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The UK Environmental Change Network after twenty years of integrated ecosystem assessment: key findings and future perspectives

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Highlights

- The UK Environmental Change Network has been in operation for 20 years
- The ECN addresses the causes and consequences of environmental change
- The range of papers in this issue illustrates wide applicability of the network
- Tighter integration with complementary programmes is highly desirable
- Evolving environmental challenges will require network development and adaptation

Abstract

The UK Environmental Change Network (ECN), the UK's Long-Term Ecosystem Research (LTER) network, has now been operating for over twenty years. It was established in 1992 as a set of terrestrial sites at which sustained observations relevant to a range of ecological indicators and environmental parameters could be made. An additional ECN freshwater network was launched in 1994. In this paper we provide a brief history of the network, and describe its current structure and role within a complementary wider range of UK environmental monitoring and observation programmes that are either more focussed on specific parameters or habitats, or operate at different temporal and spatial scales. We then provide a review of the other papers within this Special Issue, which exemplifies the broad range of environmental concerns that ECN data and sites are helping to address. These include network-wide summaries of environmental and biological trends over the first two decades of monitoring, more site-specific assessment of the ecological impacts of local pressures resulting from changes in management, biological and ecosystem service indicator development, and the testing of new monitoring technologies. We go on to consider: (i) future directions of network development and adaptation in light of recently emerging environmental concerns, dwindling financial resources and the consequent need for greater efficiency; (ii) the desire for tighter integration with other monitoring and observation programmes both nationally and internationally; (iii) opportunities raised by recent technological developments; and (iv) the need to process and make available data more rapidly to increase the capacity of ECN sites as early warning systems. In its first two decades of operation the ECN has accumulated a robust set of baseline data that describe environmental and biological variability across a range of habitats in unprecedented detail. With appropriate, informed development, these should prove invaluable in discerning the causes and consequences of environmental change for decades to come.

Keywords: Long-term monitoring; ECN; LTER; Climate change; Air pollution; Indicators

1. Introduction

The diverse range of ecosystems that characterise the non-urban environment serve a host of vital functions that underpin human health and wellbeing. A comprehensive overview of the value and changing state of the UK's ecosystems, conducted by the UK Natural Ecosystem Assessment in 2009-2011 (UK NEA, 2011), concluded that around 30% of these 'ecosystem services' were in a state of decline, while several others, including functions provided by soils and wild species diversity, were in a reduced or degraded state. The UK NEA identified a range of pressures, often acting in concert, contributing to this degradation, including urbanisation, intensive agriculture, pollution and climate change. It argued that the benefits derived from ecosystems were currently undervalued in an economic sense and that future sustainable development would require their true worth to be taken into account in any decision-making process. Among its conclusions the NEA states: 'In order to refine our understanding of the fundamental ecosystem processes underpinning the delivery of ecosystem services we need to both extend our observations and experimental manipulations, and also improve our models of the key mechanisms.'

Of course, concern over the decline in the extent and quality of natural environments and resources extends back well before the recent articulation of concern over ecosystem services. Researchers, conservationists and decision-makers have long recognized the importance of understanding processes that determine how ecosystems function, how and why they may be changing, and how resilient they are to both short term and more sustained disturbances. This need is served through a continuously evolving scientific understanding founded on inter-dependent disciplines of repeated observation, controlled experiments and process-based and mathematical modelling (Parr et al., 2003).

The first of these disciplines requires precise measurements to be made over much longer periods of time than may be covered by standard scientific research grants (typically of 3-5 years duration). Indeed, strong natural variation in climate at a range of frequencies dictates that several decades of data may be necessary to identify and quantify some key underlying trends in the environment resulting, for example, from climate change or changing pollution emission policy. The establishment and maintenance of systems of consistent, repeated measurements over long periods, therefore, requires a clear long-term vision, sustained and often substantial investment and the patience of funding bodies – particularly during the early years of operation. Consequently, robust long-term environmental monitoring and research programmes in the UK are relatively few and vary with respect to scope, structure and funding models.

The most long standing and scientifically valuable UK monitoring or observation programmes range from the series of occasional but measurement-rich GB Countryside Surveys (CS) (Carey et al., 2008), to higher frequency – but often more measurement or habitat-specific – programmes such as the UK Acidifying and Eutrophying Atmospheric Pollutants network (UKEAP), the UK Upland Waters Monitoring Network (UWMN; Battarbee et al., 2014), and the UK Butterfly Monitoring Scheme (UKBMS). These are complemented further by extensive freshwater monitoring networks operated by national agencies to ensure compliance of water quality standards, and a wealth of observations of species occurrence, often made by amateur experts and managed by the Biological Records Centre (Pocock et al., 2015), that inform particularly on changing species distributions. This conceptual gradient of largely complementary programmes, from broad-scale, spatially extensive, low frequency measurement to narrower, more site-focussed and measurement-intensive observation can be represented in schematic form as a pyramid or triangle (Figure 1). The UK Environmental Change Network (ECN; www.ecn.ac.uk) fills a particular niche toward the apex, with its emphasis on multi-disciplinary site-focussed monitoring.

Established in 1992 as a network of a relatively small number of instrumented sites, the ECN spans a wide range of ecosystems at which sustained long-term observations of selected physical, chemical and biological variables are made according to tightly defined protocols. The resulting quality controlled data are lodged in a central database (Rennie, this issue) which is openly available. The ECN originally comprised eight terrestrial sites, but four more terrestrial sites joined the network during the period 1993-1999, bringing the total to 12 (Table 1). In 2014 ECN monitoring ceased at Drayton, reducing the number to 11. A freshwater ECN network was established in 1994 and currently comprises 45 freshwater sites (lakes, rivers and streams). The map (Figure 2) shows the locations of ECN sites.

