic qualities of the uplands (*e.g.* Holden *et al*. 2007a). History and ecology suggest that the most rapid and pronounced changes are likely to occur in upland valleys, which are also the main locations for rural settlement, since they provide better soils, seed sources and more sheltered conditions, and will be driven largely by lower grazing pressures, as was the case during periods of agricultural contraction in the post-medieval period in Lancashire and on the North York Moors (Mackay & Tallis 1994, Atherden 2004).
- Debates about the potential environmental benefits of abandonment (*e.g.* favouring 'natural processes', creating 'wild land') are generally conducted without considering the social and economic implications for rural communities and the wider service network or ecosystem services. Past rural depopulations had far-reaching social impacts, remain contentious today and provide a potential insight into the broader consequences of abandonment (*e.g.* Hunter 1976, Richards 2000; 5 Climatic & economic change: risk & rural resilience).

3.3 *Managing biodiversity: positive management*

- Conservation emphasis on designated or otherwise 'special' sites and the desire to repair 'unfavourable' conditions often gives the impression that management legacies are largely negative, leading to conflict with land managers (*e.g.* Johnston & Soulsby 2006). A long-term perspective provides insights into 'good practice' for managing diversity through land-use and can help strengthen the development of sustainable agri-environmental systems which benefit rural communities.
- The value of less-intensive grazing for conservation and agri-environmental schemes is becoming more widely recognised and an increasing number of modern and historical studies across Europe indicate the positive contributions of land-use to diversity and the negative impacts of abandonment (*e.g.* Lindbladh & Bradshaw 1995, Bignal & McCracken 1996, Bokdam & Gleichman 2000, MacDonald *et al*. 2000, Maurer *et al*. 2006, Berglund *et al*. 2007).

- Conservation values benefit from the maintenance of spatial complexity and a diversity of land-uses in upland and mountain areas (Vandvik *et al*. 2005, Mauer *et al*. 2006). Small-scale farming systems helped maintain upland heterogeneity and species diversity through the agricultural intensification of the last 200 years, at least until the mid-20th century (Davies 1999, 2003, Davies *et al*. 2006). Systems such as crofting and 'hobby' farming could provide similar agri-environmental values as well as delivering social benefits (cf. Land Use Consultants *et al*. 2006, Scotland Rural Development Programme 2008).
- It has been suggested, based on current composition, that the tendency to maintain lower sheep numbers on sporting estates had a cushioning effect and contributed to the better condition of heather on some grouse moors (Bardgett *et al*. 1995). However, independent long-term data required to test this inference support are lacking and associated long-term faunal changes transcend sheep/sporting moor boundaries (Smith 1993, Smout 2000, Lovegrove 2007).
- In semi-natural woods, abandonment, neglect and non-intervention have resulted in a loss of arboreal diversity and simplification of woodland structure, to the detriment of natural and often poorly understood cultural heritage. A continued absence of active management may further reduce biodiversity compared with reinstating management (cf. Sutherland *et al*. 2006; 4.2 Woodland management & creation in the uplands).
- Long-term data are largely absent for other 'traditionally' managed habitats, many of which are designated, including upland hay meadows, wood pastures, dunes and machair (*e.g.* Brown 2006, McKenna *et al*. 2007, Holl & Smith 2007).
- 'Traditional', less intensive systems are valuable tools for conservation, but they are not necessarily sustainable by definition: market-driven fluctuations contributed to cycles of woodland regeneration and influenced grass- and heathland biodiversity within 'traditional' systems by effecting changes in stocking density (*e.g.* Hanley *et al*., accepted; 4.2.3 Woodland-grazing dynamics).

3.4 *Implications & gaps: wildness & management benefits & deficits*

- The intensification of resource management since the 19th century has contributed to the unprecedented scale of upland ecosystem change over the last two centuries, in some cases intensifying earlier climate- and grazing-mediated changes (*e.g.* erosion). On a scale of centuries, these have been driven largely by economic incentives, emphasising the role of policy as a driver of environmental change.
- Negative legacies are likely to be exacerbated rather than repaired by abandonment and non-intervention. This includes the uncertainties and subjectivities associated with 'wild land' and 'naturalness'.
- Lower-intensity management systems can provide strong support for biodiversity, including maintenance of landscape character and cultural heritage, but this requires greater recognition of the 'cultural' contributions underlying many current biodiversity and conservation values.
- The extent to which climate change, drainage and erosion will hasten the speed and extent of tree invasion is unknown as there are few historical precedents (4.2.1 Climate change, the fate and future of upland woods).
- The relative long-term impacts of sporting and different grazing management regimes (*e.g.* common grazings, grousemoors, deer management) are not fully understood.

