Special Issue Paper

Environmetrics

Received: 20 May 2010, Revised: 27 July 2010, Accepted: 5 August 2010, Published online in Wiley Online Library: 21 March 2011

(wileyonlinelibrary.com) DOI:10.1002/env.1069

A comparison of ecosystem services delivered by 11 long-term monitoring sites in the UK environmental change network[†]

J. Dick[a*], C. Andrews[a], D. A. Beaumont[b], S. Benham[c], D. R. Brooks[d], S. Corbett[e], D. Lloyd[f], S. McMillan[g], D. T. Monteith[h], E. S. Pilgrim[b], R. Rose[h], A. Scott[h], T. Scott[d], R. I. Smith[a], C. Taylor[i], M. Taylor[j], A. Turner[f] and H. Watson[i]

The Millennium Ecosystem Assessment (MA 2003) framework was applied to provide a holistic assessment and comparison of ecosystem services delivery from 11 environmental change network (ECN) sites, following a workshop of ECN site managers. A list of common variables was agreed to represent the high level categories defined by the MA. The resultant 73 variables, either direct ecosystem services or proxies, were divided into two subsets (readily accessible biogeographical data from all sites and additional site specific data). Similarity analysis of the biogeographical data indicated four site clusters: land with at least 50% forest cover, productive livestock farmland, uplands and a lowland grass/arable group. The first three clusters were also evident for both the additional data and for the larger combined dataset. The lowland grass/arable sites were a 'mixed use' cluster that was not apparent in the analysis of the additional or combined datasets indicating a mismatch between particular ecosystem services and specific landscapes/habitats. Procrustes analysis of the biogeographical data and the combined dataset suggested that the primary differences between datasets were due to variables associated with local management decisions which prevented harvesting of provisioning services or denied public access to the site. Drawing on comparable data from some of the most intensively researched and monitored ecosystems in the UK, this study demonstrates the challenges and limitations involved in attempting holistic assessments of ecosystem services at the site and inter-site level and highlights the importance of both local expert knowledge and consistent scientific measurement in contributing to the process. Copyright © 2011 John Wiley & Sons, Ltd.

Keywords: ECN; LTER; ecological assessment; biodiversity

* *Correspondence to: J. Dick, Centre for Ecology and Hydrology, Bush Estate, Penicuik, EH26 0QB U.K.*

a *J. Dick, C. Andrews, R. I. Smith*
Centre for Ecology and Hydrology, Bush Estate, Penicuik, EH26 0QB, U.K.

b *D. A. Beaumont, E. S. Pilgrim*
North Wyke Research, Okehampton, Devon, EX20 2SB, U.K.

c *S. Benham*
Forest Research, Alice Holt Lodge, Wrecclesham, Farnham, Surrey, GU10 4LH, U.K.

d *D. R. Brooks, T. Scott*
Rothamsted Research, Harpenden, Hertfordshire, AL5 2JQ, U.K.

e *S. Corbett*
Porton Down, Salisbury, Wiltshire, SP4 0JQ, U.K.

f *D. Lloyd, A. Turner*
Countryside Council for Wales, Maes-Y-Ffynnon, Ffordd Penrhos, Bangor, Gwynedd, LL57 2DW, U.K.

g *S. McMillan*
ADAS UK Ltd., c/o Newcastle University, NEFG Offices, Nafferton Farm, Stocksfield, Northumberland NE43 7XD, U.K.

h *D. T. Monteith, R. Rose, A. Scott*
Centre for Ecology and Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster, LA1 4AP, U.K.

i *H. Watson, C. Taylor*
Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen, AB15 8QH, U.K.

j *M. Taylor*
Centre for Ecology and Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford, OX10 8BB, U.K.

† *This article is published in Environmetrics as a special issue on Quantitative approaches to ecosystem service evaluation, edited by R. I. Smith, Centre for Ecology and Hydrology, UK; E. M. Scott, School of Mathematics and Statistics, University of Glasgow, UK; J. McP Dick, Centre for Ecology and Hydrology, UK.*

1. INTRODUCTION

Much has been written about the desirability of evaluating the goods and services delivered by ecosystems to society as a prerequisite to managing environments sustainably. The concept of evaluating both social and ecological aspects of ecosystems simultaneously is not new, as Dick *et al.* (2011) argue in this volume. Recent reviews have considered the issues surrounding the delivery of goods and services by ecosystems from different perspectives including agriculture (Glendining *et al*., 2009; Porter *et al*., 2009; Stoate *et al*., 2009), conservation (Carpenter *et al*., 2006; Bennett *et al*., 2009; Carpenter *et al*., 2009) and forestry (Eamus *et al*., 2005; Burton *et al*., 2006; Chopra and Dasgupta, 2008) and a range of tools from mathematics (Seppelt *et al*., 2009) and economics (Liu *et al*., 2010). These reviews all conclude that a holistic approach is valuable when formulating policy.

The Millennium Ecosystem Assessment (MA) carried out between 2001 and 2005 provides a useful theoretical framework for assessing ecosystem services and was used in this study as a recognised source of definitions and as a framework to identify goods and services for which variables or proxies were required. A full ecosystem service assessment using MA protocol was out of the scope of this exercise. The MA defines ecosystem services as the benefits people obtain from ecosystems. These include the provisioning, regulating and cultural services that directly affect people and the supporting services needed to maintain the other services (MA 2003).

A workshop was held in January 2010 in order to characterise and attempt to quantify the ecosystem services currently delivered by 11 sites in the UK environmental change network (ECN) (Morecroft *et al*., 2009). The ECN is a network of long-term ecological research (LTER) sites established to provide scientifically robust monitoring of biodiversity and environmental change. As such, it has concentrated on the collection of biophysical and chemical data. However, ECN site managers each have extensive knowledge of the social and other uses of their sites, and this allows for a much wider range of variables to be collated through other data sources and local expert judgement.

In this paper, we describe the process of compiling a uniform set of metrics to represent holistically ecosystem services delivered by ECN sites, apply classification and ordination procedures to determine the extent to which sites compare in respect to delivery, consider the primary factors determining similarities and differences in delivery and the extent to which comparisons are influenced by the scope of the information available and finally summarise the main challenges and limitations encountered.

