# Article (refereed) - postprint

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

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9  **Highlights**

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

15

16  **Abstract**

17  The UK Environmental Change Network (ECN), the UK's Long-Term Ecosystem Research
18  (LTER) network, has now been operating for over twenty years. It was established in 1992 as
19  a set of terrestrial sites at which sustained observations relevant to a range of ecological
20  indicators and environmental parameters could be made. An additional ECN freshwater
21  network was launched in 1994. In this paper we provide a brief history of the network, and
22  describe its current structure and role within a complementary wider range of UK
23  environmental monitoring and observation programmes that are either more focussed on
24  specific parameters or habitats, or operate at different temporal and spatial scales. We then
25  provide a review of the other papers within this Special Issue, which exemplifies the broad
26  range of environmental concerns that ECN data and sites are helping to address. These
27  include network-wide summaries of environmental and biological trends over the first two
28  decades of monitoring, more site-specific assessment of the ecological impacts of local
29  pressures resulting from changes in management, biological and ecosystem service indicator
30  development, and the testing of new monitoring technologies. We go on to consider: (i)
31  future directions of network development and adaptation in light of recently emerging
32  environmental concerns, dwindling financial resources and the consequent need for greater
33  efficiency; (ii) the desire for tighter integration with other monitoring and observation
34  programmes both nationally and internationally; (iii) opportunities raised by recent
35  technological developments; and (iv) the need to process and make available data more

36 rapidly to increase the capacity of ECN sites as early warning systems. In its first two decades
37 of operation the ECN has accumulated a robust set of baseline data that describe
38 environmental and biological variability across a range of habitats in unprecedented detail.
39 With appropriate, informed development, these should prove invaluable in discerning the
40 causes and consequences of environmental change for decades to come.

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

42

43 ## 1. Introduction

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

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

66 The first of these disciplines requires precise measurements to be made over much longer
67 periods of time than may be covered by standard scientific research grants (typically of 3-5
68 years duration). Indeed, strong natural variation in climate at a range of frequencies dictates
69 that several decades of data may be necessary to identify and quantify some key underlying
70 trends in the environment resulting, for example, from climate change or changing pollution
71 emission policy. The establishment and maintenance of systems of consistent, repeated
72 measurements over long periods, therefore, requires a clear long-term vision, sustained and
73 often substantial investment and the patience of funding bodies – particularly during the

74  early years of operation. Consequently, robust long-term environmental monitoring and
75  research programmes in the UK are relatively few and vary with respect to scope, structure
76  and funding models.

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

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

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

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

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

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

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

163  The ECN also has an integrative role internationally as the UK's official Long-Term Ecosystem
164  Research (Müller et al. (eds), 2010) network and as a member of the International Long-Term
165  Ecological Research network (ILTER; Kim, 2006) and its European regional component, LTER-
166  Europe (LTER-Europe; Mirtl, 2010). Several ECN sites are included in other international
167  networks. Cairngorms is in the European GLORIA network (alpine vegetation; Gottfried et al.,
168  2012; Pauli et al., 2012), whilst Alice Holt is part of the pan-European ICP Forest Level II
169  network. Among ECN freshwater sites, Windermere (Maberly & Elliott, 2012) and Loch Leven
170  (May & Spears, 2012) are particular focal points for long-term research into lake ecosystem
171  dynamics, while a number of lowland river sites, monitored by the Environment Agency of
172  England and Wales, the Scottish Environmental Protection Agency and the Northern Ireland
173  Environment Agency, are key sites within their Water Framework Directive monitoring
174  networks.