- There is a pressing need for both the potential environmental and socio-economic impacts to be included in debates over of abandonment and reduced upland populations.

4. Resilience & restoration management

'*A great deal of current management practice is based on traditional techniques that did not originally have conservation objectives. Their effectiveness is often unknown and may be little more than myth*' (Sutherland *et al*. 2006)

- More flexible management and reducing potentially damaging stresses are central to enhancing the resilience (i.e. adaptability) of species and ecosystem processes in vulnerable environments, particularly to climate change (Hulme 2005). This 'managing for change' approach must be underpinned by a secure understanding of the likely responses to these threats over the longer term. In many instances, this involves some element of restoration. While restoration practice is based on ecological *science*, a historical lens indicates the prevalence of *preconceptions*, myths and value judgements which may threaten the success of restoration initiatives.
- Although changes in climate and habitat over time mean that restored systems may develop along different trajectories to the past, a long-term view can help assess whether recovery and restoration are feasible (i.e. within acceptable boundaries of ecological change), help shape realistic targets and monitor progress towards these, including estimates of the likely processes and timescales of change, and the effort and costs required (*e.g.* Parr *et al*. 2003).

Key findings & uncertainties:

- Long-term perspectives emphasise the prevalence of misconceptions inherent in restoration, including underestimates of timescales, feasibility and the extent of intervention required to achieve current targets.
- Management visions based on preconceived notions of 'normal' conditions are restrictive and threaten the resilience of the habitats they seek to restore and maintain.
- Uncertainties relating to future climatic impacts on peatlands and woodlands are not sufficiently integrated into current restoration strategies.

4.1 *Peatland resilience & restoration management*

4.1.1 *Natural hydrological variability: acceptable limits of change*

- Water-tables are integral to peatland functioning, wildlife values, maintaining C stores and erosion prevention (Bragg & Tallis 2001, Bragg 2002, Charman 2002). There is, however, a tendency to assume that many bogs should be wetter than present, and that, without human intervention, bogs would be treeless and that *Sphagnum*-dominated peatlands would be the 'norm' (Whild *et al*. 2001, Hendon & Charman 2004).
- This downplays the extent of past variability in hydrological, climatic and disturbance regimes that has been part of the developmental history of peatlands. Management based on misguided views or *ad hoc* decisions threatens the inherent adaptability and flexibility of upland ecosystems, potentially increasing their vulnerability to climate variability, especially to extreme events (Holden *et al*. 2004, 2007a, Hulme 2005).
- Peatlands have taken thousands of years to develop (*e.g.* Tallis 1998, Tipping 2007) and the most basic instruction from history for restoration is that extended timescales, with potentially high costs, will be required to return them to fully functioning and self-sustaining ecosystems.
    - *E.g.* The re-vegetation of bare peat under restoration may begin rapidly, but old peat cuttings in lowland Europe have taken more than 100 years to

  regenerate and is more likely where the original cuttings formed a relatively small proportion of the total mire, thus providing sources for seeds or other propagules, and relatively high water-tables (Charman 1997, 2002).

- Peatlands exhibit substantial spatial and temporal variability which has been lost from many extant examples and therefore potentially overlooked in local management and restoration targets.
  - *E.g.* Microtopographic differentiation of the blanket mire surface into pools, hollows and hummocks occurred through differential rates of local peat accumulation over more than 1000 years in the south Pennines (Tallis & Livett 1994). A system of pools and hummocks may have been present until relatively recent times on mires in N York Moors and N Pennines, prior to the rise to dominance by *Calluna* since the 19th century (Chambers *et al*. 2006). Many current moors provide little evidence for such diversity due to intensive erosion, pollution and land-use disturbance (Tallis 1987, 1997).