2. STUDY SITES

A major issue for any ecosystem assessment is the definition of the area boundary. The MA recommends using either the coincidence of a number of discontinuities, as in the distribution of organisms, soil types or drainage basins, or resource management systems and institutions in delimitating boundaries. Both biogeophysical features and social discontinuities were considered here, in particular land management and land ownership boundaries, i.e. a scale was selected that corresponded to human systems for decision-making (MA 2003). Land ownership provided the main boundary for data acquisition for the sites in this study (Table 1), and this coincided with the official ECN site boundary at four of the 11 sites assessed. ECN sites were commonly embedded within the management unit, e.g. the whole farm, at other sites. Three sites also encompassed complete water basins (Cairngorm, Moorhouse and Snowdon).

The MA recognised 10 combined social and ecological land categories each of which may contain a number of ecosystems. Overlapping categories are recognised to better reflect real-world biological, geophysical, social and economic interactions. In this study, five sites had a significant forestry component and seven were classed as cultivated landscapes. Approximately half were classed in more than one MA land class category. Although several encompassed buildings and habitation, none included an urban category (defined by the MA as human settlements of 5000 people or more).

One concern with the use of long-term monitoring sites as test landscapes for tools and approaches of ecosystem service research is their representativeness within the wider countryside. The environmental factors most likely to dominate differences between sites in ecosystem

Table 1. Total area and description of study area boundaries for each of the ECN sites included in this study using MA criteria (MA 2003)

	Boundary delimitating characteristics					MA reporting categories		
Site	Total area (ha)	Water basin	Land management	Land ownership	ECN site boundary	Forest	Mountain	Cultivated
Alice Holt (ALI)	850		√	√	√	√		
Cairngorm (CAI)	1000	√	√	√	√	√	√	
Drayton (DRA)	200		√	√				√
Glensaugh (GLE)	1125		√	√				√
Moor House (MOO)	3500	√		√			√	
North Wyke (NOR)	248		√	√		√		√
Porton Down (POR)	1564		√	√				√
Rothamsted (ROT)	341		√	√	√	√		√
Snowdon (SNO)	544	√	√	√	√		√	
Sourhope (SOU)	1120		√	√				√
Wytham (WYT)	770		√	√		√		√
Total	11262	3	10	11	4	5	3	7

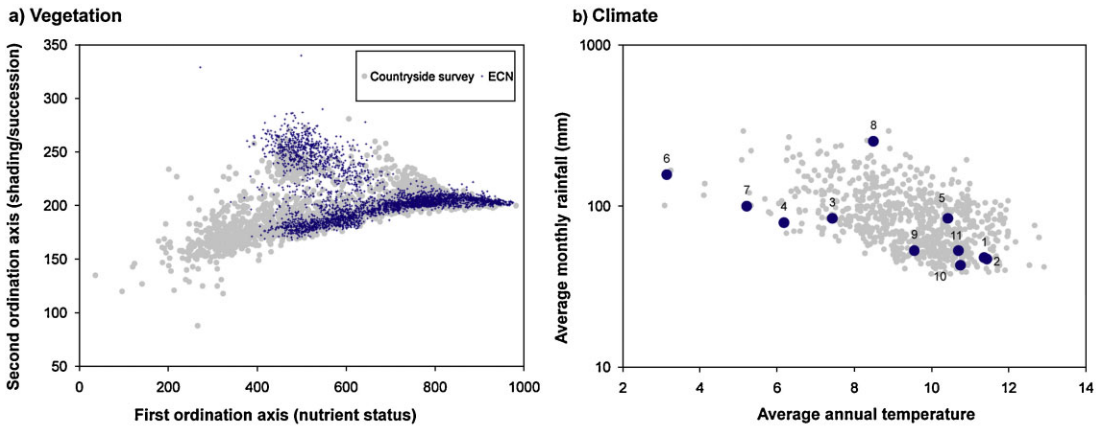

Figure 1. Characteristics of ECN sites in relation to data from a representative sample of GB locations collected as part of the CS 2007 (a) vegetation and (b) rainfall and temperature. Sites are: 1 = Alice Holt, 2 = Wytham, 3 = Glensaugh, 4 = Sourhope, 5 = North Wyke, 6 = Cairngorm, 7 = Moor House, 8 = Snowdon, 9 = Drayton, 10 = Rothamsted, 11 = Porton. This figure is available in colour online at wileyonlinelibrary.com/journal/environmetrics

functioning in the UK are differences in climate, land cover and land management. To examine the representativeness of ECN sites with regard to these factors, ECN data were compared with data obtained through the UK Countryside Survey (CS) (http://www.countrysidesurvey.org.uk/index.html), an approximately decadal survey of the vegetation and soil diversity in the British countryside most recently conducted in 2007. The survey is based on a stratified random sample of 1 km squares from the intersections of a regular 15 km grid superimposed on the rural areas of Great Britain.

Figure 1a shows the ECN and CS vegetation data plotted against the first two axes of a detrended correspondence analysis ordination of the CS data. ECN plots cover a similar range of vegetation types to the CS with the exception of arable (lower left hand quadrant of Figure 1a), a land use category not assessed for vegetation at ECN sites although present on several. Comparison with rainfall and temperature values for CS squares across Great Britain (Figure 1b) shows ECN sites effectively span the range of values for both variables (rainfall is presented on a log scale because of its skewed distribution).

3. DATA SOURCES FOR ECOSYSTEM SERVICE ASSESSMENT

Three types of data were used in the analysis of ecosystem services at each ECN site (i) data collected for the ECN to standard ECN protocol (http://www.ecn.ac.uk/protocols/index.asp), (ii) data obtained by site managers from a variety of other sources for their site and (iii) expert knowledge of site managers. A site managers' workshop was held in order to standardise the selection, definition and application of metrics used to represent ecosystem services across the Network. The key role of LTER sites is to provide environmental and biodiversity measurements consistently over time and space, but for this initial study comparisons between sites were made using data for a single year (commonly 2009), or averages of annual measurements, to remove any component of temporal variability. Area-dependent variables were scaled by the area of the site. A total of 73 variables with their assessment criteria were agreed (Table 2).