175  Observations and publications based on ECN data inform environmental policy development
176  across a range of disciplines. For example, the ECN soil solution chemistry records provided
177  the primary evidence, reported in the UK Review of Transboundary Air Pollution (RoTAP,
178  2012), for soil chemical responses to reductions in the deposition of acid air pollutants, and
179  evidence for links between the release of dissolved organic carbon from peatlands and both
180  acid deposition (Stutter et al., 2011) and droughts (Clark et al., 2006). The same data were
181  fundamental in recognising that hydrochloric acid deposition had made a significant
182  contribution to soil acidification at a UK scale (Evans et al., 2011) and this is now feeding into
183  a revision of dynamic models used to determine the sensitivity of soil biogeochemistry to
184  long-term changes in acid deposition (e.g. Rowe et al., 2014b). ECN bulk soil chemistry data
185  have also been used to determine long-term changes in woodland soil carbon storage as a
186  consequence of increasing soil horizon depth (Benham et al., 2012). These studies are of
187  particular interest to stakeholders concerned with carbon accounting, natural capital
188  assessments and water quality management.

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

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

214

215 **2. Paper synopses**

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

221 In order to support the wide range of research into environmental change exemplified by the
222 other papers in this issue, it is essential that data are collected, processed, stored and
223 distributed in a systematic and fully traceable manner. The ECN has pioneered the
224 development of an informatics approach to handling and integrating a diverse array of
225 environmental time-series data. The organisation, structure and function of the ECN
226 database, from initial data capture, through quality control and centralised data

227    management, to making data publicly available are presented by Rennie (this issue). The
228    paper also covers the importance of complying with current data and metadata standards,
229    such as the European INSPIRE Directive, and considers recent technological opportunities to
230    receive and manage ever larger volumes of telemetered data, and develop online data
231    exploration interfaces.

232    Background environmental context for several of the following papers is provided by
233    Monteith et al. (this issue) who present an analysis of change and variation in a range of
234    weather and atmospheric deposition indicators measured at terrestrial ECN sites between
235    1993 and 2012. Regional-scale influences of climate change and air pollution are likely to be
236    the most important drivers of environmental change at these sites, since local land
237    management tends not to vary much over time. Perhaps surprisingly, Monteith et al. (this
238    issue) found no evidence of significant change in monthly mean air temperatures over the
239    full time series, but noted a marked increase in precipitation over summer months, which
240    was linked to an unusually prolonged directional shift in the summer North Atlantic
241    Oscillation (NAO). The intensity of extreme precipitation events also increased. More
242    generally inter-annual variability in weather was strongly linked to variation in the NAO, thus
243    illustrating the challenge of separating signals of long-term climate change from shorter
244    term variability. Arguably the most ecologically influential changes in the environment of
245    ECN sites over the past two decades resulted from substantial reductions in acid deposition,
246    and much of the wider UK countryside is likely to have experienced similar trends over the
247    period. Sites experienced large declines in the concentration of sulphate in precipitation,
248    while concentrations of nitrogen species, i.e. nitrate ($NO_3^+$) and ammonium ($NH_4^+$), also fell
249    slightly at several sites. Regional scale drivers of environmental change are therefore likely to
250    be responsible for both widespread increases in soil solution pH, reflecting reductions in acid
251    deposition, and wetter conditions over the middle of the growing season.

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

267    that are being developed to help water quality managers predict likely future changes in
268    DOC and develop appropriate adaptation and mitigation strategies.

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

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

299    Assessment of the impact of changing farming practices on vegetation diversity and
300    productivity, a key issue in the development of food security policy, is investigated in further
301    detail at a single lowland agricultural ECN site by Pallett et al. (this issue). Using vegetation
302    data collected from a long-term experiment at Wytham, which switched from conventional
303    to organic agriculture mid-way through the ECN monitoring period, they demonstrate that
304    the withdrawal of nitrogen-based fertiliser applications resulted in an immediate reduction in
305    grassland productivity while species richness increased by 300%. They argue, therefore, that

306   the study illustrates a clear trade-off, whereby the increase in biodiversity occurs at the

307   expense of productivity, as a consequence of high-yielding nitrogen loving grass species

308   being replaced by a more diverse mix of less productive grasses and forbs. The study brings

309   into clear focus the challenges of meeting potentially conflicting policy agendas.