Case study 6: Peatland responses to environmental variability

- Raised and blanket mires have fluctuated between wetter and drier conditions on millennial and centennial scales, primarily as a result of climatic fluctuations: these were a normal part of ecosystem dynamics (Charman 2002).
- Over the last 200 years the Border Mires (N England) have experienced relatively dry conditions during the early 19th century, followed by increasingly wet conditions during the late 19th-early 20th centuries, before becoming drier since *c*.1930, in each instance altering surface composition (Hendon & Charman 2004). When drying was observed in the mid-20th century, it was attributed to afforestation on the surrounding peatland (most of which post-dates WWII) (cf. Battarbee *et al*. 1985, Shotbold *et al*. 1998) or the cessation of prior management. A longer view shows that these factors may be contributory but are not the sole cause.
- Pre-management change data, which may be lacking in many observational datasets, are essential to understand the origins and drivers of change, and thus instigate appropriate management. Remedial management (drain blocking, tree felling) may reverse a small component of mire drying, but efforts to raise water-tables may not be effective against long-term predicted climate change (cf. Evans *et al*. 2006, Holden *et al*. 2007b; 2.3 Carbon sequestration).

4.1.2 *Legacies of change: threats to peatland & moorland resilience*

- As current conditions for many drier moors and peatlands lie near the limits of past habitat change, these habitats may be close to crossing ecological thresholds, especially under predicted climate change scenarios which may give rise to conditions for which there is no past analogue in the last 10000 years (Mauquoy & Yeloff 2008).
  - Even modest climate change predictions are likely to cause significant drying in extensive wet *Sphagnum* carpets on ombrotrophic mires over the next 100 years, threatening highly valued conservation habitats (Charman 1997).
  - Reduced resilience to drought is likely to be a particular threat in some areas owing to a history of hydrological and ecological perturbations, combined with predicted future shifts. Summer droughts may be especially damaging since peatland water-tables are correlated with summer precipitation, which is predicted to decline in the future (Charman *et al*. 2004, Hendon & Charman 2004, Worrell *et al*. 2006b, IPCC 2007).

  - Risks are higher where conditions for peat formation are marginal and where moorland hydrology has already been severely affected by erosion and drainage, as agricultural impacts are also likely to be greater here (Hendon & Charman 2004, Yeloff *et al*. 2006). This must influence strategic planning and prioritisation in conservation decisions.
  - Reduced *Sphagnum* growth and increased cover of vascular plants, including trees, are likely to result and, in some cases, may already be doing so (Mauquoy & Yeloff 2008; 4.2.1 Climate change, the fate & future of upland woods).
- While drought alone poses a threat to peatlands and wetland restoration, drought coupled with other factors may prove even more difficult to predict and manage as impacts may be delayed or cumulative.
  - *E.g.* Low rainfall during the early 1900s on Fairsnape Fell (Lancashire) lowered water-tables and, in combination with an exceptional summer drought in 1921 and a decline in management during WWI, precipitated a catastrophic burn. This reduced heterogeneity, affecting invertebrate and bird populations (Mackay & Tallis 1996). Comparable circumstances have been recognised elsewhere in Lancashire, the North York Moors and South Pennines (Mackay & Tallis 1996, Yeloff *et al*. 2006).
- This threat compounds the loss of resilience caused by erosion, atmospheric pollution by S and N, and the cumulative impacts of increased and long-term grazing on moorland biodiversity (2.1 Erosion and 3.1 The attrition of diversity).

4.2 *Woodland management & creation in the uplands*

- Contributions on the distribution, composition and dynamics of past ‘wildwood’ have appeared in many publications on current upland and woodland management *(e.g.* O’Sullivan 1977, Birks 1988, Bennett 1995, Froyd & Bennett 2006, Tipping *et al*. 2006), and have also been the focus of the recent debates over large herbivore impacts and naturalistic grazing (Hodder *et al*. 2005, Luxmoore & Fenton 2005). While this pre-anthropogenic view is important for understanding woodland responses to climate change and may be relevant to ‘rewilding’ initiatives, extant semi-natural woods are largely products of cultural intervention, so the recent past is more appropriate for understanding (1) what underlies conservation current values, (2) the processes controlling wood-open ground dynamics and tree regeneration, especially interactions with grazers and climate, and (3) the most appropriate management tools, whether cultural (intervention) or natural (mimicry, non-intervention).

