Applications of Palaeoecology in Conservation

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Abstract: We review several case studies (water quality, upland management, woodland management) where palaeoecological data are able to contribute to current debate in conservation practice and ecology, as part of a wider consideration of the relationships between palaeoecology and conservation. We conclude that, although there are structural and inherent barriers that currently limit flow of information and collective working, the current environment of challenging policy targets and rapid environmental change makes better collaboration particularly urgent.

Keywords: Applied palaeoecology, horizon scanning, conservation baselines, biodiversity, Water Framework Directive, Atlantic woodland, Scots pinewood, moorland management, woodland ecology.

INTRODUCTION

The prospect of environmental change beyond the range of variability within which conservation practice has developed provides a powerful stimulus to evaluate the effectiveness of current practice. It is giving impetus to explore how additional sources of evidence can reduce uncertainty and improve decision-making, including interdisciplinary approaches to conservation planning, incorporating social, economic, political and scientific constraints and evidence (*e.g*. Parr *et al*. 2003; Holden *et al*. 2007; Reed *et al*. 2009). Facing challenging policy targets and rapid environmental change, conservation practitioners need the most complete evidence base possible to balance the competing demands of protecting and enhancing the natural environment, whilst maintaining the range of ecosystem services that society derives from it.

One area of apparent weakness in much of the evidence-base used for conservation is the strong present-future focus. Long-term perspectives are implied in the language used in conservation policy documents, since terms such as 'sustainability', 'heritage' and 'resilience' are concepts with a substantial time dimension. However, this implication is seldom followed up by any substantive use of long-term perspectives in ecological research agendas or conservation practice. Outside the spheres of built heritage and archaeological monuments, past and historical perspectives tend to be marginalised in debate. Although their considerable potential value for helping landscape and ecosystem conservation activities achieve the targets and goals defined in light of neoecological, social and pragmatic constraints is recognised in the academic literature (*e.g*. Foster *et al*. 1990, Swetnam *et al*. 1999, Birks 1996, Willis *et al*. 2007, Froyd & Willis 2008), they as yet rarely play much part in ecological or management debates. For instance, analysis of the 100 questions of conservation importance identified by Sutherland *et al*. (2006) found that answering 54 of those questions required at least some consideration of processes acting over multiple years or of conditions in the past as well as the present (see Table **1**). In practice, and despite the many papers setting a clear rationale for the value of alternative long-term records, datasets used as the evidence base for practice tend to be relatively short-term and rely overwhelmingly on ecological observation and experiment. For example, no dataset used in the Millennium Ecosystem Assessment (2005) is longer than 50 years in duration. This apparent lack of time-depth can generate misleading inferences and potentially lead to inappropriate management activities.

'Long-term' studies, those incorporating data from a time range of fifty years or more, exceed human generations, and are one or more orders of magnitude longer than the typical 3-5 year span of research funding, management planning or political programming. Such datasets matter because many ecological processes 'play out' over decades and centuries (Delcourt & Delcourt 1991, Morecroft *et al*. 2009). The relatively long life spans of many important taxa (*e.g*. trees, dwarf shrubs, larger mammals and birds) mean that population consequences of system change may not be fully seen for decades (Willis *et al*. 2005, Grant & Edwards 2008, Lindbladh *et al*. 2008). A particularly striking example of this is the concept of 'extinction debt' (Kuussaari *et al*. 2009).

These issues are recognised in a recent review of the first fifteen years of monitoring at the Environmental Change Network sites, where Morecroft *et al*. (2009: 2830) write that "trends in physical, chemical and biological parameters are emerging which could not have been detected at an earlier stage. This is still, however, a relatively short time compared to many ecological processes". Longer-term effects were often masked by substantial inter-annual variability during

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Table 1. Summary of Potential for Palaeoecological Data to Contribute to Discussion of the 100 Key Questions for UK Conservation Policy Identified by Sutherland *et al.* (2006)

	Potential for palaeoecological data to contribute to the discussion	major	minor	minimal
	ECOSYSTEM SERVICES			
1	What are the benefits of protected habitats… relative to non-protected land?	X		
2	What is the role of biodiversity in maintaining specific ecosystem functions?	X		
3	What are the roles of soil biodiversity (…) in ecosystem function, resilience and recovery?			X
4	How does soil biodiversity both influence and respond to above ground biodiversity?			X
5	What is the role of marine biota and benthopelagic coupling in ocean-atmosphere carbon coupling and primary production?			X
6	How can we measure natural capital (…) and integrate such a measure into GDP?		X	
	FARMING			
7	How will CAP reform affect biodiversity at the landscape scale?	X		
8	What are the environmental consequences of farming patterns…?	X		
9	How do farming systems … compare in terms of their effects on… environmental impacts?	X		
10	How for current agricultural practices affect the conservation value and extent of non-agricultural habitats… and how can detrimental impacts be mitigated?		X	
11	What are the impacts of agricultural activities…on soil biodiversity and function?		X	
12	What are the ecological consequences of changes in upland grazing regimes for biodiversity and soil ecology?	X		
13	What are the impacts on soil and…invertebrates of poaching… and soil compaction at different stocking levels?			X
14	What are the impacts on biodiversity of prophylactic treatment of farm livestock…?			X
15	What lessons can be learnt from agri-environment schemes to optimise their…benefit?			X
16	How does the ecological impact of UK farming compare internationally?		X	
	FORESTRY			
17	What are the environmental benefits of large-scale woodland planting schemes…?			X
18	Where should new woodlands be located?		X	
19	What overall number, age structure and spatial distribution of trees are necessary for the long-term survival of species dependent on ancient/veteran trees?		X	
20	What are the relative benefits for biodiversity of the re-introduction of management to… semi-natural woodlands *vs*…. absence of active management?	X		
21	Why have many woodland birds declined?		X	
22	Which approach to the removal of plantations on ancient woodland sites… yields the greatest biodiversity benefit?			X
	FISHERIES, AQUACULTURE AND MARINE CONSERVATION			
23	What is the biodiversity impact of the harvest of forage fish…?			X
24	What are the ecological impacts of… [inputs] from aquaculture?		X	
25	How important are caged fishes as reservoirs of parasites and pathogens…?			X
26	What are the direct… and indirect… impacts of commercial fishing on cetaceans and seabirds?			X
27	How large should marine protected areas be, and where should they be located…?			X
28	What will be the impact of marine protected areas on wide-ranging species…?			X
29	How important are coastal, estuarine, and fluvial habitats for endangered migratory fish populations…?		X	
30	What is the range of minimal viable population sizes for broadcast spawning marine species?			X
31	How long does it take the seabed to recover from disturbance…?	X		

(Table 1) Contd…..