The ECN is operated by a consortium of organisations (see ECN website, www.ecn.ac.uk, and acknowledgements for details) who contribute variously to the provision of monitoring sites, sampling/recording and analytical chemistry services. Separate partner organisations are responsible for the management of individual ECN terrestrial sites. They provide data to a small team at the NERC Centre for Ecology & Hydrology, who coordinate and promote the network and manage the ECN's central database and website. Rennie (this issue) describes in more detail the ECN's approach to – and recent developments in – field data capture, data management and provision of data access. ECN datasets are freely available for use under licence for research and educational purposes, and have supported a wide range of research to date. A list of publications based on research using ECN data or taking place at ECN sites is maintained on the ECN Data Centre website (ECN).

The ECN Data Centre team also manage data generated by related networks including the UK Environmental Change Biodiversity Network (ECBN), the UK Lake Ecological Observatory Network (UKLEON) and the UWMN (chemistry database). At each ECN site, measurements are made and samples collected according to published protocols (Sykes & Lane, 1996; Sykes et al., 1999). The indicators monitored (Table 2) were selected to provide an integrated suite of driving, state and response variables, to enable relationships to be tested, whilst at the same time taking into consideration issues such as cost, practicality and safety (Sykes & Lane, 1996).

Several sites in the network were already important platforms for monitoring and research before the onset of the ECN. For example: Rothamsted is the oldest continually functioning agricultural research station in the world, and home to the Sir John Lawes's 'Classical Experiments' (e.g. Silvertown et al., 2006), started between 1843 and 1856; Moor House-Upper Teesdale and Wytham contributed to the Tiger Programme (Cummins et al., 1995); Moor House, along with Snowdon and Cairngorms, also participated in the International Biological Programme (IBP; Heal and Perkins, 1978); Oxford University owned Wytham Woods have also been the focus for internationally recognised research over many decades (Perrins et al., 2010), while Alice Holt is one of three Research Forests equipped with an eddy covariance tower for studying carbon dynamics. Indeed, most terrestrial ECN sites were selected primarily on the basis of their long histories of environmental monitoring and research. Consequently, while ECN terrestrial sites cover a broad spectrum of UK habitats (Dick et al., 2011), they are relatively few in number and have relatively limited power, in isolation from the wider available evidence base, to inform on environmental change at a UK scale.

Regardless of the spatial extent of the network, however, the ECN is nationally unique with respect to the range of high frequency physical, biogeochemical and biological measurements that are made in close proximity. This provides unparalleled opportunities to directly link pressures and responses associated with long-term environmental change over various timescales. For example, bi-weekly measurements of soil water chemistry can be linked with weekly measurements of precipitation chemistry to assess the impact of reductions in the emissions of acidic pollutants to the atmosphere on soil acidity, while the wider impacts of emissions control on these ecosystems can be examined with reference, for example, to vegetation assemblages. Similarly, the potential risks to biodiversity posed by an increasingly erratic climate can be investigated using weather data specific to the location of butterfly, moth and carabid beetle population assessments. The latter may be particularly useful with respect to assessing the impact of changes in the frequency and intensity of precipitation or drought, effects of which may be too localised to be represented by spatially extrapolated meteorological data, and these in turn may shed light on drivers behind national-scale temporal patterns.

Arguably, however, the full potential of the ECN in the assessment of the causes and consequences of environmental change is realised only when data and observations from this site-focussed network are integrated within a more spatially extensive 'network of networks' comprising other national and international monitoring and observation systems. Some elements required to facilitate this are already in place. Thus several of the monitoring protocols are shared with other UK networks, including the Rothamsted Insect Survey (Rothamsted Research), the UKBMS and the Ammonia Network (Defra), while six ECN freshwater sites are drawn from the UWMN. ECN sites contribute to these other programmes, while patterns of change at individual ECN sites are providing fine temporal-scale context for observations made by other systems. For example high frequency ECN vegetation measurements have been used by the CS to determine the extent to which botanical measurements made in specific survey years may have been influenced by atypical conditions such as very wet or very dry summers (Scott et al., 2010).

The ECN also has an integrative role internationally as the UK's official Long-Term Ecosystem Research (Müller et al. (eds), 2010) network and as a member of the International Long-Term Ecological Research network (ILTER; Kim, 2006) and its European regional component, LTER-Europe (LTER-Europe; Mirtl, 2010). Several ECN sites are included in other international networks. Cairngorms is in the European GLORIA network (alpine vegetation; Gottfried et al., 2012; Pauli et al., 2012), whilst Alice Holt is part of the pan-European ICP Forest Level II network. Among ECN freshwater sites, Windermere (Maberly & Elliott, 2012) and Loch Leven (May & Spears, 2012) are particular focal points for long-term research into lake ecosystem dynamics, while a number of lowland river sites, monitored by the Environment Agency of England and Wales, the Scottish Environmental Protection Agency and the Northern Ireland Environment Agency, are key sites within their Water Framework Directive monitoring networks.

Observations and publications based on ECN data inform environmental policy development across a range of disciplines. For example, the ECN soil solution chemistry records provided the primary evidence, reported in the UK Review of Transboundary Air Pollution (RoTAP, 2012), for soil chemical responses to reductions in the deposition of acid air pollutants, and evidence for links between the release of dissolved organic carbon from peatlands and both acid deposition (Stutter et al., 2011) and droughts (Clark et al., 2006). The same data were fundamental in recognising that hydrochloric acid deposition had made a significant contribution to soil acidification at a UK scale (Evans et al., 2011) and this is now feeding into a revision of dynamic models used to determine the sensitivity of soil biogeochemistry to long-term changes in acid deposition (e.g. Rowe et al., 2014b). ECN bulk soil chemistry data have also been used to determine long-term changes in woodland soil carbon storage as a consequence of increasing soil horizon depth (Benham et al., 2012). These studies are of particular interest to stakeholders concerned with carbon accounting, natural capital assessments and water quality management.