4.2.1 *Climate change, the fate & future of upland woods*

- While there are likely to be more woods in the future (4.2.4 New woods), the largely treeless state of the British uplands is often held to be a defining characteristic and concerns are raised about the adverse impacts of tree or scrub invasion on the quality of grazing and grouse moors, especially in England, in addition to the drying effects of trees growing on peat (Battarbee *et al*. 1985, Mackay 1995, Shotbold *et al*. 1998, Holden *et al*. 2007a, Fenton 2008).
- A consistent belief that bogs ‘should not’ have trees is an oversimplification (Chambers 1997, 2001, Wilkinson 2001), as is the assumption that the loss of upland woods, in general, is primarily a result of over-exploitation which can be rectified through restoration.

- Woodland growth was widespread in the uplands, forming the pre-moorland landscape, but the most extensive losses occurred in prehistory, not in the recent past (*e.g.* Tipping 1994, Simmons 2001, 2003). Significant changes in ecology, soils, land-use, settlement and climate in the intervening millennia pose difficulties for recreating similar woods and negate the use of historic over-exploitation to justify extensive woodland restoration.

- A prehistoric perspective is invaluable for assessing climate risks to woodland stability as the relationship between upland tree regeneration and climate was complex, particularly on peat.
  - Future scenarios include a combination of warmer climatic conditions with more frequent drought and reduced grazing pressures. This may create more favourable conditions for upland tree growth, even on wetter areas, since discrete episodes of tree colonisation have been a feature of blanket and raised bogs when mire surfaces were drier or when grazing and population pressures declined (Bridge *et al*. 1990, Gear & Huntley 1991, Mackay & Tallis 1994, Tipping *et al*. 2006).
  - Although drier conditions may favour trees, this may be countered by increased climatic variability, particularly increased wetness. Increased *winter* wetness in particular may lead to a southward retreat in the treeline in favour of wet heaths and bog, especially in northern, oceanic climates (Crawford *et al*. 2003). Past increases in oceaniticity caused stress and mortality in bog-grown trees on northerly peatlands, notably pines (Gear & Huntley 1991, Clark 2003, Tipping *et al*. 2006). Predictions of variability in the future and current uncertainties about how seasonality may change need to be understood in order to assess the long-term sustainability of planting and restoration schemes.
  - Furthermore, although species ranges are also strongly influenced by climate, we cannot expect most forest plant species to closely track the expected 21st century climatic changes as new analyses suggest that even the ranges of many widespread forest plant species may still be moderately to strongly limited by postglacial migrational lag (Svenning *et al*. 2008).

4.2.2 *'Ancient' & 'semi-natural' woodlands: management & diversity*

- A high proportion of semi-natural woods in the UK are located in upland areas and these are a subject of conservation concern due to the extent of decline over the last 50-60 years and the often poor state of regeneration (*e.g.* http://www.forestry.gov.uk/website/forestresearch.nsf/ByUnique/INFD-63AJF7).
- It is often assumed that existing woods provide an appropriate template for long-term management and that human impact has been largely detrimental. However, narrow definitions of what a native wood 'should' look like, using 'present-natural' or 'future-natural' approaches (Peterken 1996), data covering timescales less than a single generation of trees, or visible historical features (*e.g.* pine stumps in peat, veteran trees), can seriously underestimate 'natural' diversity and lead to the preservation and creation of impoverished woods which are less resilient to change (*e.g.* Tipping *et al*. 1999, Willis *et al*. 2005). Equally, if used simply as a baseline for woodland re-creation, 'past-natural' conditions provide little more than snapshots which will not accommodate future edaphic, climatic or biotic change (Tipping *et al*. 1999).