	Potential for palaeoecological data to contribute to the discussion	major	minor	minimal
	RECREATION AND FIELD SPORTS			
32	What are the impacts of recreational activities on biodiversity?		X	
33	Which ecological principles should guide the choice of…species appropriate for game exploitation?			X
34	What overall impacts do introductions of game species… (including recreational fishing) have on biodiversity?		X	
35	What are the ecological impacts… of a ban on hunting with dogs?			X
	URBAN DEVELOPMENT			
36	How can provision for wildlife be maximised in… urban [sites]?			X
37	What are the consequences for biodiversity of fragmentation by development and infrastructure?		X	
38	What are the ecological impacts on semi-natural habitats and ecosystems of adjacent large developments…?		X	
39	How can sustainable urban drainage systems be optimally designed…?			X
	ALIENS AND INVASIVE SPECIES			
40	What criteria should be used to determine when to intervene to deal with invasive species?		X	
41	How can we manage microbial ecology to control invasive plant pathogens?			X
42	How can we understand better the epidemiology… of diseases within wildlife reservoirs…?			X
43	What are the genetic threats to UK biodiversity posed by introgression from genetically modified organisms…?			X
44	What is the optimal method of managing bracken-dominated habitats…?		X	
45	What are the effects of domestic cats on vertebrate populations…?			X
	POLLUTION			
46	What impact does plastic-derived litter have on the marine environment?			X
47	How can one ameliorate the effects of aerially deposited nitrogen…?		X	
48	What are the critical thresholds for nitrogen and phosphorus inputs into water…?	X		
49	…which [chemicals] are or are likely to become significant environmental problems…?			X
50	What are the long-term impacts of depositing… organic wastes on to agroecosystems?			X
51	How can catchment management be used to reduce diffuse pollution?		X	
52	How will acidification of surface water from rising CO_2 concentrations affect… marine organisms?	X		
53	What are the effects of light pollution… on wildlife…?			X
	CLIMATE CHANGE			
54	Which species are likely to be the best indicators of the effects of climate change on natural communities?	X		
55	Which habitats and species might we lose completely in the UK because of climate change?		X	
56	What will be the ecological impacts of changing agricultural patterns in response to climate change?			X
57	What time lags can be expected between climate change and ecological change?	X		
58	What is the likely relationship between the extent of climate change and the pattern of species extinction?	X		
59	How does climate change interact with other ecological pressures…?	X		
60	How can we increase the resilience of habitats and species to cope with climate change?	X		
61	How well suited is the current UK protected area system for conserving biodiversity… and how can it be enhanced…?		X	
62	How will changes in oceanographic conditions… affect marine ecosystems?	X		
63	What actions are required to recreate the full range of coastal landscapes, habitats and species distributions to compensate for their loss, for example as a result of sea level rise?			X

(Table 1) Contd…..

	Potential for palaeoecological data to contribute to the discussion	major	minor	minimal
	ENERGY GENERATION AND CARBON MANAGEMENT			
64	What are the consequences of biofuel production for biodiversity at field, landscape and regional levels?			X
65	What are the potential impacts of a) terrestrial and b) marine windfarms on biodiversity?			X
66	What are the comparative biodiversity impacts of newly emerging types of renewable energy such as tidal energy?			X
67	How can soil carbon be retained and further carbon sequestered in the soil?		X	
	CONSERVATION STRATEGIES			
68	How can biodiversity action plans be designed to take account of larger scale population processes?		X	
69	How can we best measure favourable conservation status for each of the species and habitats listed within the EU's habitats directive?			X
70	How effective is the current UK protected area network…under current conditions?			X
71	With what precision can we predict the ecological impact of different policy options and the ecological effects of management action?	X		
72	At an international scale, what are the ecological implications of conservation actions and policies adopted within the UK?			X
73	How effective as indicators of overall biodiversity are current indicators…?			X
74	Why are common moths declining and are their declines driving declines in other taxa…?			X
75	What scale and type of land-use change is required to halt the decline in biodiversity…?		X	
76	Are there reliable ways to predict the long-term sustainability of populations of poorly known species (*e.g.* most invertebrates) using … ecological characteristics?		X	
	HABITAT MANAGEMENT AND RESTORATION			
77	What are the costs and benefits of concentrating conservation work on designated sites…?		X	
78	What are the ecological consequences of 'wilding'…as a long-term conservation strategy?	X		
79	What are the consequences of different moorland management techniques… for the uplands…?	X		
80	What measures of habitat condition should we use to measure habitat change in protected areas?		X	
81	How should ditches… be managed...?			X
82	What hedgerow structure and…management produce the greatest wildlife benefits?			X
83	How do recreated habitats differ from their semi-natural analogues?	X		
84	How can we effectively prioritise ...large-scale ecological restoration projects…?			X
85	What is the most appropriate and ecologically sustainable way of dealing with excess nutrients during …habitat restoration?		X	
86	What are the implications of changing deer densities for agriculture, forestry and biodiversity in different landscape types?			X
87	In reintroductions, does local provenance matter?...			X
	CONNECTIVITY AND LANDSCAPE STRUCTURE			
88	What are the lag times between habitat fragmentation and the loss of species…?	X		
89	Is it better to extend existing habitat patches or create further patches within a landscape?			X
90	How should we manage landscape mosaics for the conservation of diverse taxa that operate on different spatial scales?			X
91	What are the relative merits of different indices of habitat connectivity?...			X
92	What is the value of linear habitats…?			X
93	For [relevant] species… how can 'source' and 'sink' populations.. be identified…?			X
94	How important are core versus peripheral areas in the conservation strategy of a species?		X	
95	How reliant are animal and plant populations in small nature reserves on the maintenance of habitat in surrounding non-protected areas?		X	

(Table 1) Contd…..