Elsewhere, ECN vegetation data have been central to the development of a new indicator of ecological impacts of nitrogen deposition, as requested by the Convention on Long Range Transboundary Air Pollution (Rowe et al., 2014a), and ECN chemistry data from Rothamsted have enabled Storkey et al. (2015) to identify some of the first indications of recovery in plant biodiversity from the long-term impact of nitrogen deposition. Time series analysis of ECN ecological data (Morecroft et al., 2009) contributed to the development of the UK Biodiversity Report Card (Morecroft & Speakman, 2013) and a UK government report on Biodiversity Indicators of Climate Change BICCO-Net (Pearce-Higgins et al., 2015). ECN invertebrate data also contributed to an assessment of links between climate change and phenological change (Thackeray et al., 2010) that was cited as evidence in the Intergovernmental Panel on Climate Change's recent assessment of Terrestrial and Inland Water Systems.

Two decades since the ECN was launched, 20 year time-series have been assembled for the terrestrial network and published under a series of digital object identifiers (DOIs; ECN Data Centre). This Special Issue provides an opportunity to exploit these datasets in order to characterise and quantify some of the key changes that have occurred over this period both at a network level and at individual sites. It also provides examples of how ECN datasets and sites are contributing to the development of clearer process understanding, model testing and development, and the trialling and calibration of new monitoring technologies. In the following section we briefly review the other papers in the issue, focussing particularly on key scientific findings of relevance to management and policy development. In Section 3, we go on to consider, in the light of changing environmental pressures, evolving management and policy needs and dwindling budgets, how the ECN might best continue to develop and adapt in order to remain centrally relevant to the UK's evidence base serving the detection and attribution of environmental change.

2. Paper synopses

The breadth of papers in this Special Issue illustrates the versatility of ECN data and ECN sites in addressing a range of issues of concern surrounding the assessment and interpretation of environmental change. They range in scope from the broad-scale quantification of change across sites, to site-specific investigations aimed at developing clearer process understanding, method testing and the development of the ECN data management system.

In order to support the wide range of research into environmental change exemplified by the other papers in this issue, it is essential that data are collected, processed, stored and distributed in a systematic and fully traceable manner. The ECN has pioneered the development of an informatics approach to handling and integrating a diverse array of environmental time-series data. The organisation, structure and function of the ECN database, from initial data capture, through quality control and centralised data management, to making data publicly available are presented by Rennie (this issue). The paper also covers the importance of complying with current data and metadata standards, such as the European INSPIRE Directive, and considers recent technological opportunities to receive and manage ever larger volumes of telemetered data, and develop online data exploration interfaces.

Background environmental context for several of the following papers is provided by Monteith et al. (this issue) who present an analysis of change and variation in a range of weather and atmospheric deposition indicators measured at terrestrial ECN sites between 1993 and 2012. Regional-scale influences of climate change and air pollution are likely to be the most important drivers of environmental change at these sites, since local land management tends not to vary much over time. Perhaps surprisingly, Monteith et al. (this issue) found no evidence of significant change in monthly mean air temperatures over the full time series, but noted a marked increase in precipitation over summer months, which was linked to an unusually prolonged directional shift in the summer North Atlantic Oscillation (NAO). The intensity of extreme precipitation events also increased. More generally inter-annual variability in weather was strongly linked to variation in the NAO, thus illustrating the challenge of separating signals of long-term climate change from shorter term variability. Arguably the most ecologically influential changes in the environment of ECN sites over the past two decades resulted from substantial reductions in acid deposition, and much of the wider UK countryside is likely to have experienced similar trends over the period. Sites experienced large declines in the concentration of sulphate in precipitation, while concentrations of nitrogen species, i.e. nitrate (NO_3^+) and ammonium (NH_4^+), also fell slightly at several sites. Regional scale drivers of environmental change are therefore likely to be responsible for both widespread increases in soil solution pH, reflecting reductions in acid deposition, and wetter conditions over the middle of the growing season.

One of the major strengths of the ECN is the co-located measurement of weather, pollutant deposition and soil solution chemistry. The same suite of measurements is also made by the Forest Level II monitoring network. Sawicka et al. (this issue) combined data from the two networks to explore dynamic links between changes in the chemistry of deposition and weather parameters, and soil solution chemistry. They focussed particularly on the dynamics of Dissolved Organic Carbon (DOC), which has been increasing in upland surface waters around the UK. Dissolved Organic Carbon poses a particular problem for the water industry since it has to be removed using costly water treatment processes prior to disinfection by chlorination to prevent the production of potentially toxic bi-products. Non-linear trend analyses were used to characterise the timing of large reductions in sulphur deposition at several sites and the resulting impact on soil chemistry. These changes included rising soil pH and an increase in DOC concentrations in the surface organic layers particularly, thus supporting the rarely tested hypothesis that the widely observed increase in DOC in surface waters (Monteith et al., 2007) has its origins in soil processes. The findings help to clarify process understanding and should benefit the parameterisation of process-based models that are being developed to help water quality managers predict likely future changes in DOC and develop appropriate adaptation and mitigation strategies.

Impacts on vegetation of these recent changes in weather, acid deposition and soil acidity, in addition to land management, were considered by Rose et al. (this issue). They analysed trends in vegetation data collected at the 12 terrestrial ECN sites for the period 1993-2012. These data are unique nationally with respect to the unusually high frequency of measurements (annual to tri-annual surveys) – and thus serve as particularly sensitive records of long-term change. They found a network-wide increase in both plant species richness and an ecological indicator characterising species associations with soil pH (Ellenberg R), while species increasing in frequency tended to be characteristic of less acid soils. In some lowland habitats, increasing species richness could also be linked to increased soil moisture availability (perhaps reflecting the trend towards wetter summers (Monteith et al., this issue)), and to a reduction in intensive farming practices (particularly with respect to reductions in the application of nitrogen fertilisers). The apparent positive response of plant species richness to declining soil acidity, which in turn is driven predominantly by reductions in sulphur deposition, draws into question some current assumptions regarding the role of nitrogen deposition in reducing plant diversity, which underpin the national and international setting of critical loads for nitrogen. Plant species richness is known to be strongly negatively correlated with nitrogen deposition and species richness, but as nitrogen and sulphur deposition tend to co-vary spatially, it is feasible that part of this 'effect' is actually attributable to the historical impacts of sulphur deposition that are now waning. The study therefore highlights a clear policy need for a more thorough evaluation of the relative impacts of atmospheric eutrophication and acidification on botanical biodiversity.