Case study 7: Management legacies in oak- & pinewoods

- Many semi-natural upland woods show limited regeneration under non-intervention management strategies because supposedly 'natural' features actually stem from past management.
- The distinctive, apparently natural characteristics of internationally important Atlantic oakwoods in N England, W Scotland, N Wales and SW Ireland have no long history: they have developed since the cessation of timber and grazing management around 100-200 years ago (Edwards 1986, 2005, Mitchell 1988, 1990, Birks 1996, Sansum 2004). Many of the currently dominant oaks, if not planted, were nurtured under previous management regimes and have matured under conditions of more recent neglect.
- Current appearances reflect a legacy of manipulation of woodland structure, age distribution and species composition over the last c.400-1000 years to provide products ranging from timber, coppice poles, charcoal, tanbark and grazing. These factors limited shrub growth, maintained a more open, disturbance-adapted ground flora and made timber harvesting easier, while species selection and repeated disturbance have reduced tree-species diversity (Mitchell & Kirby 1990, Mitchell 1988, Birks 1993, Sansum 2004, Edwards 2005, Davies & Watson 2007). 'Natural' features such as deadwood accumulation and limited numbers of shade-tolerant species have been scarce or absent for at least two centuries before 1900 owing to this management history (Sansum 2004).
- Consequently, a disturbance regime is required to maintain current values and herbivore exclusion alone is unlikely to result in widespread regeneration (*e.g.* Palmer *et al*. 2004).
- Bryophytes have limited value as ancient woodland indicators since the persistence of valued, rich bryophyte floras stems from the presence of 'semi-woodland' habitats and microrefugia (*e.g.* streamsides, crags), and the fact that the woods were never temporarily converted to other land-uses (Edwards 1986, Mitchell 1988, Sansum 2004, cf. Day 1993, Willis 1993).
- The present single-dominant stands in many ancient Scots pinewoods are also a legacy of formerly extensive management and their subsequent relaxation. Before intensive management during the 18-19th centuries, woods in Abernethy (NE Scotland) and Glen Affric NNR (NW Scotland) contained a more diverse mix, including more birch and less heather in Abernethy (O'Sullivan 1977, Shaw & Tipping 2006). Furthermore, at least some of the apparently mature woodland stands in Migdale NNR (N Scotland) have become comparatively unstable and depauperate over recent centuries owing to the cessation of timber and grazing management (Davies & Smith in press), with similar loss of diversity in Glen Affric over the last c.200 years (Shaw & Tipping 2006). Tree-ring data emphasise the extent of demographic change and generally low recruitment in these pinewoods, particularly in unmanaged sites (*e.g.* Edwards & Mason 2006).

4.2.3 *Woodland-grazing dynamics*

- Recent debates over wood-grazing interactions have focussed on extinct 'wildwood', 'naturalistic' conditions and the role of large herbivores (Hodder *et al*. 2005, Luxmoore & Fenton 2005). These have little in common with existing semi-natural woods, which may benefit from controlled grazing to maintain conservation priorities owing to their long management histories (Kirby 2004). Historical perspectives indicate the regeneration impacts of a broader variety of grazing regimes than ecological data, which mostly relate to grazing exclusion (Mitchell & Kirby 1990).

   - Over the longer-term, variable grazing pressures have beneficial impacts on regeneration, including those arising from market-led fluctuations in livestock and timber prices (*e.g.* Davies & Watson 2007, see Grant & Edwards 2007 for a lowland context). While chance variability cannot be relied upon to maintain conservation values or encourage regeneration in upland woods, particularly during times of increased climatic and economic uncertainty, variable disturbance provides the basis for flexible management regimes which foster tree seedling recruitment and maturation, since grazing exclusion only has short-term benefits (*e.g.* Mountford & Peterken 2003).

- Many semi-natural upland woods have formed under managed grazing regimes to the extent of creating wood pastures, which require grazing to maintain their distinctive open character (Mitchell & Kirby 1990, Kirby *et al*. 1995, Davies & Watson 2007, Holl & Smith 2007).
   - Remnants of wood pasture systems support high conservation value invertebrate, bird and lichen communities and are probably widespread, but there is no inventory and little historical basis for their identification, making them vulnerable to mismanagement, including overgrazing (Kirby *et al*. 1995, Begg & Watson 1999, Holl & Smith 2007). They are also threatened by misconceptions over naturalness, which, in other semi-natural woods, has led to the loss of conservation values through clearance and under-planting by 20th century afforestation (*e.g.* Truscott *et al*. 2004).