4. STATISTICAL ANALYSIS

For this study the data matrix was divided into two sets (i) readily accessible biogeographical variables for each site (25% of the variables in the full dataset) and (ii) all other biophysical and socio-cultural data relating to MA-defined ecosystem services that were available for all sites and agreed at the site managers' workshop (Table 2). The variables were a mixture of binary, ordered categorical and continuous data. All analyses were performed on both sets individually and in combination.

A multivariate approach to statistical analysis was adopted with the measured variables converted into similarities between sites from which the site differences were then determined. The conversion to similarity measures standardises the unit measurement system reducing the influence of differing measurement scales but does not avoid the variable selection problem where more influence can be attributed to underlying factors expressed through multiple variables. This latter issue is endemic to ecosystem services studies as the variable selection commonly reflects available data and will always be to an extent partial.

In order to assess the overall comparability of ecosystem services delivered by individual sites, a range of similarity measures were investigated using Genstat12 software. The city-block or Manhattan measure was found to recover the similarity configurations derived from a principal coordinate analysis most effectively. The Manhattan measure provides a continuum linking together distance concepts from continuous variables with comparisons between classified variables and the simple matching available for binary variables. It is more robust against extreme data values than the Euclidean distance, is standardised by sample totals and has proved to be a good ecological distance measure with complex ecological datasets (Digby and Kempton, 1987; Faith *et al.*, 1987). A hierarchical agglomerative clustering of sites, based on average linkage grouping criteria was drawn. Principal coordinate analysis of the similarity matrices was utilised to provide a visual representation of distances between the individual sites, with larger distances reflecting less similarity, and canonical variate analysis was used to determine the separation between the groups using the principal coordinate scores as input. Sufficient ordination axes were retained to explain over 50% of the cumulative variance in the distances, which kept the first three principal coordinate axes for all three analyses. The

Table 2. Definitions agreed by ECN site managers of criteria to assess ecosystem service for ECN sites (variables denoted in italics and emboldened formed the biogeographical subset of the data)

Service	Category	Variable no.
Provisioning		
Food	Meat produced on site as live weight of animals (tonnes ha^{-1})	1
	Vegetables, fruit, mushrooms, eggs, cereals? (yes/no)	2,3,4,5,6
	Number of provisioning (food) categories per site	7
Fibre	Weight of wool produced by sheep or goats grazing on the site (tonnes ha^{-1})	8
	Weight of wood produce (not fire wood) grown on the site (tonnes ha^{-1})	9
Fuel	Weight of wood grown for fuel on the site (tonnes ha^{-1})	10
	Hydropower electrical output (MWh per site)	11
Genetic Resources	Number of animal species within site which are held for use as a genetic stock	12
	Number of plant species held for use as a genetic stock	13
	National collections of species for use as genetic stock? (yes/no)	14
Biochemicals &	The number of species or breeds grown or raised for use in industries/research	15
pharmaceuticals	Quantity of materials grown/raised for use in industries/research (tonnes ha^{-1})	16
Ornamental	Resources produced for use in producing ornaments, arts, crafts etc? (yes/no)	17
Fresh Water	Quantity extracted for human consumption (cubic meters per year)	18
Regulating		
Air quality regulation	***Nitorgen flux per hectare from national deposition model***	19
	Sulphur flux per hectare from national deposition model	20
Climate regulation	***Net CO_2e for site calculated by greenhouse gas auditing tool CPLAN or Bsort (tonnes of CO_2e ha^{-1} yr^{-1})***	21
Water regulation	***Is there a Dam/Reservoir within the site boundary? (present/absent)***	22
	Number of flood events per year at each site	23
Erosion	***Estimate of erosion by site managers. 1 = little erosion to 3 = lot of erosion***	24
Human diseases	Presence of human diseases at site. 1 = good at regulation to 3 = higher risk	25
Biological control	Presence of pest species at site. 1 = good at regulation to 3 = higher risk	26
Pollination	***Average number of butterflies per year at each site (site average)***	27
Natural hazard	Annual average number of fires recorded in the last 10 years	28
Other hazard	Does the site regulate noise pollution? (yes/no)	29
Cultural		
Cultural diversity	Use by botanists, anglers, bird watchers, climbers, cyclists, mountain bikers, model/kite enthusiasts, special need groups, walkers, yoga enthusiasts, Lepidoptera enthusiasts, farmers, foresters, researchers, or for fungal forays, ‘green’ weddings, horse riding, skiing, shooting, film making, military/rescue training, education? (yes/no)	30,31,32,33,34,42, 41,45,46,47, 40,35,36,43,37, 38,39,48,44,50,49, 51
	Total of relevant cultural diversity classes per site	52
Spiritual and	Number of natural features (e.g. Significant mountain summits, fairy pools etc…)	53
religious values	Number of relevant manmade features (e.g. churches, chapels, standing stones)	54
	Total number spiritual and religious elements at each site	55
Educational values	Is the site used in part for formal education purposes (e.g. school visits)? (yes/no)	56
	Site used for informal education? (yes/no)	57
Educational values	Number of educational/research visitors per year. Log_{10} scale (1 = 0–10 to 5 = 10 001–100 000)	58
Aesthetic values	***Average number of butterflies, Carabidae, moth, bat, bird species per year***	59,60,61,62,63
	Number of distinct interstitial elements (ditch, path/track, road, hedge, fence, wall, waterway)	64
	Number of distinct OS symbols on site map (1:25k) Water bodies and flowing water counted separately	65
	Number of species (plants, bryophytes and lichens) from survey of site	66
	Numbers of aggregate or individual CVS types within site	67,68
	Statutory designations governing areas within the site (e.g. SSSI, SAC)? (yes/no)	69
Social relations	Approximate population within 5 miles of the site. Log_{10} scale (1 = 0–10 to 5 = 10 001–100 000)	70
	Is there easy access to the site e.g. via metalled road, rail link etc…? (yes/no)	71
Heritage	Number of special features present e.g. Argyll stone in Cairngorms	72
Ecotourism	Approximate no. tourist visitors to site each year. Log_{10} scale (1 = 0–10 to 5 = 10 001–100 000)	73

ordinations from principal coordinate analyses of the biogeographical subset of the data and the full dataset were compared using a generalised procrustes rotation. As with the canonical variate analysis, only the first three axes were retained as these explained over 50% of the variability in distances from the similarity matrices. The graphs show which sites differ most in a common configuration and thus provide an indication of the extent to which the classification of each site is sensitive to the dataset included.