ECN vegetation data collected at particularly high frequency (i.e. annually) also enabled Morecroft et al. (this issue) to assess the resilience of vegetation by quantifying the extent of inter-annual variation in plant communities. Their findings challenge the commonly held assumption that plant communities change relatively little from one year to the next. They show that the extent of variability was dependent on habitat type. Plant communities associated with low levels of disturbance and low agricultural inputs were the most stable, and, they propose, are therefore more likely to be resilient to gradual environmental changes. They conclude that plant monitoring scheme design needs to take into account the extent of inter-annual variability, in order to correctly identify longer-term trends.

Assessment of the impact of changing farming practices on vegetation diversity and productivity, a key issue in the development of food security policy, is investigated in further detail at a single lowland agricultural ECN site by Pallett et al. (this issue). Using vegetation data collected from a long-term experiment at Wytham, which switched from conventional to organic agriculture mid-way through the ECN monitoring period, they demonstrate that the withdrawal of nitrogen-based fertiliser applications resulted in an immediate reduction in grassland productivity while species richness increased by 300%. They argue, therefore, that the study illustrates a clear trade-off, whereby the increase in biodiversity occurs at the expense of productivity, as a consequence of high-yielding nitrogen loving grass species being replaced by a more diverse mix of less productive grasses and forbs. The study brings into clear focus the challenges of meeting potentially conflicting policy agendas.

In a further assessment of impacts of lowland agricultural management on biodiversity, Eyre et al. (this issue) investigated land use effects on the spatial and temporal variation in the community structure of carabid beetles. These are an important group of crop pest predators and have been the focus of previous studies using ECN data (e.g. Brooks et al., 2012; Pozsgai & Littlewood, 2014). There is considerable interest in reducing dependence on pesticides by boosting predatory insect abundance using non-crop field margins. The authors focussed on carabid data from two English lowland agricultural research sites in England: the ECN site Drayton in the west midlands and Nafferton Farm in Northumberland. They found carabid activity in non-crop habitats, often used as 'beetle banks' in bio-control management of crop pests, to be sub-optimal, and that the species composition of these environments was influenced by surrounding management activity. They conclude that some management is likely to be required to maximise the potential of these features to contribute to pest control.

Milligan et al. (this issue) explored the implications of less intensive upland management on biodiversity, drawing on data (over the period 1954 – 2000) generated by a long-term sheep exclosure experiment at the Moor House ECN site in the northern Pennines. They found that species diversity declined significantly in the sheep-grazed plots over this period, compared with plots that were protected from grazing. The results contrast with those of Rose et al. (this issue) who identified positive trends in vascular species richness across ECN sites in more recent years, but there was little overlap between the two studies and grazing intensity has declined at Moor House since 2000. Nevertheless the study emphasises the vulnerability of upland systems to traditional farming practices and raises issues regarding what may be the most appropriate targets for habitat management.

A holistic approach to upland management needs to consider marginal benefits and potential trade-offs to ensure the optimal delivery of ecosystem services. At the Moor House ECN site, in addition to sheep production and biodiversity conservation, this includes carbon sequestration by the peat soils that also deliver high loads of dissolved organic carbon (DOC) to drainage waters. Rising concentrations of DOC in surface waters might be expected to be accompanied by greater losses of carbon from waters to the atmosphere in the form of CO_2 and methane following microbiological and physical degradation of dissolved organic matter. The extent of these losses is difficult to quantify but is a potentially important policy parameter with respect to national carbon accounting. Moody et al. (this issue) harnessed the unique co-located long-term measurements of DOC and other solutes in atmospheric deposition, soil water and stream water available for the ECN peatland site, Moor House. The difference between a theoretical soil input flux of DOC (based on estimated DOC contributions from various catchment sources), and the flux measured in stream runoff was taken to represent either a carbon loss to the atmosphere or a gain by the stream, depending on the method applied. Despite the conflicting results, the novel approach, blending co-located soil and surface water time series, showed considerable potential for contributing to our understanding of fluvial carbon dynamics.

This Moor House study illustrates the growing demand from policymakers for methods to quantify how the UK's natural capital assets (such as soils, fresh water and biodiversity) contribute to human health and wellbeing, in order to advise environmental decision-making. Consequently, a range of tools has been developed to parameterise the delivery of ecosystem services provided by the natural environment. In recent years, ECN data and the expert knowledge of those responsible for managing individual sites have been used to assess the validity and applicability of some of these methods (Dick et al. (2011). In this volume, Dick et al, (this issue) go on to explore how recent environmental change at ECN sites translates into changes in ecosystem services using both qualitative and quantitative approaches to ecosystem service assessment. The authors observed a gradual change in the balance of ecosystem service delivery toward cultural services at most sites, associated, for example, with the increased use of land for recreation and education. While the quantitative method was more robust statistically, they concluded that a blend of qualitative and quantitative approaches provided a more holistic picture of long-term trends in ecosystem service delivery.