4.2.4 *New woods: restoration & multi-purpose resources*

- Policy initiatives are likely to support woodland expansion to enhance biodiversity and provide multiple-purpose resources, incorporating 'ancient semi-natural' woodland, new native woods, forestry and perhaps 'rewilding' (Lee 2001, Land Use Consultants *et al*. 2006, Holden *et al*. 2007b, Slee 2007). However, this desire must balance ecological, agri-economic, archaeological and aesthetic concerns over more trees in the uplands, including the pressure this will place on moorland habitats, as well as concerns over the future sustainability of new woods (Scottish Natural Heritage 2002b, Holden *et al*. 2007a, b, Fenton 2008).
- As indicated above, most woodland expansion cannot be justified by assuming that past human influences have been either excessive or superficial. Using past over-exploitation and pine stumps preserved in peat to justify woodland replanting risks repeating the erroneous assumptions used to justify the afforestation of the Flow Country blanket peat in northern Scotland (Huntley 1991).
- A historical perspective contributes information on the biodiversity value of upland woods relative to other habitats, the potential long-term feasibility and appropriate structure for new native upland woods. Many woods were managed for multiple purposes in the past, and understanding the range of potential ecological and diversity impacts can inform the drive to establish more multi-purpose native woods.

Case study 8: Planning for new pinewoods & expanding the old

- Current managers wish to expand the existing pinewoods into treeless areas around Glen Affric NNR (NW Scotland) and to link woods in the neighbouring catchments of Abernethy and Glenmore (NE Scotland) (Forestry Commission 2003, Beaumont *et al*. 2005, Midgley 2007). It is assumed that this will restore more widespread former distribution, contribute to connectivity and foster resilience and diversity, frequently with the implication that people were causal in woodland contraction.

- Long-term evidence suggests that the likelihood of achieving these aims is, at best, uncertain. More extensive woodland cover of the type envisaged in these proposals has been absent for nearly 4000 years in Affric, owing to climatic change, subsequently exacerbated by grazing pressures and increased peat depth, while the pass between the pinewoods in Abernethy and Glenmore has been dominated by open heath since at least the fifth millennium AD, with sparse tree growth for the last 1000 years or more (O'Sullivan 1973, Tipping *et al*. 2006).
- Management must allow flexibility and incorporate rather than seek to replace open ground habitats: many upland woods show shifting patterns of regeneration such that only a small proportion of the Abernethy pinewoods, for example, has been continuously wooded and fluctuations between heaths and trees were essential to long-term regeneration and diversity (O'Sullivan 1973a, Smout *et al*. 2005, Shaw & Tipping 2006, Tipping *et al*. 2006).

4.2.5 *Implications: woodland restoration & creation*

- Management decisions based on woodland appearances are frequently misleading as a historical perspective contradicts many ideas of 'naturalness': continuity of woodland cover should be equated with a long-valued and managed resource, not with structural or compositional stability or a high degree of naturalness.
- 'Present natural' woods do not resemble existing woods with regeneration: human impacts are not a superficial veneer but integral to many conservation values. This subject requires re-examination comparable with that afforded to 'naturalistic' grazing in woods following the work of Vera (2000, *e.g.* Hodder *et al*. 2005).
- Non-intervention, promoting natural processes or the pursuit of pre-anthropogenic baselines or 'naturalistic' systems in habitats which do not, in reality, have a high degree of naturalness may result in the loss of current conservation values and their underlying cultural histories, so increasing future uncertainties (Tallis 1998, Hodder *et al*. 2005, Midgley 2007, Grant & Edwards 2007).
- Management policies that do not take account of the relatively recent and successional character of the present canopy of such woods may seek to preserve idealised rather than functional ecosystems (Huntley 1991, cf. Midgley 2007, Grant & Edwards 2007).
- Similarly, evidence of past woodland sensitivity to climatic perturbations means that the pivotal role of climate must be integral to the management of existing and new woods if they are to outlast one generation, especially since centennial timescales will be needed to attain these goals, with a strong likelihood of further climatic variability during this period.
- Patchy and scattered tree growth, not closer grown 'woodland', is likely to provide a more feasible and appropriate target under future scenarios, particularly on peat.
- Target treelines in restoration must always be seen as a theoretical, moving target since treelines have always fluctuated in response to climatic conditions, human activity, grazing and browsing pressures (*e.g.* McConnell & Legg 1995, Tipping 1997).