5. INTERSITE COMPARISONS

For the biogeographical dataset, the 11 sites clustered into four groups (Figure 2a). These represent sites with substantial forests (Alice Holt and Wytham), primarily productive livestock farmland (Glensaugh, Sourhope and North Wyke), upland sites (Cairngorm, Moorhouse and Snowdon) and a cluster with mixed uses (Drayton, Rothamsted and Porton Down). The dendrogram representing the additional data (Figure 2c) shows three broad categories in common with the biogeographical analysis, i.e. substantial forest, livestock farmland and upland sites in the ECN network but the 'mixed use' group in the former analysis did not form a cluster. Drayton was effectively isolated and Porton Down was more similar to the upland and farm groups while Rothamsted was found to be more similar to the sites with substantial forestry. The dendrogram for the complete dataset was very similar to that based on the additional data alone (Figure 2e).

Principal coordinate analysis of the similarity matrices and canonical variate analysis revealed that all four groups were distinct when the subset of biogeographical data are used (Figure 2b), whereas the 'mixed use' cluster overlaps with the farm and forest clusters for the additional data variables (Figure 2d) and the 'mixed use' and forest clusters overlap for the full dataset (Figure 2f).

A biplot in combination with a minimum spanning tree reveals the variables which best discriminate between site groupings (Figure 3). For the biogeographical dataset (Figure 3a), the upland group was most associated with relatively high values for erosion, floods and number of dams, while the forestry group, i.e. Alice Holt and Wytham, showed a higher diversity of landscape features (number of vegetation classes, plant species, spiritual elements and features on the OS maps—a metric for landscape diversity). The mixed use and livestock farming groups overlap and are associated with greater numbers of moths, birds, interstitial elements (i.e. paths, roads, hedgerows, fences, walls, etc.), manmade spiritual features and larger emissions of greenhouse gases.

For the additional data (Figure 3b), the picture is less clear with only the forest cluster of Alice Holt and Wytham now joined by Rothamsted and with Drayton isolated in the top right of the graph. The sites classed as upland and farmland are intermixed to the left hand side of the graph. It is important to note that this study is restricted to what services the ecosystems currently deliver rather than their potential to deliver. The additional data primarily represent provisioning and cultural services and, therefore, the management of the ecosystem rather than its biophysical character.

Analysis of the full dataset gives a clearer separation of the sites (Figure 3c). The upland sites are associated with more flood and erosion events (a lack of key water regulating services) and the cultural activity of skiing; forest sites are more closely associated with cultural activities such as yoga, film making, Lepidoptera enthusiasts and fungal forays. The most striking feature of Figure 3c is the degree of dispersion of the 'mixed use' group of sites from the analysis of the biogeographical subset of data (Rothamsted, Drayton and Porton Down). The similarity distance between these sites reveals that Rothamsted has more in common with Wytham and Alice Holt. These sites, all relatively close to population centres, sustain the greatest 'cultural' diversity with Wytham and Alice Holt both supporting 17 and Rothamsted 14 different cultural activities. In contrast, the less accessible Porton Down, although biophysically similar to Rothamsted, is more similar to the livestock farms (Glensaugh, North Wyke and Sourhope) when the combined dataset is analysed, while Drayton is again relatively isolated; no public access is allowed at this site and, consequently, it scored poorly for the cultural services in this assessment.

In the first two dimensions of the generalised procrustes rotation (Figure 4) reveals that the upland and forest clusters are relatively compact and sites move little between datasets. On the third axis the forestry cluster is also compact but the upland sites are more spread out, indicating a greater difference between datasets.

Of the farmland sites, Glensaugh and Sourhope are more closely associated with each other than with North Wyke in all three dimensions. In addition, they move less between the two datasets, i.e. biogeographical subset and combined datasets give very similar results. The large movement of North Wyke suggests significant differences in the assessment of North Wyke when the additional variables are added to the biogeograpical subset. Sites in the 'mixed use' group are not tightly bound. The location of Drayton is similar on all three axes for both datasets indicating that its relationship with the other sites is adequately expressed by the biogeographical subset alone. Rothamsted, in contrast, shows a substantial difference between ordinations emphasising how differently the site might be viewed as a provider of ecosystem services when the scope of variables assessed is expanded from biogeographical to include social-cultural variables.

6. DISCUSSION

Quantification is necessary to manage ecosystem services and goods (Willemen *et al*., 2010), but even the initial tasks of identifying and categorising services can be challenging for rural landscapes in the UK which are multifunctional at a relatively small spatial scale. We encountered a range of issues with this first stage assessment which we consider below.

6.1. Spatial and temporal definitions

In practice, ECN site managers did not find it difficult to specify their site boundaries for the purposes of this study. The decisive factors were utilitarian, being determined by a variety of biogeographic and managerial reasons. We recognise that ecosystem service assessments need to be sensitive to multiple scales in time as well as space (Millenium Ecosystem Assessment, 2005; Carpenter *et al*., 2006; Bennett *et al*., 2009). In this broad initial study, however, in common with many others (Nicholson *et al*., 2009), it was necessary to control for temporal variation so we conducted a static analysis focusing on a single time point as an initial test of the utility of this approach at these sites.