	Potential for palaeoecological data to contribute to the discussion	major	minor	minimal
	MAKING SPACE FOR WATER			
96	What have been the consequences of past and present riparian engineering works…?	X		
97	What would be the ecological implications of large-scale rive and floodplain restoration schemes… and would they be... cost-effective...?	X		
98	What are the likely consequences for biodiversity of changes in water quality and sedimentation in rivers?		X	
99	What methods most accurately measure ecological status in the EU water Framework Directive?	X		
100	How can flood control be assisted by... habitat management and restoration…?		X	

shorter monitoring periods. Results like this suggest that reliance on short timeframe monitoring and experimental data for the evidence base in conservation practice is insufficient. Given the rapid rate of change in landscape-impacting human activities and projected climate changes, extending conventional methods to longer time frames using a ‘wait and see’ approach is not possible either. Conservation practice needs to explore other routes to the necessary evidence base; Pullin & Knight (2003) identify shortcomings in current research practice networks, and others call for increased horizon scanning to improve anticipation of change (Sutherland *et al.* 2008, Sutherland & Woodroof 2009). While palaeoecology remains an underused resource in conservation, it is clear long-term ecological datasets are an essential resource for predicting the consequences of management interventions and for establishing appropriate strategies in research, policy and practice. They can assist in identifying alternate steady states, quantifying natural variability and identifying thresholds of risk for state change events, and remind us of the probability of future ‘ecological surprises’.

In this paper, we draw together previously published palaeoecological case studies to give concrete examples of how a long-term perspective can contribute to ecological debate and conservation management. Recent literature shows increasing awareness of the potential use of palaeo-ecological data, and by giving specific illustrations of practical application this paper aims to contribute to the transition from awareness of potential towards regular use of long-term data in conservation ecology, and improved communication with conservation ecologists in the design and dissemination of palaeoecological research. We then consider briefly some of the barriers to achieving this transition and means of lowering them.

PALAEOECOLOGY IN THE CONSERVATION TOOL KIT

Palaeoecology is one of a suite of approaches available for acquiring long-term datasets. It forms a time-efficient alternative to long-term monitoring, since data covering several hundred (or thousand) years of change can be acquired from months of research effort. Palaeoecology can be understood as reading the results of natural or historical experiments that were begun a long time ago, and whose evolution is recorded in the sedimentary archives of lakes and mires. Much published palaeoecological research begins by or focuses on reconstructing past ecosystems and system dynamics over time. These reconstructions offer an evidence-based challenge to short-term understandings of ‘typical’ ecosystem function, and can be particularly useful in disentangling the relative importance of different drivers and disturbance regimes, such as management activities and climate change, in ecosystem development or population dynamics. Site histories contextualise and explain the present status of the site, offer a means of presenting landscape as cultural heritage, and can be of considerable interest to stakeholder groups and an effective tool in engaging local community interest. They can also provide clear grounds to support management decisions; for example, demonstrating that a site has been a raised mire for 3000 years and was only colonised by trees in the last 20 years can be a compelling argument for woodland clearance.

A common misconception is that these techniques only provide generalised background to a site, disconnected from current management concerns, or are solely useful for definition of a restoration target in terms of known past conditions. Whilst palaeoecological data can effectively deliver these outcomes, they also offer insight into processes and system function. Demonstrating that sites formerly had a higher ecological value or which sites are closest to ‘pristine’ or ‘pre-disturbance’ status can be used directly to prioritise sites and set targets for highly interventionist conservation activities such as restoration or re-creation of habitats in a minority of situations (Cumming *et al.* 1994). However, in most cases it is questionable whether selecting fixed points from the past as future goals will result in sustainable ecosystems, particularly in the face of unprecedented and uncertain anticipated environmental changes. Palaeoecology demonstrates the ephemeral nature of community composition over the longer term, and since present environmental conditions and the wider landscape setting are different to those prevailing in the past, faithful re-creation of the past is unrealistic (William & Jackson 2007). Target-setting can however draw on palaeoecological data to define more general measures of ecosystem health relative to present ecosystem status (*e.g.* estimates of water chemistry, dominant species or relative biodiversity).

Britain has a long tradition of palaeoecological research, partly owing to the combination of climate and geomorphology which means that mires and lakes - and therefore waterlogged sediments containing palaeoecological records - are fairly common landscape elements. Since relatively undisturbed sites often occur in areas of conservation interest, records tend to come disproportionately from such locations. This means that there is already a rich resource of data in the academic literature, generated over the last 40 or so years (*e.g*. Oldfield 1970, Huntley 1991, Birks 1993, 1996, Brown 2002), which can be mined to explore a variety of issues relevant to the current state and future trajectories of the physical environment. To illustrate these principles and applications of long-term evidence to current questions of conservation importance, and consider the extent to which they influence conservation practice, five UK case studies are presented in response to questions raised by Sutherland *et al*. (2006).

CASE STUDY 1: THE WATER FRAMEWORK DIRECTIVE (QUESTION 99: SUTHERLAND *et al*. 2006; SEE TABLE 1)

The European Union Water Framework Directive (WFD; European Union 2000) is designed to drive integrated management of surface waters at the catchment scale throughout Europe over several decades, and its main objectives are to prevent further deterioration, provide long-term protection and enhance the status of water resources by achieving 'good ecological quality' in all relevant surface water bodies by 2015. Since its goal is integrated management of fresh water bodies, the WFD emphasises ecological structure and function, with physical and chemical parameters recorded as supporting elements. The definition of ecological quality is intrinsically historical in character, since quality is "judged by the degree to which present-day conditions deviate from those in the absence of anthropogenic influence, termed reference conditions. Sites in which the various elements correspond totally or almost totally to undisturbed (reference) conditions will be classed as High status" (Bennion & Batterbee 2007: 285).