310   In a further assessment of impacts of lowland agricultural management on biodiversity, Eyre

311   et al. (this issue) investigated land use effects on the spatial and temporal variation in the

312   community structure of carabid beetles. These are an important group of crop pest

313   predators and have been the focus of previous studies using ECN data (e.g. Brooks et al.,

314   2012; Pozsgai & Littlewood, 2014). There is considerable interest in reducing dependence on

315   pesticides by boosting predatory insect abundance using non-crop field margins. The

316   authors focussed on carabid data from two English lowland agricultural research sites in

317   England: the ECN site Drayton in the west midlands and Nafferton Farm in Northumberland.

318   They found carabid activity in non-crop habitats, often used as 'beetle banks' in bio-control

319   management of crop pests, to be sub-optimal, and that the species composition of these

320   environments was influenced by surrounding management activity. They conclude that some

321   management is likely to be required to maximise the potential of these features to

322   contribute to pest control.

323   Milligan et al. (this issue) explored the implications of less intensive upland management on

324   biodiversity, drawing on data (over the period 1954 – 2000) generated by a long-term sheep

325   exclosure experiment at the Moor House ECN site in the northern Pennines. They found that

326   species diversity declined significantly in the sheep-grazed plots over this period, compared

327   with plots that were protected from grazing. The results contrast with those of Rose et al.

328   (this issue) who identified positive trends in vascular species richness across ECN sites in

329   more recent years, but there was little overlap between the two studies and grazing intensity

330   has declined at Moor House since 2000. Nevertheless the study emphasises the vulnerability

331   of upland systems to traditional farming practices and raises issues regarding what may be

332   the most appropriate targets for habitat management.

333   A holistic approach to upland management needs to consider marginal benefits and

334   potential trade-offs to ensure the optimal delivery of ecosystem services. At the Moor House

335   ECN site, in addition to sheep production and biodiversity conservation, this includes carbon

336   sequestration by the peat soils that also deliver high loads of dissolved organic carbon (DOC)

337   to drainage waters. Rising concentrations of DOC in surface waters might be expected to be

338   accompanied by greater losses of carbon from waters to the atmosphere in the form of $CO_2$

339   and methane following microbiological and physical degradation of dissolved organic

340   matter. The extent of these losses is difficult to quantify but is a potentially important policy

341   parameter with respect to national carbon accounting. Moody et al. (this issue) harnessed

342   the unique co-located long-term measurements of DOC and other solutes in atmospheric

343   deposition, soil water and stream water available for the ECN peatland site, Moor House. The

344   difference between a theoretical soil input flux of DOC (based on estimated DOC

345  contributions from various catchment sources), and the flux measured in stream runoff was
346  taken to represent either a carbon loss to the atmosphere or a gain by the stream,
347  depending on the method applied. Despite the conflicting results, the novel approach,
348  blending co-located soil and surface water time series, showed considerable potential for
349  contributing to our understanding of fluvial carbon dynamics.

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

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

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

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

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

423  provide excellent research platforms at which new approaches can be tested alongside more
424  conventional measurements.

425

426  ## 3. Current and future development

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

440  *3.1 Emerging environmental concerns*

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

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

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

482   *3.2  Strengthening links with other programmes and initiatives*

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

494   Further promising opportunities for integration at a national scale have arisen recently with
495   the development of the NERC funded Cosmic-ray soil moisture monitoring network
496   (COSMOS-UK). This focusses principally on measuring variations in soil moisture at the field-
497   scale, but monitoring also includes meteorological and spectrometric measurements, and
498   high frequency telemetry of data to a central database. Several COSMOS-UK stations have

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499  been sited at or near ECN terrestrial sites and this should allow a close coupling of
500  observations.