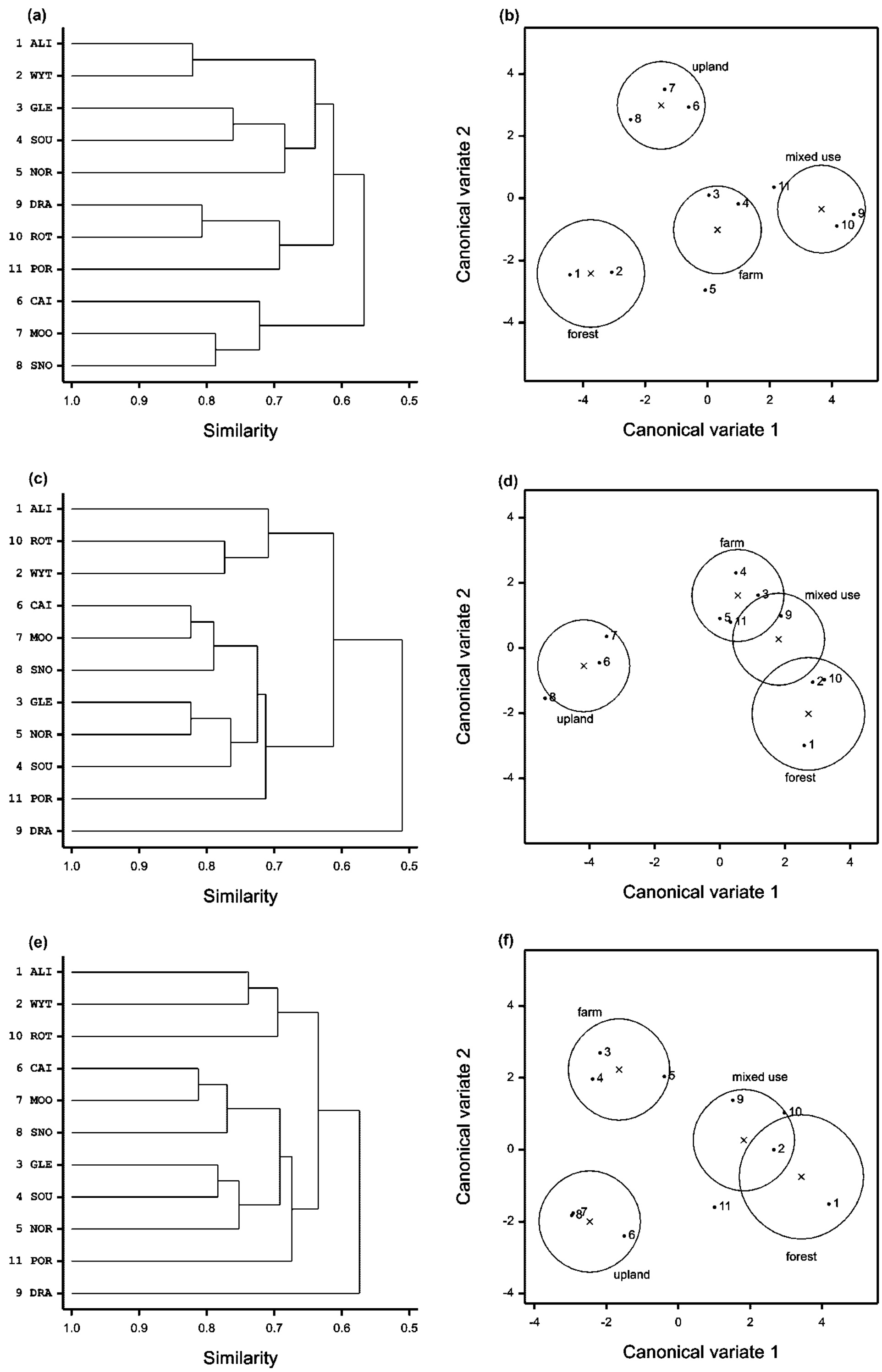

Figure 2. Dendrograms from hierarchical clustering on the similarity matrices using average linkage grouping and canonical variate plots showing 95% confidence circles round the group centroids; (a,b) biogeographical subset (c,d) additional data and (e,f) all 73 variables assessed. Sites are: 1 = Alice Holt, 2 = Wytham, 3 = Glensaugh, 4 = Sourhope, 5 = North Wyke, 6 = Cairngorm, 7 = Moor House, 8 = Snowdon, 9 = Drayton, 10 = Rothamsted, 11 = Porton

6.2. Quantifying ecosystem services

The MA described four different forms of ecosystem services: provisioning, regulating and cultural services directly affect people, while supporting services underpin the delivery of the other services (MA 2003). The categorisation of variables into provisioning, regulating and cultural services was not used in deriving the between-site similarities in these analyses but was useful to provide the underlying structure for the identification of variables included in the analysis (Table 2). It is recognised that most management focuses on the provisioning and/or