The availability of multiple ecological time series linked to both physical and chemical supporting data provides various opportunities to test existing, and develop new, indicators of environmental and ecological change and resilience. To date, climate change impacts on species and ecosystems in various parts of the world have been clearest with respect to changes in phenology and distribution ranges. However, population sizes and community structure are also likely to be affected. Indicators are therefore required to quantify the extent of these effects in order to inform climate change impact assessments. Martay et al. (this issue) describe a new community-based climate change indicator approach to assess climate impacts on moths and butterflies. Conventional climate change indicators are calibrated using spatial relationships between species distributions and climate. However, these can be very dependent on data being drawn from across wide geographical ranges, and are also based on the assumption that species variations in climatic space can be applied to predict change at individual locations over time. The authors have, therefore, explored an alternative approach that exploits temporal relationships between species abundance and climate. These were then tested on ECN sites where lepidopteran communities and weather parameters are measured in close proximity. The authors found that the approach was effective at predicting spatial and temporal variation in lepidopteran communities at ECN sites but only when models were calibrated at a seasonal scale, thus emphasising the need, in this case, to take seasonality into account.

The high frequency and taxonomic detail of several of the ECN datasets also provide excellent opportunities to explore variation (between sites and over time) in community structure, and its importance in underpinning ecological resilience. However, the characterisation and application of ecological networks remains a great challenge for ecologists. Pozsgai et al. (this issue), therefore, explored the potential of a Bayesian Network approach to study interspecific relationships among carabid beetles at two ECN upland sites, Glensaugh and Sourhope. They conclude that Bayesian networks are effective tools for modelling interspecific relationships between carabid species and, given the relative ease by which the necessary field data can be collected, propose that such methods could now start to routinely inform ecological assessments and conservation plans.

High quality, long-term time series are essential not only for quantifying environmental change but also to calibrate models that can then be used to predict likely future behaviour, in response to changes in land use or climate change, for example. Elliott et al. (this issue) investigated past changes in cyanobacteria and nutrient chemistry in the UK's largest lake, Lough Neagh, in Northern Ireland. One of several lakes on the ECN freshwater network, the water quality and biota of Lough Neagh has been severely affected by chronic nutrient enrichment from agricultural and domestic sources. Potentially toxic cyanobacterial blooms, which thrive when levels of phosphorus are high, present a particular societal threat, since Lough Neagh provides drinking water to approximately one million people. Using the PROTECH phytoplankton response model, calibrated with ECN input data, the authors predicted how the lough's phytoplankton might respond to a potential increase in temperature driven by climate change and to a gradual reduction in nutrient load as a consequence of tighter controls on nutrient releases. The results suggest that future warming could simply lead to the replacement of one cyanobacterial species by another, unless phosphorus inputs are reduced more substantially.

As many of the studies in this issue demonstrate, accurate and repeatable measurements are vital for the assessment of long-term trends in ecosystem structure or function. However, some well-established monitoring techniques can be time consuming and therefore expensive, and may also be prone to subjective variations arising, for example, from recorder bias. There is an increasing expectation internationally for long-term environmental monitoring programmes to become more efficient and thus less demanding on resources. Recent technological developments provide a variety of opportunities to make measurements at lower cost, and in some cases to higher levels of accuracy and provision. Baxendale et al. (this issue), working at the Moor House ECN site, investigated the use of several digital image techniques for recording vegetation cover at the plant functional type level. Whilst not, in this case, a replacement for the current vegetation monitoring protocol, this approach presents the potential to rapidly and accurately assess plant functional type cover during spatial surveys and over time at fixed locations. ECN sites should not only be able to benefit from such technologies in the longer term, but in the meantime they also provide excellent research platforms at which new approaches can be tested alongside more conventional measurements.

3. Current and future development

As the previous section demonstrates, the first two decades of consistent measurements for the majority of the original parameters are serving to increase our understanding of the changing state of the environment at ECN sites. The scientific potential of the network should only increase as the datasets continue to lengthen. All long-term environmental monitoring programmes, however, ultimately face conflicting pressures from the desire to maintain uninterrupted records and the need to adapt to evolving environmental concerns and policy priorities. Furthermore, new opportunities frequently arise from the development of new monitoring and measurement technologies, while tightening financial constraints often impose a need to increase the efficiency of data collection and management. In this section, therefore, we consider the challenges and opportunities that the ECN, and the terrestrial network in particular, needs to address to ensure optimal delivery of data of value to science, land management and policy development over the next two decades and beyond.

3.1 Emerging environmental concerns

At the time of initiation of the ECN, concerns over the possible impact of global climate change had only recently begun to emerge (Huntingford and Friedlingstein, 2015), while issues associated with air pollution, and acid rain particularly, dominated the environmental policy agenda. Over the last two decades the balance has clearly shifted, particularly as a consequence of large reductions in acid deposition as well as a heightened awareness of changes in global climate. Trends in weather at ECN sites have been documented in some detail (Morecroft et al., 2009; Monteith et al. this issue). While long-term change in air temperature is arguably the element of climate change that receives most attention, the strongest shifts in weather identified over the past two decades mostly involve changes in hydrology, particularly increases in summer rainfall and the magnitude of extreme precipitation events. Within the period covered by the ECN there have also been significant periods of drought, e.g. 1995-97 and 2004-06. The likelihood that changes in the distribution of precipitation extremes across the northern hemisphere are linked to climate change is receiving increasing attention within the climate modelling community (see, for example, Min et al., 2011). The co-location of high frequency meteorological, biogeochemical and biological measurements places the ECN in a unique position to begin to assess the implications of such effects on ecosystems. However, more detailed quantification of these episodes, including higher frequency rainfall recording (until recently summarised at hourly intervals only) and the deployment of more intelligent instrumentation, for example to assess rain drop size and intensity, may be necessary to further enhance this capability.

While the UK NEA has highlighted threats to a range of ecosystem services it is also clear that some of the potentially most important elements and processes contributing to these services are rarely monitored in a consistent manner within a wider integrated framework of measurements over long time scales. Indeed, several key components of nutrient cycling (including soil microbial and animal communities, decomposition and net primary productivity) and response variables such as gaseous fluxes of carbon dioxide, methane and nitrous oxide are currently not assessed routinely at ECN sites; methods and instrumentation in these areas were either underdeveloped and/or prohibitively expensive at the time of initiation of the network. Recent methodological advances in, for example, gene sequencing and microclimatological instrumentation, provide new opportunities to quantify processes at various temporal and spatial scales, and link these to the broader measurements made at ECN sites.