Identifying reference conditions is a vital first step to compliance with the WFD, and the Directive itself includes hindcasting methods such as palaeolimnology (the study of long-term ecosystem dynamics within lakes and ponds) in the list of possible methods to be used. Member States define river basin districts, identify and characterise the water bodies into ecotypes, and then describe type-specific reference conditions. Since almost all European waters are affected by human activity to some extent, identifying a suite of undisturbed comparison sites ranges from difficult to impossible (*e.g*. for highly cultural landscapes such as lowland England), depending on the river basin district and ecotype. Long-term monitoring series rarely extend to before major periods of disturbance (*e.g*. the Industrial Revolution) and even when data series do exist, problems such as a lack of methodological continuity frequently restrict their usefulness. Derivation of site-specific reference conditions from the sediment record therefore offers a valuable addition to the tool kit and, for some sites such as shallow lowland lakes, may be the only way to determine pre-impact conditions (Bennion *et al*. 2003).

Since the WFD focuses on ecological quality, a multi-proxy approach to reconstruction is needed. Bennion and Battarbee (2007) review various ways in which palaeolimnological methods are used to determine physico-chemical reference conditions, such as *via* diatom-inferred Total Phosphorous and pH (*e.g*. in Scotland: Battarbee *et al*. 2005, Finland: Kauppila 2006 and Ireland: Leira *et al*. 2006). These reconstructions are supplemented by a range of indicators representing different parts of the trophic web, including both flora (*e.g*. diatoms, aquatic plant macrofossils and pigments) and fauna (*e.g*. chironomids, cladocerans, fish scales), which potentially allow reconstruction of structural and functional characteristics of the ecosystem at points in the past, including the 'pre-human-impact' point required to determine good ecological status under the WFD. Such direct ecological information provides a sound basis for management decisions, and numerous studies illustrate the effectiveness of the approach for assessing ecological change and defining reference conditions (*e.g*. Meriläinen *et al*. 2003, Hynynen *et al*. 2004, Guilizzoni *et al*. 2006, Taylor *et al*. 2006).

However, reconstructing the history of the ecosystem is not sufficient to define the baseline reference state. A single point in time has to be selected from the multi-millennial record that is usually available, and it seems sensible that baseline 'pre-impact' dates will vary between ecotypes, reflecting historical and contextual differences. Bennion *et al*. (2004) chose A.D. 1850 as the reference date for Scottish lochs, since this pre-dates the major changes made by large-scale industrialisation and agricultural intensification in the region. Palaeoecological studies from Denmark (*e.g*. Bradshaw and Rasmussen 2004; Bradshaw *et al*. 2006), where a long history of agricultural exploitation of most catchments is clear in the lake records, suggest that true pre-impact baselines should be sought several millennia ago. Pragmatic and political considerations will also play a part in setting an age for reference conditions; in the densely populated, long settled agricultural lowlands of Europe, setting a target of the state of the ecotype in the pre-agricultural forests of the early Holocene would be unrealistic and unachievable.

Once a reference date for an ecotype is chosen, it is possible to reduce the costs and increase the speed of the palaeolimnological analyses by using dating methods to identify the location of the reference date within the core, and analyse just two samples, one from this date and one from modern surface sediments (to assess the degree of deviation from the reference state). Whilst we argue above that single reference states are not generally identifiable, WFD target-setting in the UK context requires that a single, measureable reference state be identified. Defining a baseline date allows efficient quantification of this reference state. This 'before and after' sampling can be rapidly applied to a large number of lakes, and the data used to classify sites in terms of degree of deviation from the reference state, which gives a clear basis for planning and costing management action. More detailed analysis of the record from representative lakes in each ecotype can provide supplementary information such as how recently good status was lost and an indication of the primary cause of loss of good status, which can then inform the detailed planning of intervention strategies.

Using the sedimentary record to assess present status offers an advantage over conventional monitoring, since sampling an appropriate depth of sediment integrates the record from several years, offering a good picture of overall conditions. In order to measure the ecosystem health of a lake effectively, conventional monitoring needs to be carried out at several dates during at least one yearly cycle, and therefore the palaeoecological approach reduces the number of visits needed.

Assessment and active management of sites classed as having poor ecological status is not just an issue for fresh water systems, although there is no single terrestrial equivalent of the WFD. Management plans and strategies at multiple levels, from the Millennium Ecosystem Assessment to national networks (*e.g*. Countryside Survey and Environmental Change Network), national and regional Biodiversity Action Plans and assessments of individual designated sites, all give repeated examples of threatened habitats in 'unfavourable' state and in need of restoration (*e.g*. Britton *et al*. 2005,Williams 2006). Just as in the freshwater situation, effective planning and restoration action depends on sound understanding of ecosystem processes, particularly system responses to environmental change, and definition of appropriate 'baselines' and targets. Two case studies are used to illustrate how long-term datasets can inform and support terrestrial ecosystem restoration initiatives.

CASE STUDY 2: MOORLAND MANAGEMENT TECHNIQUES (QUESTION 79; SUTHERLAND *et al.* 2006; SEE TABLE 1)

UK moorland ecosystems are of national and international importance for their biodiversity, landscape, cultural heritage and ecosystem services contributions to human livelihoods (Millennium Ecosystem Assessment 2005, Reed *et al*. 2009). However, they are also threatened by the loss of conservation values and by widespread erosion (*e.g*. Grieve *et al*. 1995, Thompson *et al*. 1995, Higgitt *et al*. 2001, Holden *et al*. 2007). It is predicted that peatlands will show heightened sensitivity to disturbance as a result of climatic change over coming decades (Bragg & Tallis 2001, Moore 2002); these threats and the subsequent risk of non-reversible damage are therefore expected to increase without active intervention. Understanding local drivers of change is essential for establishing appropriate responses on a site level.