4.2 River management & restoration

- The growth of interest in river restoration reflects concerns over water quality and supply, pollution, flood prevention, the quality of fish populations, as well as habitat and biodiversity losses, strengthened by the Water Framework Directive (Scottish Natural Heritage 2002a, Land Use Consultants *et al*. 2006, Sear & Arnell 2006; 2.1 Pollution and 2.2 Erosion).
- More naturalistic river ecosystems could help with water management, erosion and flood control, in addition to enhancing biodiversity (Brown 2002). However, data on more natural river systems are scarce owing to an extensive history of management and modification, as reflected in the high proportion of river sites designated as SSSIs that remain in unfavourable condition. This makes it difficult to define the 'natural' range of conditions and sensitivity to climatic and land management factors which are required to establish robust principles for river corridor and floodplain restoration and management (Brown 2002).
- Channel structure affects sediment flow patterns and flood implications, and is shown to have been complex prior to extensive modification (Brown 2002, Sear & Arnell 2006). Consequently, many of the wetland communities which have been depleted or lost through floodplain modification were characterised by diversity and flexibility to respond to natural instability caused by flooding and sediment reworking. This includes formerly extensive alluvial and floodplain woods (largely relegated to prehistory in the UK; *e.g.* Innes & Simmons 1988, Davies 2003), as well as open and less intensely managed floodplains and river corridor habitats, such as marsh, floodplain meadow and wet grassland (Brown 2002). Work on lowland sites demonstrates the high diversity of such habitats (*e.g.* Brown 2002), but comparable data remain relatively scarce for the uplands.
- Over the last 100 years, river catchment dynamics have been determined by land management more than climate (Owens and Walling 2002), but climate is a significant driver over decadal and longer timescales, particularly as a determinant of flood frequency (Macklin & Rumsby 2007) and therefore must be incorporated into management and restoration strategies (cf. Wilby *et al*. 2006).
- Retrospective data are also valuable for developing and validating models of river structure, behaviour and flood risk (Anderson *et al*. 2006, Sear & Arnell 2006).

5. Climatic & economic change: rural risk & resilience

‘*Over the next century, the climate is in predicted to change more rapidly than at any time in the recent geological past, and also to attain a state unparalleled during that same period.*’ (Huntley & Baxter 2002)

- The socio-economic and environmental challenges of climate change are central to current Rural Development Strategies, especially since climatic impacts are often exacerbated by management practices and economic incentives (*e.g.* Defra 2007, Stern 2006). A retrospective view thus helps identify conditions which contribute to the vulnerability or resilience of upland communities (*e.g.* Hulme 2005, Fraser 2003, 2007).

Key findings & uncertainties:

- Analysis of past climatic risk to farming emphasises the extent to which economics outweighs climate as a driver of upland agriculture.
- The reliance of agricultural communities on economic incentives and support mechanisms limits opportunities for local diversification and increases the vulnerability of rural communities.
- This should provide a strong impetus for collaboration between social and natural scientists, policy-makers and rural stakeholders, to create more effective links between local production and management, and national policy and patterns of consumption.

- This brief section focuses on past social responses to climate change relative to economic change to emphasise warning signals and possible options for supporting rural communities.
- Partial abandonment is a potential future scenario for the uplands (*e.g.* Land Use Consultants *et al*. 2006). Reference to the past reinforces the severity of the stresses currently facing upland farmers since abandonment has always been a last resort, often resulting from the disintegration or ineffectiveness of support systems, particularly policy and economics.
    - *E.g.* Instances of medieval and historic upland abandonment were caused by repeated harsh weather, severe disease and the associated failure of crops and redistribution support systems, often exacerbated by reliance on a narrow production base, as is best documented by the 1840s potato famine (Mackay & Tallis 1994, Fraser 2003, Yeloff & van Geel 2007). The constant reiteration that rural communities need to diversity reflects the continuing risk of relying on a narrow production base.
- There is stronger evidence for adaptation via short-term abandonment (lasting a few years), extensification and amalgamation, i.e. abandonment of a farmstead but not necessarily of the land, as well as evidence of continuity which suggests that economic drivers or incentives at times overrode climatic difficulties (Whyte 1981, Tipping 1998b, Dodgshon 2006).
    - However, present conditions are more acute and pressures to diversify more intense since many past support systems are now absent: production-related economic incentives are no longer a viable means of supporting land-use, and most current upland farming systems lack social buffers or the ability to vary production to suit economic or weather conditions.
- As ecological damage and biodiversity loss have often arisen during periods of high economic incentives (*e.g.* Hanley *et al*. accepted), monitoring systems must incorporate environmental/natural, social and economic criteria to avoid the risk