The ECN would clearly stand to gain from the incorporation of these new technologies as they become more affordable and deployable. Alternatively, certain parameters of potential importance could be modelled from data generated by other networks. For example, there is growing concern that background ozone concentrations in the UK are rising to levels potentially harmful to natural vegetation, which, when coupled with the occurrence of drought, could lead to synergistic impacts (Mills et al., 2009). While ozone in not currently measured routinely at ECN sites there is potential for ozone measurements made by the Automatic Urban and Rural Network (Defra) to be extrapolated to ECN sites, while rotation of a small number of ozone monitors might be sufficient to validate model predictions.

3.2 Strengthening links with other programmes and initiatives

As emphasised in Section 2, progress is being made in the development of stronger links between the ECN and other networks and programmes. At a UK level the Environmental Observation Framework (UKEOF) has been established to develop greater collaboration and integration of observation systems and enhance the collective policy and scientific potential of existing programmes. It also aims to secure benefits from the sharing of measurements, data, equipment, skills and resources. One example of more collaborative working is the ECN's recent adoption of the central data management role in Natural England's Long-Term Monitoring Network (LTMN), the main contributor to the ECBN. Indeed, the ECBN was conceived as a complementary network that would increase the spatial coverage of ECN-compatible ecological measurements and thus provide greater capacity to assess environmental change at a national level.

Further promising opportunities for integration at a national scale have arisen recently with the development of the NERC funded Cosmic-ray soil moisture monitoring network (COSMOS-UK). This focusses principally on measuring variations in soil moisture at the field-scale, but monitoring also includes meteorological and spectrometric measurements, and high frequency telemetry of data to a central database. Several COSMOS-UK stations have been sited at or near ECN terrestrial sites and this should allow a close coupling of observations.

As previously mentioned, the ECN is a member of ILTER and its European regional component, LTER-Europe, but until recently the extent of international cooperation, in terms of joint data analysis, has been limited (Vihervaara et al., 2013). However, LTER-Europe is now receiving EU funding (from 2015-19) through the eLTER project (eLTER) to advance the European network of Long-Term Ecosystem Research sites and socio-ecological research platforms. This will include the design of a cost-efficient pan-European network, able to address multiple ecosystem research issues. The ECN is represented in the project via the NERC Centre for Ecology & Hydrology. One aim of eLTER is 'to develop the organisational framework for data integration and enable virtual access to the LTER data'.

Data integration becomes much easier and more cost effective when core variables are measured in comparable ways. The eLTER project will, therefore, build on earlier work by LTER-Europe and the EnvEurope and ExpeER projects to develop a recommended set of standard parameters and harmonised sampling methods (Firbank et al., 2014). One challenge for the LTER community will be to ensure the widespread uptake of these methods, and additional resources may be needed in order to safeguard the most important long-term records of some well-established national LTER networks.

3.3 Linking ECN observations to wider areas

There is potential to both scale up observations made at ECN sites, and use ECN sites as earth observation (EO) calibration platforms, particularly through (i) greater integration with EO communities and (ii) other national and international cooperation. Earth observations range from simple photographs made by fixed cameras deployed at a plot scale through to more complex multi-spectral imaging and the deployment of Unmanned Aerial Vehicles (UAVs; or drones) and satellites gathering data from landscape to international scales. Earth observation data have only been used to a limited extent to date in assisting assessments of ECN sites. For example, Dick et al. (2014) compared data on ecosystem service indicators determined at 11 ECN sites with ecosystem service indicators obtained from pan-European databases, based on sources including remote sensing, agricultural statistics and model simulations. More recently, a series of UAV-derived images of the ECN Moor House site is now enabling key site features, and the distribution of some elements of natural capital such as peatland extent and the distribution of plant functional types, to be mapped in greater detail than has been possible previously, and similar approaches are being considered for the wider network.

The case for greater national cooperation between monitoring and survey programmes has already been made with respect to the added value of bringing together measurements made at different temporal and spatial scales. Broader environmental gradients can also provide useful context for local observations. For example, assessment of the effects of climate change or nitrogen deposition on an ecosystem will benefit from knowledge of current environmental status and trends in regions that are warmer, cooler, or more or less nitrogen impacted. In this respect even greater gains can be brought from effective international cooperation. To this end the eLTER project will include two case studies. One aims to demonstrate the ability of the network to gather – from selected European LTER sites – a range of climate, soil and atmospheric deposition data with which to model climate and pollution impacts on plant biodiversity and ecosystems (using LTER-derived vegetation data). A second study will assess the potential of European Long-Term Socio-Ecological Research (LTSER) platforms (Haberl et al., 2006) to address scientific and societally-relevant questions concerning terrestrial and freshwater ecosystem services, natural capital (stock and change), and related issues such as human wellbeing. The ECN will contribute to these case studies by providing relevant data (in the case of LTSER platforms, from the Cairngorms National Park, currently the UK's only LTSER platform). The ECN site within this LTSER platform has already been used to study the ecological, economic and socio-cultural adaptive cycles at three politically relevant spatial scales: National Nature Reserve, National Park and devolved government (Dick et al 2011). Such studies can help land managers and policymakers to evaluate risks to the delivery of ecosystem services posed by management practices, and can be used to predict future service delivery.

3.4 Increasing early warning capability

There is a clear need to increase the speed of data capture and processing in order to improve the capacity of environmental observation systems to provide early warnings of change. The suggestion that ecological data may contain information indicative of approaching 'tipping points' continues to be debated (Scheffer et al., 2009; Burthe et al., 2015), but there is clearly merit in developing systems that are able to identify anomalous behaviour rapidly, such as the sudden absence of a previously constant species. Furthermore, the possibility that extreme climatic events are occurring more frequently heightens the need to identify where and when these occur at as close to real time as possible. This would then enable additional targeted sampling campaigns that might be required to quantify effects to be conducted efficiently. Advances have already been made in accelerating the processing of ECN field measurements, through the use of digital data entry templates, and with respect to the telemetry of physical data (Rennie, this issue). Currently, the ECN is focussing on the development of automated statistically-based analytical tools that should enable the most recently collated biological and environmental data to be rapidly screened, allowing, for example, variation in species community metrics to be assessed in the context of prevailing weather conditions.