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

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

517      *3.3 Linking ECN observations to wider areas*

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

533  The case for greater national cooperation between monitoring and survey programmes has
534  already been made with respect to the added value of bringing together measurements
535  made at different temporal and spatial scales. Broader environmental gradients can also
536  provide useful context for local observations. For example, assessment of the effects of

537   climate change or nitrogen deposition on an ecosystem will benefit from knowledge of
538   current environmental status and trends in regions that are warmer, cooler, or more or less
539   nitrogen impacted. In this respect even greater gains can be brought from effective
540   international cooperation. To this end the eLTER project will include two case studies. One
541   aims to demonstrate the ability of the network to gather – from selected European LTER sites
542   – a range of climate, soil and atmospheric deposition data with which to model climate and
543   pollution impacts on plant biodiversity and ecosystems (using LTER-derived vegetation data).
544   A second study will assess the potential of European Long-Term Socio-Ecological Research
545   (LTSER) platforms (Haberl et al., 2006) to address scientific and societally-relevant questions
546   concerning terrestrial and freshwater ecosystem services, natural capital (stock and change),
547   and related issues such as human wellbeing. The ECN will contribute to these case studies by
548   providing relevant data (in the case of LTSER platforms, from the Cairngorms National Park,
549   currently the UK's only LTSER platform). The ECN site within this LTSER platform has already
550   been used to study the ecological, economic and socio-cultural adaptive cycles at three
551   politically relevant spatial scales: National Nature Reserve, National Park and devolved
552   government (Dick et al 2011). Such studies can help land managers and policymakers to
553   evaluate risks to the delivery of ecosystem services posed by management practices, and can
554   be used to predict future service delivery.

555   *3.4  Increasing early warning capability*

556   There is a clear need to increase the speed of data capture and processing in order to
557   improve the capacity of environmental observation systems to provide early warnings of
558   change. The suggestion that ecological data may contain information indicative of
559   approaching 'tipping points' continues to be debated (Scheffer et al., 2009; Burthe et al.,
560   2015), but there is clearly merit in developing systems that are able to identify anomalous
561   behaviour rapidly, such as the sudden absence of a previously constant species. Furthermore,
562   the possibility that extreme climatic events are occurring more frequently heightens the need
563   to identify where and when these occur at as close to real time as possible. This would then
564   enable additional targeted sampling campaigns that might be required to quantify effects to
565   be conducted efficiently. Advances have already been made in accelerating the processing of
566   ECN field measurements, through the use of digital data entry templates, and with respect to
567   the telemetry of physical data (Rennie, this issue). Currently, the ECN is focussing on the
568   development of automated statistically-based analytical tools that should enable the most
569   recently collated biological and environmental data to be rapidly screened, allowing, for
570   example, variation in species community metrics to be assessed in the context of prevailing
571   weather conditions.

572   Clearly, early warning capacity could be further enhanced through wide scale deployment of
573   environmental sensors coupled with automated, digital data transfer, processing and
574   visualisation, as exemplified by the German Terrestrial Environmental Observatories network
575   (TERENO) and the US National Ecological Observatory Network (NEON), although this would

576  take considerable new investment. It is clearly vital, however, that the integrity of the ECN's
577  long-term records remains paramount, and that the use of more rapid, perhaps automated,
578  modes of data collection and transfer from the field to the end-user does not result in breaks
579  in key time series, poorer data quality or less rigorous scrutiny of data.

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581  ## 4. Concluding remarks

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

602  **Acknowledgements**

631 **Figure captions**

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

635 <u>Key</u>
636 ECN: UK Environmental Change Network
637 UWMN: Upland Waters Monitoring Network
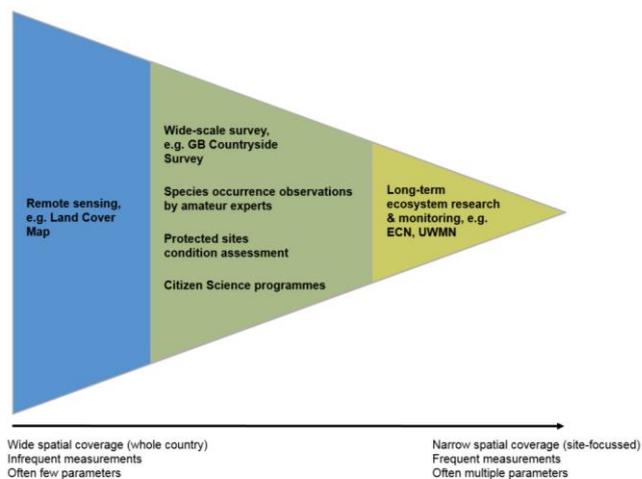


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641  **Figure 2: Map of ECN sites. The sites referred to in this Special Issue are labelled. Trout**
642  **Beck (a stream) is on the Moor House site.** Full details of all ECN sites can be found on the
643  ECN website, www.ecn.ac.uk/sites.