Frank Chambers and colleagues have investigated the causes and process of degradation at several sites on Exmoor (England) and in Wales using pollen, plant macrofossil, peat stratigraphy, radiocarbon-dating and the occurrence of soot particles (fossil fuel-derived pollutants used to date peat accumulated since *c*.1850). Their work (Chambers *et al*. 1999, 2007a, 2007b) establishes that degradation is associated with strong directional shifts in the competition balance between dominant taxa and species impoverishment. This involved a switch from mixed, dynamic heather-grass moors to unpalatable and homogeneous grass moors, dominated by *Molinia caerulea* (purple moor grass), and occurred in the late 19th and early 20th centuries. Causes of this switch include changes in grazing regime, in burning patterns and in atmospheric nitrogen deposition, which may be continuing to favour grass dominance (Chambers *et al*. 1979, 1999, Holden *et al*. 2007, Hughes *et al*. 2007). These data suggest strongly that efforts to 'restore' these degraded blanket bogs by reducing *Molinia* growth are justified, since the shift in dominance is recent and unprecedented. However, the conservation preference often given to Callunetum needs to be mitigated with the knowledge that its presence may not always be long-standing (Chambers *et al*. 2007b). In contrast with the loss of heather cover from blanket peat catchments in some parts of the UK over recent centuries (Stevenson & Thompson 1993), in northern England and South Wales *Calluna* dominated communities are part of the relatively recent shifts towards mono-specific dominance on blanket mires (Atherden 2004, Chambers *et al*. 2007a).

In contrast with the uniformity of some present-day grass moors and Callunetum, palaeoecological data show that upland moorlands were historically vegetated with a dynamic mosaic of communities, reflecting both local-scale variations in topography and hydrology and spatial heterogeneity in landscape use. Although many moors were, as now, characterised by a small number of dominant taxa, this mosaic offered a wider variety of habitat structure and microclimate within relatively small areas, which probably sustained local biodiversity in many taxonomic groups (*e.g*. Littlewood *et al*. 2006). Rather than prioritising a single dominant or community type, management strategies which aim to ensure structural, if not phyto-taxonomic, diversity within *Calluna*- or grass-dominated areas contribute to improvements in condition in terms of biodiversity and system function.

CASE STUDY 3: CURRENT SEMI-NATURAL ANALOGUES IN HABITAT RESTORATION (QUESTION 83: SUTHERLAND *et al.* 2006; SEE TABLE 1)

In upland moorland, the replacement of mixed communities by either Callunetum or grass moor is relatively recent. This is not the case for some woodland restoration target areas in northern Scotland, where trees have not been present for centuries to millennia (Tipping 1994). The UK is one of the least densely forested countries in Europe and in Scotland the majority of existing tree cover consists of conifer plantations, interspersed with extensive tracts of moor and peatland. This has given rise to numerous woodland restoration initiatives (Caledonian Partnership 2003, Hobbs 2009). Despite frequent emphasis on human 'degradation' of native habitats (*e.g*. Darling 1955, McIntosh 2006), existing woods or current soil and climatic criteria are often assumed to provide suitable templates for establishing appropriate locations and composition in woodland restoration (*e.g*. Towers *et al*. 2004). Managers in West Glen Affric (NW Scottish Highlands), however, chose to fund research into past vegetation and climate dynamics to assess the limitations of a present-analogue approach and inform future management strategies on tree planting and woodland restoration.

In contrast with the current open, peat-dominated landscape, diverse woodland communities once existed in West Affric, including a mosaic of mixed deciduous woods on alluvial soils and open pine-birch-heaths on peaty ground, with the abundance of pine decreasing westwards (Davies 2003, 2010, Tipping *et al*. 2006). Current pine-dominated woodland in East Affric thus does not provide a good analogue for past woodland communities in West Affric; woods throughout the valley were more diverse than the present remnants in East Affric (Tipping *et al*. 1999, Shaw & Tipping 2006). The abundant pine stumps eroding out of