of crossing critical thresholds and exacerbating ecological damage whilst sustaining rural economies, and *vice versa*. This gives added impetus for collaboration between social and natural scientists, policy-makers and stakeholders (cf. Parr *et al*. 2003, Turner *et al*. 2003, Dougill *et al*. 2006, Fraser *et al*. 2006, Stevens *et al*. 2007).

- It is essential not to allow the natural human tendency to downplay the severity of future risks to shape policy or management. Decisions are and were based on short-term perspectives, which tend to downplay threats during good times (*e.g.* leading to expansion onto floodplains or less favoured hill ground) and forget that extreme events, which are predicted to become more frequent, always exceed average expectations (Whyte 1981, Dodgshon 2004).
- There has always been a strong regional component in climatically driven hardships and in the responses which ensured resilience. This must affect how policy is formulated and put into practise, as reflected in the call by land managers for local flexibility in the application of rural development strategies (*e.g.* FWAG 2006).

General implications

- Reliance on short-term insights in upland policy and management may be detrimental to the future viability of the uplands since the origins of many current problems and values lie in the past.
- The most immediate observation from hindsight regards the dynamism of upland habitats; this must be recognised and accommodated in management strategies. Reference to the past helps distinguish between acceptable ranges of variability and unprecedented changes, including situations for which there is no past analogue, and indicates the sensitivity of systems to external change under a potentially broader range of landscape scenarios than is possible through short-term and experimental datasets. This can be used to identify vulnerability as well as good practice.
- Past legacies may have set some habitats on a trajectory of change, such that critical thresholds may already have been crossed, as for example, in relation to peatland susceptibility to erosion and drought, particularly on southern and eastern moors. It is likely to become increasingly difficult and costly to maintain or restore such habitats based on current or fixed values.
- A non-compartmentalised approach to policy, management and research is essential due to the damaging impacts of interacting factors, as in the case of erosion in peatlands already sensitised by a history of climatic and management change, or the detrimental ecological impacts of some economic incentives.
- Decisions must be underpinned by informed and flexible baselines and targets, since narrow or fixed definitions of ‘naturalness’, what a habitat ‘should’ look like or what constitutes current ‘good condition’ may generate unrealistic and inappropriate goals by excluding the natural range of variation and perpetuating misconceptions. Examples include the cultural influences behind the apparently ‘natural’ characteristics of many ‘ancient’ and semi-natural woodlands.
- Many valued attributes derive explicitly from cultural interactions and management strategies, rather than mimicking natural processes, are thus required to maintain existing values. This provides a positive impetus for the integration of conservation into agri-environmental schemes, which may avoid prioritising nature conservation at the cost of rural communities and cultural heritage.
- Uncertainty is implicit in non-intervention and ‘naturalistic’ management policies: considered debate is needed to assess whether these are acceptable, in view of uncertainties over the resilience of some current habitats and the need to secure sustainable livelihoods for rural communities. This applies to the feasibility of maintaining peatland water-tables against climate change and the likelihood of further woodland attrition where the extent of former modification is ignored.
- More debate is required over acceptable and ecologically sound directions of change, and what alternative aims and scenarios may be achievable; this will require a reassessment of conservation and restoration baselines, targets and the underlying assumptions to move from preserving idealised landscapes to managing dynamic and resilient ecosystems.
- Best practice approach must foster more interaction between ecologists and historical contributors, as the exchange of information will ensure that appropriate data are available to underpin policy and management decisions, so that the management of upland resources is sustainable for all stakeholders.
- Routine use of long-term sedimentary records of nutrient and pollution status in current management and policy regarding freshwater lakes provides a model which can be applied to other aquatic and terrestrial environments.

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