Clearly, early warning capacity could be further enhanced through wide scale deployment of environmental sensors coupled with automated, digital data transfer, processing and visualisation, as exemplified by the German Terrestrial Environmental Observatories network (TERENO) and the US National Ecological Observatory Network (NEON), although this would take considerable new investment. It is clearly vital, however, that the integrity of the ECN's long-term records remains paramount, and that the use of more rapid, perhaps automated, modes of data collection and transfer from the field to the end-user does not result in breaks in key time series, poorer data quality or less rigorous scrutiny of data.

4. Concluding remarks

This Special Issue was produced to mark the first twenty years of monitoring at terrestrial ECN sites, and illustrates the diverse ways in which long-term integrated environmental monitoring is helping to quantify, and elucidate the causes and consequences of environmental change across a broad range of UK habitats. The primary purpose of the network is to provide long-term environmental data and physical platforms for environmental research, but the information generated has considerably wider societal value with respect to informing policy and management strategies, and providing an educational resource. The extent of high frequency co-located physical, biogeochemical and biological measurements is unique in a UK context and makes the network particularly valuable in the development of clearer process understanding, and with respect to determining the impact of relatively short term events, such as droughts and floods, on ecosystems. The true worth of the network, however, may only be recognised through tighter integration of observations with those generated by compatible monitoring and survey programmes that operate over differing temporal and spatial scales, both nationally and internationally. Moreover, while continuation of time series is paramount, there is a continuing need to review approaches to data capture and management in order to improve efficiency, and to augment, or in some cases replace, the current range of measurements with novel instrumentation and methods that will accelerate rates of data transfer and processing. Such adaptation and development is clearly necessary if the ECN is to continue to provide important insights into the nature of environmental change over the next two decades and beyond.

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Figure captions

Figure 1: Diagram illustrating the gradient of ecosystem observation programmes in the United Kingdom, from spatially extensive, low frequency surveys to more site-focussed, measurement-intensive observations, such as the ECN.

Key

ECN: UK Environmental Change Network

UWMN: Upland Waters Monitoring Network

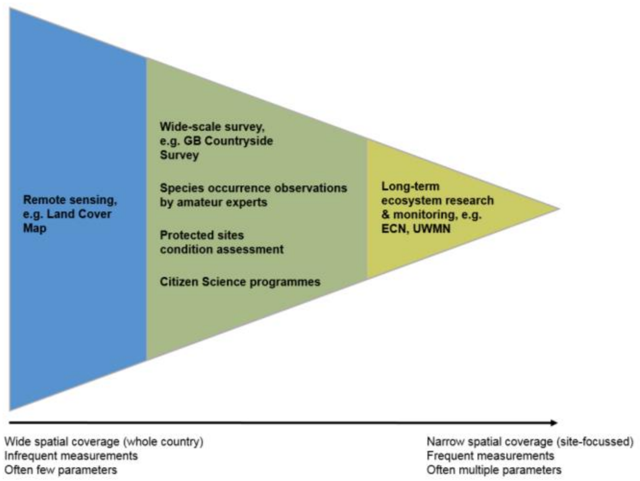


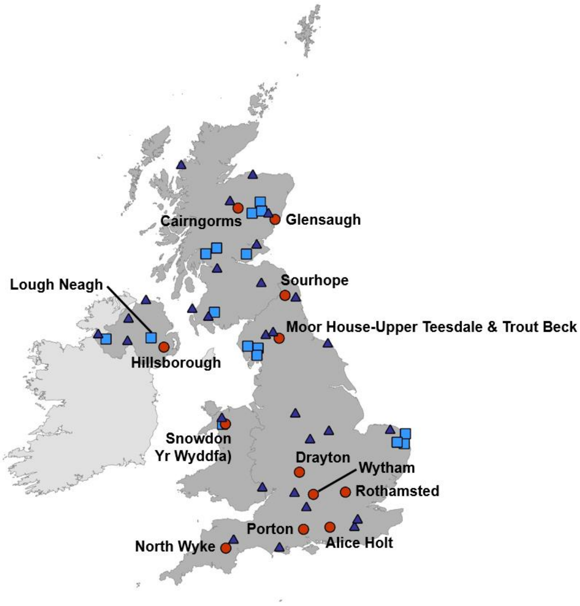
Figure 2: Map of ECN sites. The sites referred to in this Special Issue are labelled. Trout Beck (a stream) is on the Moor House site. Full details of all ECN sites can be found on the ECN website, www.ecn.ac.uk/sites.

Key

Circles: Terrestrial sites

Squares: Lake sites

Triangles: Rivers and streams



Tables

Table 1: Selected characteristics of ECN terrestrial sites. Mean annual temperature and rainfall were calculated using data from the ECN automatic weather station for the period 2000-2012, since this can be calculated for all sites. The weather stations are not necessarily sited at the mid-point of the site's altitude range