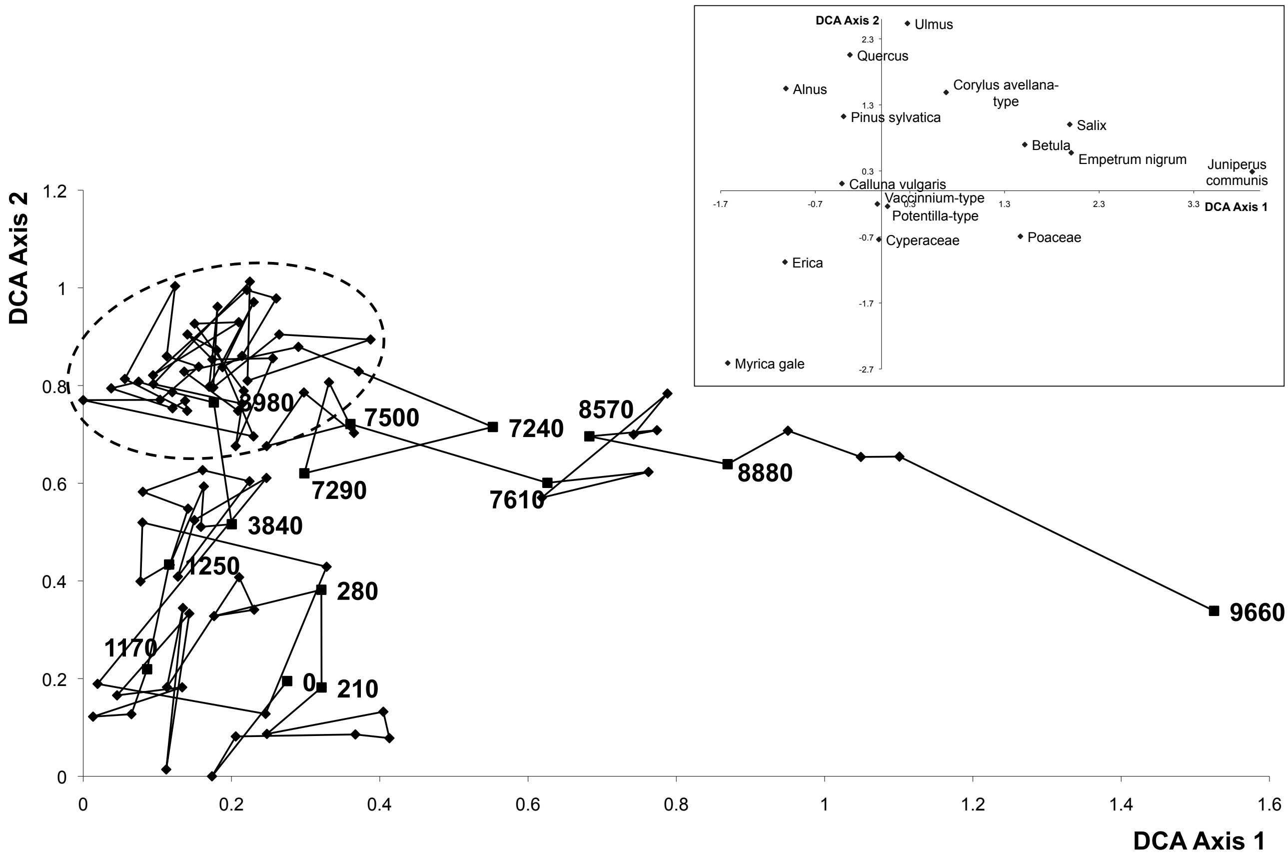

Fig. (1). Ordination (detrended correspondence analysis) plot of pollen data from Torran Beithe, an area of blanket peat cover in West Affric (NW Scotland), showing changeable post-glacial migration and succession phase (*c*.9700-7000 years ago), followed by a period of relative stability during the woodland/heathland mosaic phase (circled), followed by a shift to the present peat-dominated vegetation around 4000 years ago.

peat in West Affric and across NW Scotland are often interpreted as evidence that these areas once supported pine-dominated woodland. However, these are an artefact of preservation bias rather than a true reflection of past woodland composition or stability: drier climatic phases allowed episodic, short-lived pine colonisation events onto bogs, after which a return to wetter conditions led to the death of the invading trees, renewed growth of peat and preservation of pine stumps (Bridge *et al.* 1990). Major woodland contraction occurred during a period of climate change between 4400-3800 years ago, which first altered competitive balances between pine, birch, oak and alder, and then led to the widespread failure of tree regeneration throughout West Affric and across NW Scotland (Davies *et al.* 2004, Tipping *et al.* 2006; Fig. **1**). Given the sensitivity of these woods to past climatic change and predictions of future climatic variability, restoration approaches which rely on recent baselines and current conditions may not generate self-perpetuating or sustainable woods. In response, managers of West Affric continue to work with woodland restoration organisations, but have revised the extent of their plans for woodland growth in recognition of the palaeoenvironmental findings on past species composition and the drivers of woodland decline.

CASE STUDY 4: GRAZING IMPACTS & HISTORICAL CONTEXT OF BIODIVERSITY LOSS (QUESTIONS 8 & 12; SUTHERLAND *et al.* 2007; SEE TABLE 1)

Habitat loss and changes in agricultural practice pose major global threats to biodiversity. In particular, agricultural intensification and abandonment threaten many biodiversity, landscape and cultural heritage values that have formed through centuries of interaction with agricultural communities (Henle *et al*. 2008). This is especially the case in upland areas, where significant reductions in grazing pressure are forecast (Reed *et al*. 2009). Understanding how species respond is a priority for meeting the challenge of conserving biodiversity in the context of changes in agriculture and climate. A long-term perspective can increase the evidence-base by providing information about the effects of many different forms of agriculture on upland biodiversity, not just modern mechanised, low labour-input farming.

Hanley *et al*. (2008, 2009) analysed the effects of changes in resource management and associated socio-economic factors on plant diversity in upland Scotland over the last 400 years using an approach that combined palynological and historical datasets via panel data analysis to pool spatio-temporal information. Rarefaction analysis or palynological richness was used as a proxy for plant diversity, reflecting a combination of diversity and structural (evenness) parameters (Birks & Line 1992, Odgaard 1999). Diversity levels have varied considerably over the last 400 years, partly as a function of changes in land management, indicating that static baselines and 'naturalness' are problematic concepts in conservation and ecology more widely. Changes in livestock grazing pressures brought about by changes in market prices had significant effects on diversity: both higher grazing pressures and abandonment are associated with reductions in plant diversity. Grazing therefore needs to remain a key concern for maintaining diversity.

Numerous sites in this study (Fig. **2**) and across a range of European habitats show significant reductions in plant diversity over the last 200 years (*e.g*. Davies & Dixon 2007, Berglund *et al*. 2008, Feurdean & Willis 2008). Homogenisation is thus not simply the late 20th century trend seen in many repeated ecological surveys (*e.g*. Britton *et al*. 2009, Keith *et al*. 2009); this knowledge can help establish more realistic reference frameworks for conservation. For example, meadow and species-rich grassland diversity has suffered as a result of agricultural intensification and abandonment (Davies & Dixon 2007, Gustavsson *et al*. 2007, Hanley *et al*. 2008, cf. Lindbladh 1999). This has implications for the faunal communities that depend on the diminishing range of less intensively managed grassland habitats and on landscape heterogeneity (*e.g*. Benton *et al*. 2003, Redpath *et al*. 2010). Palaeoentomological data further support this threat faced by faunal communities due to habitat fragmentation, as many beetle species have become locally and nationally extinct owing to the loss of their preferred habitat (Whitehouse 2006). Ecosystem rearrangement and habitat fragmentation arising from climate change is likely to exacerbate the extinction risk for many species (*e.g*. Huntley *et al*. 2008). This heightens the need to use multiple datasets and 'horizon-scan' (Sutherland *et al*. 2008) beyond familiar ecological datasets to establish appropriate 'baseline' measures for diversity.