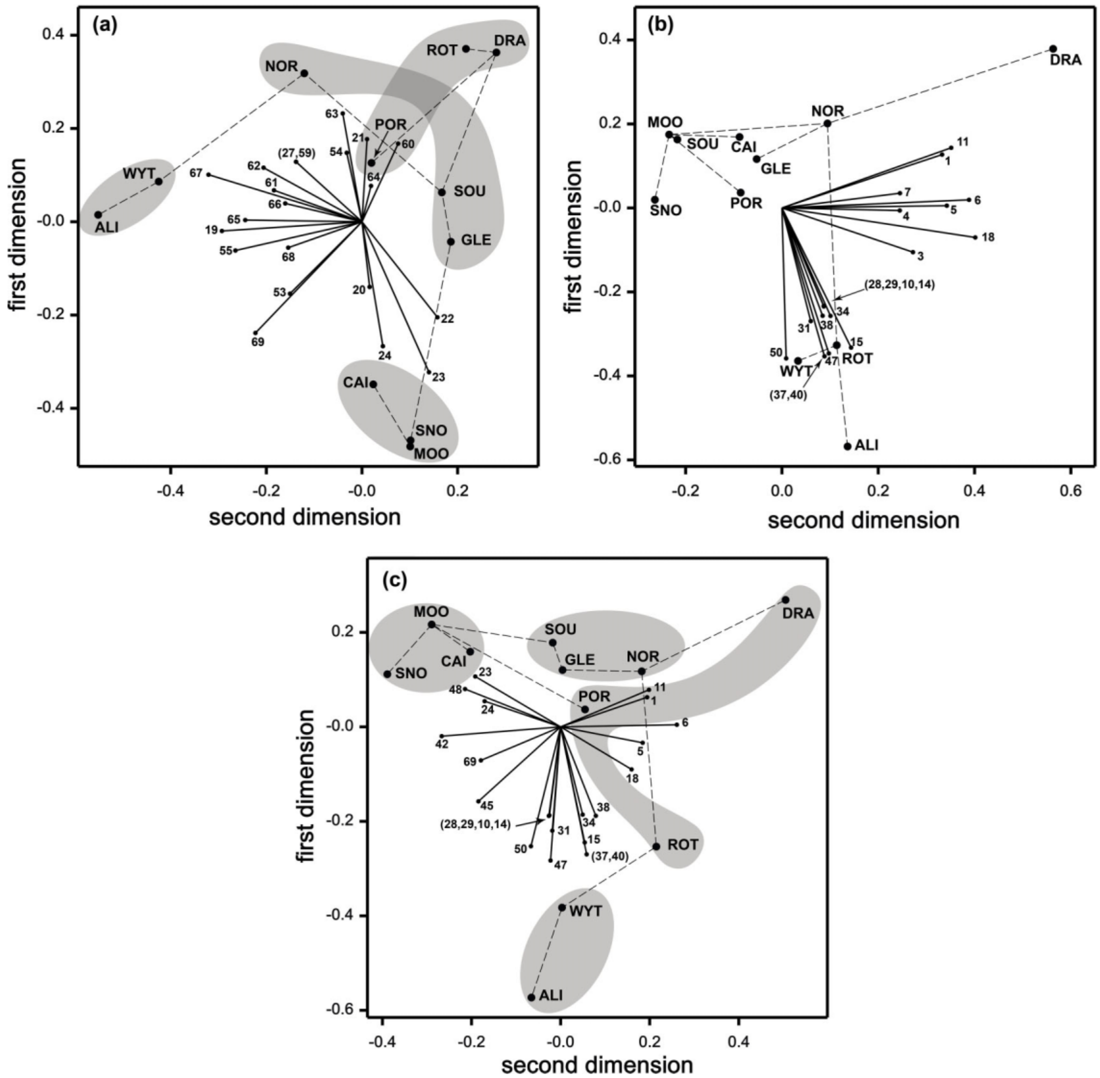

Figure 3. Minimum spanning trees and biplots of the 11 ECN sites for (a) biogeographical subset (b) additional data (c) the full dataset. Site and variable abbreviations defined in Tables 1 and 2, respectively. Shaded areas indicate clustering of sites (see Figure 2) with similar land use; substantial forests (Alice Holt and Wytham), primarily productive livestock farmland (Glensaugh, Sourhope and North Wyke), upland sites (Cairngorm, Moorhouse and Snowdon). The 'mixed use' sites (Drayton, Rothamsted and Porton Down) were not so highly clustered

cultural services (Carpenter *et al*., 2006; Carpenter *et al*., 2009) and these were found to be the easiest to quantify in this study. Quantification of supporting services was deemed beyond the scope of this initial study due to the spatially and temporally extensive level of measurement required to estimate most of these, e.g. nutrient cycling; photosynthesis, primary productivity, etc. with acceptable accuracy. However, ECN sites are particularly well placed to provide information in this area through the process-based research that is encouraged at these 'research platforms'. Regulating and supporting services are often overlooked in ecosystem service assessments but evidence has shown their importance in the context of European lowland grasslands (Pilgrim *et al*., submitted manuscript).

Any holistic approach to assessing ecosystem services delivered by a site faces first the challenge of how to objectively list and measure these. As noted earlier, we use the MA definition of services as the benefits people obtain from ecosystems. It was recognised that a single measure could contribute to separate ecosystem services which benefited people in this assessment. For example, the presence of mushrooms was codified as positive in the provisioning service category if they were known to be collected by local people for food and separately in the cultural services if 'fungal forays' were conducted at the site.

The focus on ECN sites provided a consistency of measurement for several variables including ECN biodiversity measures and vegetation types as defined by the Countryside Vegetation System (CVS). Some other non-ECN variables, based on mapped or modelled data, could also be applied consistently across sites. For example, the atmospheric sulphur and nitrogen flux to the sites are calculated from the standard UK deposition models (Smith *et al.*, 2000; Smith and Fowler, 2001). These use the gas and rain concentrations along with meteorological and landuse data to estimate the net exchange of sulphur and nitrogen between the ecosystem and the atmosphere, i.e. effectively the ability of the ecosystem to capture pollutants (which can also be nutrients).

Standard measures were, however, not available for many of variables at all sites. Face-to-face workshop discussions were, therefore, critical in maximising agreement in data collation procedures. Much detailed site-level information could not be included in this cross-site