Site	**Years as an ECN site**	**Altitude range (m a.s.l.)**	**Area (ha)**	**Mean annual temperature (°C)**	**Mean annual rainfall (mm)**	**Geology**	**Soils**	**Vegetation**	**Dominant land use**
Alice Holt	1992 to present	76-125	850	10.8	833	Clay	Sandy brown forest soils and surface water Gleysols	Woodland (hard and softwood species)	Productive forest; amenity woodland
Cairngorms	1999 to present	320-1111	1000	4.7	900	Granite	Skeletal Peaty podsol; blanket peat	Montane heath; Grass/heather mosaic; woodland (Caledonian Pine)	Conservation; recreation
Drayton	1992 to 2014	40-80	190	10.3	630	Limestone and clay drift	Clay	Mixed arable and grassland; short-rotation coppice	Mixed farming; biocrops
Glensaugh	1992 to present	137-487	1125	7.5	1153	Old red sandstone; Schists	Peaty podsols; Brown forest soils	Grass/heather mosaic	Livestock grazing
Hillsborough	1992 to present	110-170	400	9.4	1119	Silurian Shales and Greywackes; Glacial and alluvial deposits	Dystric Stagnosol	Woodland; grassland; arable	Livestock grazing; amenity woodland
Moor House - Upper Teesdale	1992 to present	290-848	7500	5.8	2065	Limestone; Sandstone; Shale	Varied: Brown earths; podsols; gleys; peats	Blanket bog; acidic and calcareous grassland	Livestock grazing; grouse moor; water supply catchment
North Wyke	1992 to present	120-180	250	9.9	1048	Clay shales	Silty clay; clay	Grassland; woodland	Livestock grazing; Experimental research on grass
Porton Down	1994 to present	100-172	1227	9.7	803	Chalk	Rendzina	Semi-natural chalk grassland; small areas of woodland	Military testing (no agriculture since First World War)

Rothamsted	1992 to present	94-134	330	10.2	705	Brown earths with gleying; Clay-with-flints; over chalk	Flinty silty clay loam (18-27 % clay)	Mixed arable and grassland; short-rotation coppice; woodland	Experimental research on grass, cereals, oilseeds and energy crops
Sourhope	1992 to present	200-601	1119	7.4	975	Old red sandstone	Peaty gleys; Brown forest soil	Grass/heather mosaic	Livestock grazing
Wytham	1992 to present	60-165	770	9.9	745	Limestone; Sand; Clay	Rendzinas; brown earths; alluvial deposits	Woodland; grassland; arable	Unmanaged woodland; livestock grazing; crop production
Yr Wyddfa / Snowdon	1995 to present	298-1085	700	7.4	3784	Rhyolite; Dolerite; Moraines	Varied: Brown earths; podsols; gleys; peats	Acid/calcareous grassland; upland and montane heath; blanket bog	Livestock grazing; recreation; hydropower

Table 2: Principle variables measured at ECN terrestrial sites. Additional measurements made only at some sites are shown in *italics*. Full protocols, including those used for monitoring freshwater sites, are available on the ECN website, www.ecn.ac.uk/measurements.

Variable measured	**Frequency of measurement**	**Notes**
Vertebrates		
Grazing animals, e.g. deer, sheep, rabbits	Two times per year	
Bats	Four times a year between June and September	
Frog spawning behaviour	Weekly phenological recording from adult congregation to full metamorphosis of tadpoles	
Birds	Two times per year	Using BTO Breeding Bird Survey methodology since 2000, prior to that the Common Bird Census and Moorland Bird survey were used
Invertebrates		
Moths	Each night or weekly at remote sites	Using Rothamsted light trap network methodology
Butterflies	Each week between April and September, provided weather conditions are favourable	Using UK Butterfly Monitoring Scheme methodology
Spittle bugs	Twice a year (nymphs in June, adults in August)	
Ground predators (beetles and spiders)	Every two weeks between May and October	
Vegetation		
Whole site baseline survey (species presence related to the National Vegetation Classification)	Once at establishment of the site	
Permanent plots monitored for species presence	Recording intervals for different plots are 1, 3 or 9 years	Some sites also record additional information on woodland plots, vegetation boundaries, grass yields and cereal field monitoring

Land use and site management		
Records of management activities		
Automatic Weather Station recording		
Solar radiation; net radiation; humidity; air temperature; wind speed; wind direction; rainfall; albedo (sky and ground); soil temperature at 10cm and 30cm; surface wetness; soil water content	Hourly summaries from 5-sec samplings	
Manual meteorological recording		
Dry bulb & wet bulb temperature; maximum & minimum temperature; grass minimum temperature; soil temperature; rainfall; wind run	Daily or weekly	Carried out for quality control purposes. Some sites have replaced manual meteorological recording with a second Automatic Weather Station
Atmospheric chemistry		
Nitrogen dioxide	Every two weeks	
Ammonia	Monthly	
Precipitation chemistry		
pH; conductivity; alkalinity; sodium; potassium; calcium; magnesium; iron; aluminium; phosphate; ammonium; nitrate; chloride; sulphate; total phosphorous; total nitrogen; dissolved organic carbon	Weekly	
Surface water discharge		
Continuous discharge measurements	Summarised every 15 minutes	
Surface water chemistry		
pH; conductivity; alkalinity; sodium; potassium; calcium; magnesium; iron; aluminium; *total*	Weekly at some sites	

phosphorous; phosphate; *total nitrogen*; ammonium; nitrate; chloride; sulphate; dissolved organic carbon		
Soil solution chemistry		
pH; conductivity; alkalinity; sodium; potassium; calcium; magnesium; iron; aluminium; *total phosphorous*; phosphate; *total nitrogen*; ammonium; nitrate; chloride; sulphate; dissolved organic carbon	Every two weeks at some sites	
5-yearly soil survey		
Horizon depth and thickness; soil moisture; pH; exchangeable acidity; exchangeable sodium, potassium, calcium, magnesium, manganese and aluminium; total nitrogen, phosphorus, sulphur, organic carbon and inorganic carbonate; particle size analysis and soil minerology	Once every 5 years	
20-year soil survey monitoring		
As fine-grain monitoring, with the addition of: Bulk density; total lead, zinc, cadmium, copper, mercury, cobalt, molybdenum, arsenic, chromium, and nickel; extractable iron, aluminium and phosphorus; particle size analysis and soil minerology	Once every 20 years	A baseline survey was made in the first year of monitoring, comprising a soil map at 1:10000 scale (or 1:25 000 for larger sites) and soil typologies derived from auger borings

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