CASE STUDY 5: SEMI-NATURAL WOODLAND MANAGEMENT (QUESTION 20; SUTHERLAND *et al.* 2007; SEE TABLE 1)

Despite recognising that no habitats in Europe have escaped human influence of some kind, (relative) naturalness continues to influence management decisions (*e.g*. Angermeier 2000). In reality, however, the current state of natural regeneration is relatively poor in many native woods, with evidence for long-term homogenisation, the continued loss of old growth woods and the spread of shade-tolerant and generalist species, partly as a consequence of limited management (Petit *et al*. 2004, Kirby *et al*. 2005, Hopkins & Kirby 2007, Keith *et al*. 2009). This has led some ecologists to question what woodland models are appropriate for

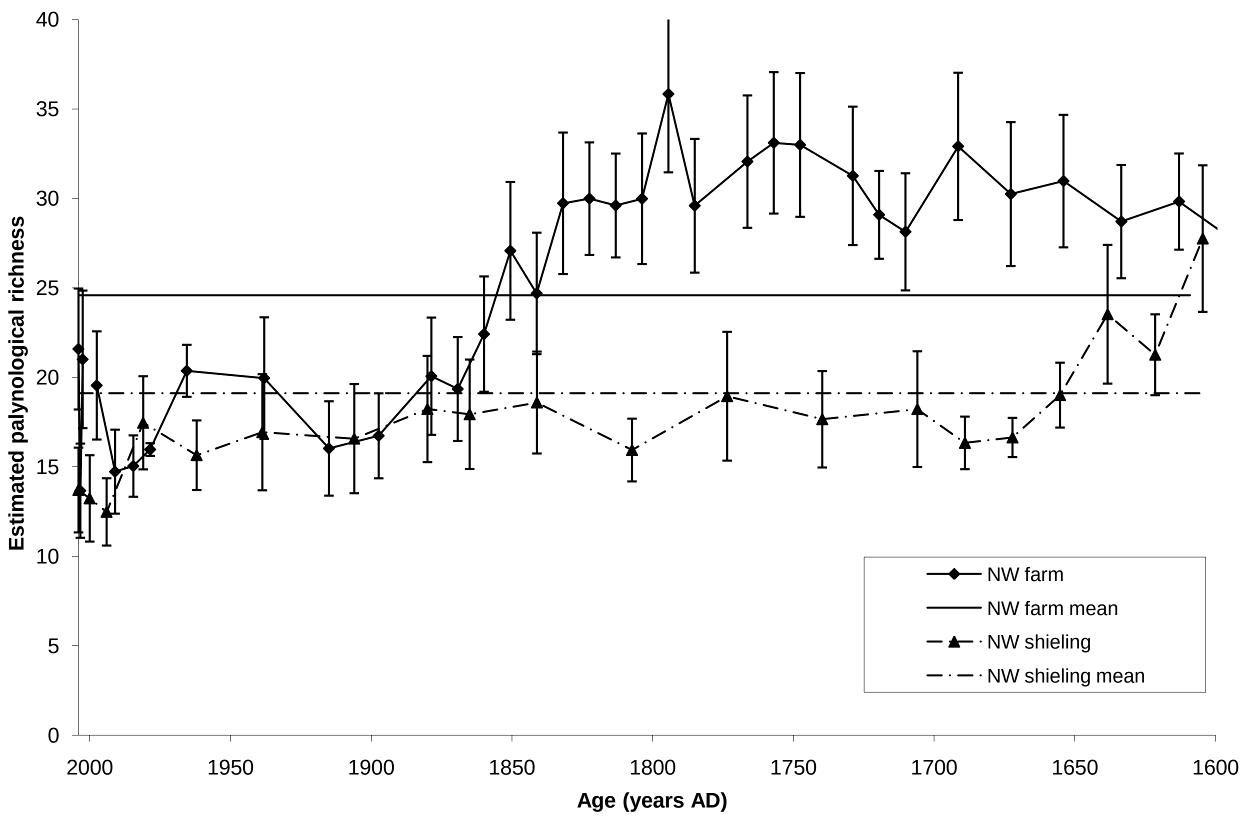

Fig. (2). Rarefaction (palynological richness) trends at two sites in NW Scotland over the last 400 years, showing 17th century loss of diversity at shieling (summer farm) site due to woodland loss with the establishment of grazing, and 19th century diversity decline at the farm owing to the eviction of tenant farmers in 1812 during the creation of an extensive sheep farm which became unviable and was then abandoned in the late 19th century.

conservation and to assess the value of managed disturbance (Amphlett 2003, Quelch 2004, Hall & Stone 2004, Hancock *et al*. 2005). Applied palaeoecology does not propose going back to past management strategies, but can help assess what disturbance regimes favoured regeneration in particular habitats to establish models and management plans that will maintain continuity and conservation values into the future.

Pollen studies in high conservation value Atlantic oakwoods in N England, W Scotland, N Wales and SW Ireland show that these valued communities have no long history: they have developed since the cessation of timber and grazing management around 100-200 years ago (Edwards 1986, Mitchell 1988, 1990, Birks 1993, Sansum 2004). The current composition and age structure of the canopy of these woods, especially the dominance of oak, reflect past management effects rather than present conditions owing to the slow rate of maturation in populations with a long generation time. Past management limited shrub growth and maintained a more open, disturbance-adapted ground flora, while species selection and repeated disturbance reduced tree-species diversity. Although bryophytes are important for current woodland conservation value, they are poor indicators of the antiquity of the observed woodland communities and structure. The persistence of the valued, rich bryophyte floras stems from the presence of 'semi-woodland' habitats and microrefugia (*e.g*. streamsides, crags), and the fact that some form of tree cover was always present. 'Natural' features, such as deadwood accumulation and limited numbers of shade-tolerant understorey species, have been scarce or absent for centuries owing to this management history. Consequently, as indicated by ecological experiments and monitoring, disturbance is required to maintain current values and herbivore exclusion alone is unlikely to result in widespread tree regeneration (Palmer *et al*. 2004). Equally, the results indicate that human intervention need not be damaging or run contrary to conservation objectives which prioritise regeneration and structural heterogeneity (Sansum 2004).

DISCUSSION

These case studies show that palaeoecological data can make contributions to a range of conservation activities, from defining targets to supporting the development of effective management plans for achieving those targets. In combination with shorter-term datasets, they allow scientists to investigate how ecological processes develop over decades, centuries and millennia, and understand the past conditions whose lagged consequences are still manifest in the modern landscape. Why, therefore, does palaeoecology continue to fall outside the 'horizons' being scanned to improve anticipation of needs and threats that we face on a global scale?

Although many papers by palaeoecologists have been published in ecological journals, giving both UK and international examples of how palaeoecological data might contribute to ecology and conservation (*e.g*. Birks 1996, Brown 2002, Willis *et al*. 2005, 2007, Willis & Birks 2006), these are mostly cited by palaeoecologists and it may be that there is still a simple lack of awareness among the ecological community of the potential of palaeoecology to address ecologically interesting questions with sufficient precision to warrant attention (Froyd & Willis 2008). Several factors could contribute to this. Over the last few decades in Britain academic palaeoecologists have generally found employment in Geography or Archaeology departments, rather than Biology or Ecology, meaning that many graduates in disciplines leading to conservation-related jobs have barely encountered palaeoecological ideas during their studies.