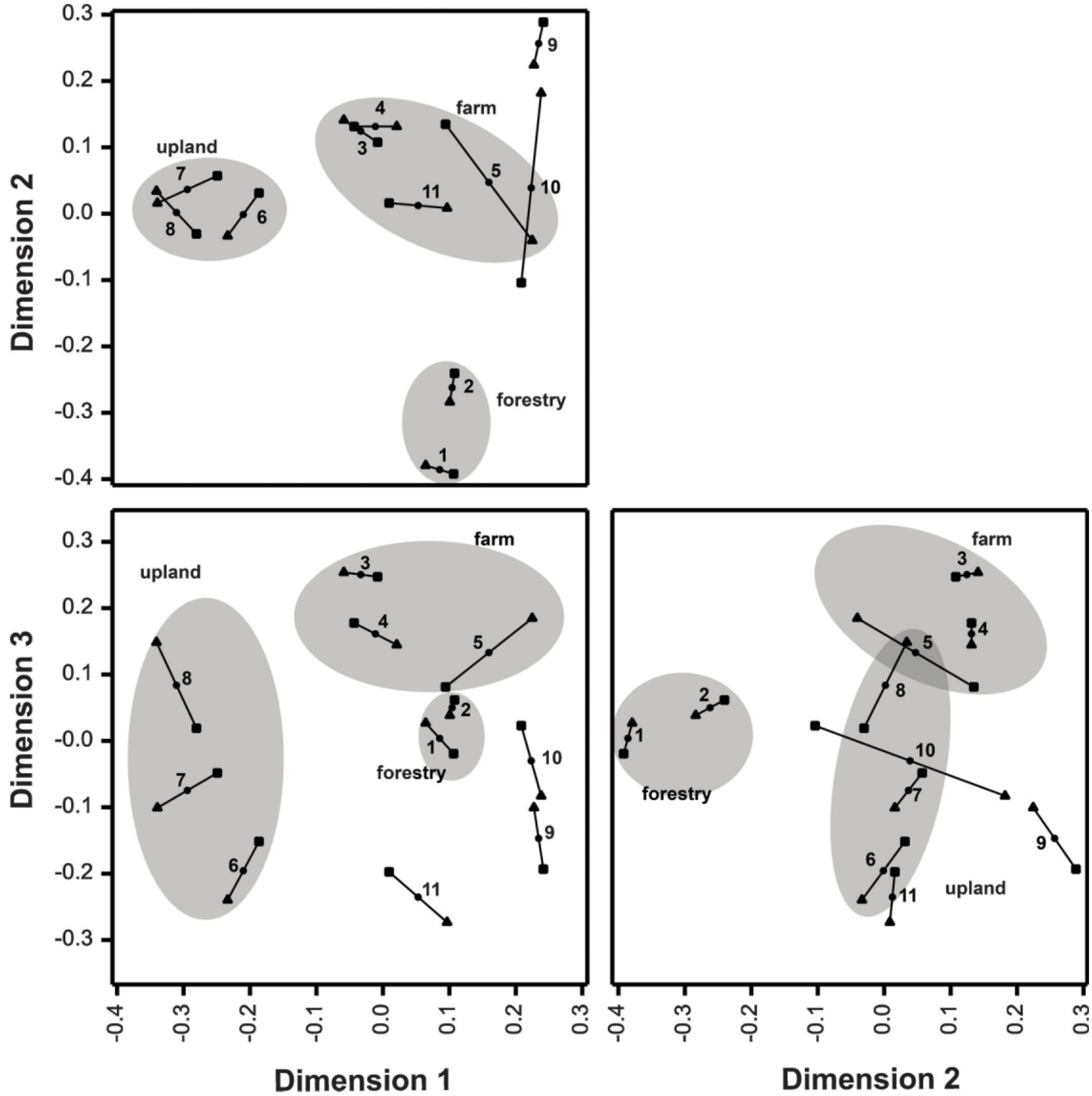

Figure 4. Procrustes analysis of two datasets (i) biogeographical subset (triangle) and (ii) full 73 variables matrix (square); farm, forestry and upland clusters marked by indicative shading, 'mixed use' cluster omitted for clarity. Site abbreviations defined: 1 = Alice Holt, 2 = Wytham, 3 = Glensaugh, 4 = Sourhope, 5 = North Wyke, 6 = Cairngorm, 7 = Moor House, 8 = Snowdon, 9 = Drayton, 10 = Rothamsted, 11 = Porton (see Figure 3 for explanation of shading)

study as the same level of detail was not available at all sites. Visitor numbers, for example, were available at very different levels of detail for the 11 ECN sites and it was, therefore, necessary to use a categorised log scale estimate as the common measure.

Some variables, we recognise, are weak proxies for the ecosystem service assessed, e.g. number of butterflies for pollination services, and more robust variables are being considered for future work, e.g. presence of plant species of known value to pollinators. For three cultural services defined by the MA (MA, 2003) no objective quantification could be determined in this study: knowledge systems, inspiration and sense of place. The use of web-based search engines to identify site images was considered as a quantifiable measure of the latter two services on the assumption that people taking time to take and post photographs on the web probably found the site inspirational in some sense. Problems with this approach included determining a robust list of search terms across all sites and the uncertainty as to whether the number of images could reasonably be taken to represent the degree of inspiration or sense of place, or if in fact they simply reflected a desire to share photographs with friends. The variables to quantify each service in this study, therefore, were pragmatically chosen; in common with many studies, we used available variables and proxies rather than necessarily the most important (Norgaard and Jin, 2008). As stated earlier, the focus of ECN monitoring is biodiversity assessment, a concept closely related to ecosystem assessment and directly linked to the provision of ecosystem services as recognised by the MA (2005). The ECN strategy includes tracking trends over time in key biodiversity components, mostly chosen for their use as wider environmental indicators. Feld *et al*., (2009) in their review of over 600 peer-reviewed papers noted that biodiversity indicators, normally represented by estimates of species richness only, were rarely used to evaluate ecosystem services, although stronger links have been made with ecosystems through ecological function (Balvanera *et al*., 2006).

6.3. Evaluation of ecosystem services

The MA recognises four valuation systems, namely economic, ecological, sociocultural and intrinsic value (MA 2003), which are clearly not independent. Biodiversity is an example of this as, in addition to its underpinning role in cultural and economic ecosystem services, it has intrinsic value for the functioning of ecosystems that is potentially independent from human existence. We have concentrated on ecological and sociocultural assessments in this initial study and not attempted economic assessment. This study has also not addressed the question of valuation between variables; analyses have treated each variable equally without attempting to allocate value.

It is important to recognise that the value of the ecological and sociocultural assessments in this study considered realised ecosystem services rather than potential ecosystem services at each site. The distinction is of particular relevance to the LTER sites since many are long-established monitoring and research sites for which the exploitation of potential ecosystem services may differ from similar areas elsewhere, i.e. the potential of the landscape/habitat is not realised. An example is the Rothamsted site which grows crops for research purposes but does not make commercial use of them. Also, Porton Down is suitable for agricultural livestock production as indicated by its proximity on the similarity distance plots (Figures 2–4) to North Wyke, Glensaugh and Sourhope but, due to its important national role as a military research and training facility, is not currently valued for its provisioning services. There are, therefore, clear examples in this study of ecosystem service valuation tradeoffs and synergies as described by Bennett *et al*. (2009).

Perhaps unsurprisingly, the analyses presented here show similar relationships between sites when comparing ecosystem services drawn from both the biogeographical data only and the wider dataset, which reflect the broadscale UK landscape categories upland, woodland and farmland and highlighting that particular ecosystem services are associated with specific landscape/habitat types. However, differences in relationships are revealed for the 'mixed use' cluster of sites in this study which do not realise their potential because of local management.

7. CONCLUSIONS

This study highlights some of the challenges involved in attempting to characterise in a holistic manner the ecosystem services delivered from a range of UK terrestrial non-urban environments. It illustrates the relatively strong commonalities in ecosystem service provision delivered by the main biogeographic types of site in the ECN and offers some explanations for discrepancies. The assessment benefited from the local expert knowledge provided by ECN site managers, the standard approaches to biophysical and ecological data collection resulting from adherence to network-wide protocols, and the workshop that standardised ontology for non-ECN variables. While not within the scope of this assessment, ECN sites, through their role as platforms for process-based research, are very well placed to contribute to the scientific assessment of the synergies and tradeoffs in ecosystem services (including supporting services) associated with the application of management practices.