644  **Key**
645  Circles: Terrestrial sites
646  Squares: Lake sites
647  Triangles: Rivers and streams

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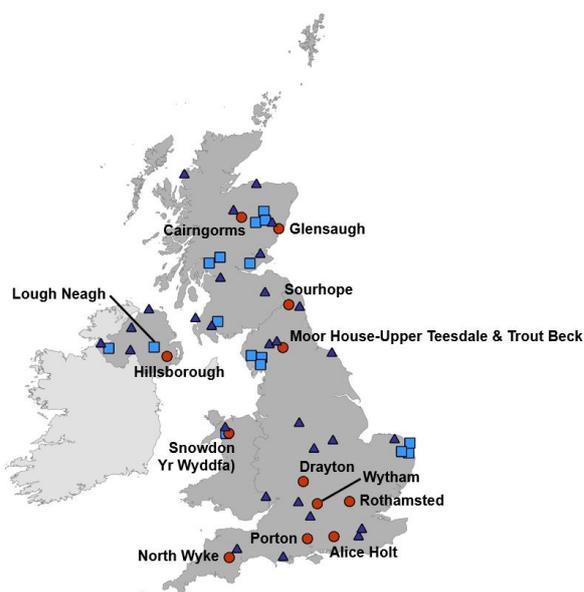


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651 **Tables**

652 **Table 1: Selected characteristics of ECN terrestrial sites.** Mean annual temperature and rainfall were calculated using data from the ECN
653 automatic weather station for the period 2000-2012, since this can be calculated for all sites. The weather stations are not necessarily sited at
654 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) |

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| 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 |

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661 **Table 2: Principle variables measured at ECN terrestrial sites.** Additional measurements made only at some sites are shown in *italics*. Full

662 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 | |

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| | | |
|---|---|---|
| *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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665 **References**

666 R.W. Battarbee, E.M. Shilland, M. Kernan, D.T. Monteith, C.J. Curtis, Recovery of acidified
667 surface waters from acidification in the United Kingdom after twenty years of chemical and
668 biological monitoring (1988–2008), Ecological Indicators, 37, Part B (2014) 267-273. DOI:
669 10.1016/j.ecolind.2013.10.011

670 C. Baxendale, N.J. Ostle, C.M. Wood, S. Oakley, S.E. Ward, Can digital image classification be
671 used as a standardised method for surveying peatland vegetation cover?, Ecological
672 Indicators. DOI: 10.1016/j.ecolind.2015.11.035

673 Benham, S.E., Vanguelova, E.I., Pitman, R.M., 2012. Short and long term changes in carbon,
674 nitrogen and acidity in the forest soils under oak at the Alice Holt Environmental Change
675 Network site. Science of the Total Environment, 421–422, 82-93. DOI:
676 10.1016/j.scitotenv.2012.02.004

677 D. Brooks, J. Bater, S. Clark, D. Monteith, C. Andrews, S. Corbett, D. Beaumont, J. Chapman,
678 Large carabid beetle declines in a United Kingdom monitoring network increases evidence
679 for a widespread loss in insect biodiversity, Journal of Applied Ecology, 49 (2012) 1009-1019.
680 DOI: 10.1111/j.1365-2664.2012.02194.x

681 S.J. Burthe, P.A. Henrys, E.B. Mackay, B.M. Spears, R. Campbell, L. Carvalho, B. Dudley, I.D.M.
682 Gunn, D.G. Johns, S.C. Maberly, L. May, M.A. Newell, S. Wanless, I.J. Winfield, S.J. Thackeray, F.
683 Daunt, Do early warning indicators consistently predict nonlinear change in long-term
684 ecological data?, Journal of Applied Ecology, (2015). DOI: 10.1111/1365-2664.12519