Time to become familiar with the field and its techniques is a luxury that few researchers, policy-makers or practitioners would lay claim to, but, in general, limited attention is given to communication with non-specialists. Many palaeoecological studies, especially older ones or book-form syntheses, focus on large-scale and long-term patterns which are less directly applicable to conservation questions, and tend to be cited only as introductory information, rather than seen as relevant to ecological results or practices. In addition, palaeoecological data are conventionally presented in the form of multivariate stratigraphic diagrams, which are information-dense, require skilled understanding to correctly interpret, and are unfamiliar to many ecologists. Ordination diagrams are just as complex and information-dense as stratigraphic diagrams, but are a more familiar method of displaying multivariate data for an ecological audience (Fig. (**1**), *e.g.* Bradshaw *et al*. 2005). The increasing number of papers that utilise alternative presentation methods (*e.g.* Lindbladh, *et al*. 2007, Hanley *et al*. 2008, van Leeuven *et al*. 2008) and incorporate ecological baselines (*e.g*. Gillson & Duffin 2007) to illustrate the conservation implications of long-term datasets may improve communication by making the information more accessible.

In addition to differences in the methods used to present data, developing ways of working around differences in the ways that ecology and palaeoecology represent ecosystems is a significant challenge, which can only be addressed through interdisciplinary cooperation. In palaeoecology a strong current area of activity is quantitative reconstruction of past vegetation from pollen records. Presenting reconstructions as vegetation cover estimates (Hellman *et al*. 2008) or even as mapped distributions (Bunting & Middleton 2009) improves legibility for the non-specialist, although they can hide uncertainties.

When long-term data are used in conservation research, old maps, documents and historical narratives remain more popular owing to their relative accessibility to non-historians (*e.g*. Holl & Smith 2007), although this may lead to uncritical and inappropriate use of datasets that are inherently biased towards changeable sets of human values (*e.g*. Bowman *et al*. 2010, Szabó 2009). Even within the discipline of ecology, changing methodologies, the challenges of relocating sites for repeat monitoring to build on historical data and changing taxonomies all make historical documents such as old plant lists or surveys difficult to integrate with current data and concerns (Ross *et al*. 2010).

This paper presents clear examples indicating how palaeoecology can contribute to conservation practice, but argues that this potential is only rarely realised. It is notable that only one of the case studies presented above involves publications where practitioners are co-authors (Stevenson & Thompson 1993, Chambers *et al.* 1999, 2007a, 2007b). Furthermore, there is only one example where long-term data have an established role in policy and practice: the Water Framework Directive. This example probably has the least 'information transfer' problem, since a single pre-industrial baseline has been defined as representative of 'favourable' condition, and results can be presented in terms of difference of present from baseline. As indicated above, this simple, easily measured approach may not be universally appropriate, but it is feasible, affordable and straight-forward to implement, which is highly valued in the practical context of the WFD. This single baseline approach contrasts markedly with the terrestrial examples considered, where palaeoecological data emphasise the undesirability of defining an inflexible single 'baseline' for dynamic ecosystems. Recent debates about vegetation structure and regeneration mechanisms in naturalistic woodlands has elicited both single-discipline and joint responses (*e.g*. Bradshaw *et al*. 2003, Hodder *et al*. 2005, Whitehouse & Smith 2010). This illustrates how the different approaches to ecology can be used together to address common questions, when there is sufficient incentive and common interest.

There is a growing risk that, by relying on the relatively small numbers of current communities considered to be 'natural' or in 'favourable condition', or defined within commonly used classification systems (*e.g*. National Vegetation Classification communities), conservation protection, management targets and objectives may become too narrow. This could lead to fixed ideas of what a site 'should' look like, excluding natural extremes of variation, and is likely to exacerbate homogenisation and reduce habitat resilience to change (*e.g*. Wilkinson 2001). Trends towards homogenisation (*e.g*. Britton *et al*. 2009, Keith *et al*. 2009) are of particular concern when environmental change is predicted to be rapid and pressures on the landscape are high. Diversity seems to be an important factor in enabling resilience, and trends towards a smaller number of communities suggest increasing vulnerability to future losses of biodiversity and of habitats. By revealing unexpected past ecosystem states, such as the diversity of woodland in West Affric and the absence of pure Callunetum in many parts of the uplands, palaeoecological data can support acceptance of a wider range of possible future ecosystem states. Overcoming the temptation to set targets tightly in terms of specific community compositions that are easily measured and focusing on fostering a diversity of sustainable, resilient habitats and ecosystem *processes*, rather than preferred *compositions*, across the landscape will be challenging. The longer term palaeoecological record shows clearly that communities are transient; whatever humans do or however climate changes, new communities will form as species respond individualistically to a wide suite of dynamic environmental factors.

Learning from the ecological surprises of the past has the potential to improve anticipation of future shifts and increase the effectiveness of conservation practice. However, just as conservation practice would benefit from drawing on the broadest possible evidence base, there is also an onus on palaeoecologists to understand the conservation concerns, such as homogenisation, to identify the ways in which their data can inform this and other current debates, and to find appropriate data formats and outlets to contribute to the debate. Palaeoecologists would thus benefit from increasing their awareness of ecological issues in order to refocus their efforts and develop research and publications that address current needs in ecological research, practice and policy.

There are structural barriers to developing the interdisciplinary, intersectoral networks needed to integrate effectively palaeoecological approaches into conservation thinking, which are exacerbated by time and resource pressures. In addition to requiring opportunities for palaeo- and neo-ecologists to exchange views, both in person and through the literature, overcoming resistance to rethinking established perceptions in ecology and conservation may remain an ongoing challenge (Carrion & Fernandez 2009). It remains to be seen whether the interdisciplinary and knowledge exchange impetus brought about by environmental uncertainty will speed changes in thought and action on both sides of the broad ecological community.

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