Acknowledgements

The authors thank the many people who have contributed to the collection and storage of ECN data both at sites and the Central Coordination Unit. ECN is funded by Agri-Food and Biosciences Institute (Northern Ireland), Biotechnology & Biological Sciences Research Council, Countryside Council for Wales, National Assembly for Wales, Defence Science and Technology Laboratory, Department for Environment, Food and Rural Affairs, Environment Agency, Forestry Commission, Natural England, Natural Environment Research Council, Northern Ireland Environment Agency, Scottish Environment Protection Agency, Scottish Government, Scottish Natural Heritage.

REFERENCES

Balvanera P, Pfisterer AB, Buchmann N, He JS, Nakashizuka T, Raffaelli D, Schmid B. 2006. Quantifying the evidence for biodiversity effects on ecosystem functioning and services. *Ecology Letters* **9**: 1146–1156.

Bennett EM, Peterson GD, Gordon LJ. 2009. Understanding relationships among multiple ecosystem services. *Ecology Letters* **12**: 1394–1404.

Burton PJ, Messier C, Adamowicz WL, Kuuluvainen T. 2006. Sustainable management of Canada's boreal forests: progress and prospects. *Ecoscience* **13**: 234–248.

Carpenter SR, DeFries R, Dietz T, Mooney HA, Polasky S, Reid WV, Scholes RJ. 2006. Millennium ecosystem assessment: research needs. *Science* **314**: 257–258.

Carpenter SR, Mooney HA, Agard J, Capistrano D, DeFries RS, Diaz S, Dietz T, Duraiappah AK, Oteng-Yeboah A, Pereira HM, Perrings C, Reid WV, Sarukhan J, Scholes RJ, Whyte A. 2009. Science for managing ecosystem services: beyond the millennium ecosystem assessment. *Proceedings of the National Academy Sciences U.S.A.* **106**: 1305–1312.

Chopra K, Dasgupta P. 2008. Assessing the economic and ecosystem services contribution of forests: issues in modelling, and an illustration. *International Forestry Review* **10**: 376–386.

Dick JM, Smith RI, Scott EM. 2011. Ecosystem services and associated concepts. *Environmetrics* **22**: 598–607.

Digby PGN, Kempton RA. 1987. Multivariate Analysis of Ecological Communities. Chapman and Hall: London, UK.

Eamus D, Macinnis-Ng CMO, Hose GC, Zeppel MJB, Taylor DT, Murray BR. 2005. Ecosystem services: an ecophysiological examination. *Australian Journal of Botany* **53**: 1–19.

Faith DP, Minchin PR, Belbin L. 1987. Compositional dissimilarity as a robust measure of ecological distance. *Journal of Vegetation* **69**: 57–68.

Feld CK, da Silva PM, Sousa JP, de Bello F, Bugter R, Grandin U, Hering D, Lavorel S, Mountford O, Pardo I, Paertel M, Roembke J, Sandin L, Jones KB, Harrison P. 2009. Indicators of biodiversity and ecosystem services: a synthesis across ecosystems and spatial scales. *Oikos* **118**: 1862–1871.

Glendining MJ, Dailey AG, Williams AG, van Evert FK, Goulding KWT, Whitmore AP. 2009. Is it possible to increase the sustainability of arable and ruminant agriculture by reducing inputs? *Agricultural Systems* **99**: 117–125.

Liu S, Costanza R, Farber S, Troy A. 2010. Valuing ecosystem services. *Annals of New York Academy of Sciences* **1185**: 54–78.

Millenium Ecosystem Assessment. 2005. Ecosystems and human well-being. Island Press: Washington D.C., USA.

Morecroft MD, Bealey CE, Beaumont DA, Benham S, Brooks DR, Burt TP, Critchley CNR, Dick J, Littlewood NA, Monteith DT, Scott WA, Smith RI, Walmsey C, Watson H. 2009. The UK environmental change network: emerging trends in the composition of plant and animal communities and the physical environment. *Biological Conservation* **142**: 2814–2832.

Nicholson E, Mace GM, Armsworth PR, Atkinson G, Buckle S, Clements T, Ewers RM, Fa JE, Gardner TA, Gibbons J, Grenyer R, Metcalfe R, Mourato S, Muuls M, Osborn D, Reuman DC, Watson C, Milner-Gulland EJ. 2009. Priority research areas for ecosystem services in a changing world. *Journal of Applied Ecology* **46**: 1139–1144.

Norgaard RB, Jin L. 2008. Trade and the governance of ecosystem services. *Ecological Economics* **66**: 638–652.

Porter J, Costanza R, Sandhu H, Sigsgaard L, Wratten S. 2009. The value of producing food, energy, and ecosystem services within an agro-ecosystem. *Ambio* **38**: 186–193.

Seppelt R, Muller F, Schroder B, Volk M. 2009. Challenges of simulating complex environmental systems at the landscape scale: a controversial dialogue between two cups of espresso. *Ecological Modelling* **220**: 3481–3489.

Smith RI, Fowler D, Sutton MA, Flechard CR, Coyle M. 2000. Regional estimation of pollutant gas dry deposition in the UK: model description, sensitivity analyses and outputs. *Atmospheric Environment* **34**: 3757–3777.

Smith RI, Fowler D. 2001. Uncertainty in estimation of wet deposition of sulphur. *Water, Air & Soil Pollution: Focus* **1**(5/6): 341–353.

Stoate C, Baldi A, Beja P, Boatman ND, Herzon I, van Doorn A, de Snoo GR, Rakosy L, Ramwell C. 2009. Ecological impacts of early 21st century agricultural change in Europe—a review. *Journal of Environmental Management* **91**: 22–46.

Willemen L, Hein L, van Mensvoort MEF, Verburg PH. 2010. Space for people, plants, and livestock? Quantifying interactions among multiple landscape functions in a Dutch rural region. *Ecological Indicators* **10**: 62–73.