685 P.D. Carey, S. Wallis, P.M. Chamberlain, A. Cooper, B.A. Emmett, L.C. Maskell, T. McCann, J.
686 Murphy, L.R. Norton, B. Reynolds, W.A. Scott, I.C. Simpson, S.M. Smart, J.M. Ullyett,
687 Countryside Survey: UK Results from 2007, NERC/Centre for Ecology & Hydrology, 2008, pp.
688 105. URL: http://www.countrysidesurvey.org.uk/outputs/uk-results-2007

689 J.M. Clark, P.J. Chapman, A.L. Heathwaite, J.K. Adamson, Suppression of Dissolved Organic
690 Carbon by Sulfate Induced Acidification during Simulated Droughts, Environmental Science
691 & Technology, 40 (2006) 1776-178. DOI: 10.1021/es051488c

692 C.P. Cummins, M.A. Berant, B.G. Bell, H.R. Oliver, The TIGER Programme, Journal of
693 Biogeography, 22 (1995) 897-905. DOI: 10.2307/2845990

694 J. Dick, C. Andrews, D.A. Beaumont, S. Benham, D.R. Brooks, S. Corbett, D. Lloyd, S. McMillan,
695 D.T. Monteith, E.S. Pilgrim, R. Rose, A. Scott, T. Scott, R.I. Smith, C. Taylor, M. Taylor, A. Turner,
696 H. Watson, A comparison of ecosystem services delivered by 11 long-term monitoring sites
697 in the UK environmental change network, Environmetrics, 22 (2011) 639-648. DOI:
698 10.1002/env.1069

699  J. Dick, C. Andrews, D.A. Beaumont, S. Benham, N. Dodd, D. Pallett, R. Rose, T. Scott, R.I.
700  Smith, S.M. Schäfer, A. Turner, H. Watson, Analysis of temporal change in delivery of
701  ecosystem services over 20 years at long term monitoring sites of the UK Environmental
702  Change Network, Ecological Indicators. DOI: 10.1016/j.ecolind.2016.02.021

703  J. Dick, J. Maes, R.I. Smith, M.P. Paracchini, G. Zulian, Cross-scale analysis of ecosystem
704  services identified and assessed at local and European level, Ecological Indicators, 38 (2014)
705  20-30. DOI: 10.1016/j.ecolind.2013.10.023

706  A.A. Elliott, Y. McElarney, M. Allen, The past and future of phytoplankton in the UK's largest
707  lake, Lough Neagh, Ecological Indicators. DOI: 10.1016/j.ecolind.2015.07.015

708  C.D. Evans, D.T. Monteith, D. Fowler, J.N. Cape, S. Brayshaw, Hydrochloric Acid: An
709  Overlooked Driver of Environmental Change, Environmental Science & Technology, 45 (2011)
710  1887-1894. DOI: 10.1021/es103574u

711  M.D. Eyre, S.D. McMillan, C.N.R. Critchley, Ground beetles (Coleoptera, Carabidae) as
712  indicators of change and pattern in the agroecosystem: longer surveys improve
713  understanding, Ecological Indicators. DOI: 10.1016/j.ecolind.2015.11.009

714  L. Firbank, C. Bertora, D. Blankman, G. Delle Vedove, M. Frenzel, C. Grignani, E. Groner, A.
715  Joseph, M. Kertész, B. Kunin, G. Matteucci, C. Menta, C. Müller, J. Stadler, Drafting of final
716  EXPEER protocols for dissemination. ExpeER project (GA262060) deliverable 2014, pp. 75.
717  [online] URL: http://www.expeeronline.eu/images/ExpeER-Reports/D2-3.pdf

718  M. Gottfried, H. Pauli, A. Futschik, M. Akhalkatsi, P. Barancok, J.L. Benito Alonso, G. Coldea, J.
719  Dick, B. Erschbamer, M.R. Fernandez Calzado, G. Kazakis, J. Krajci, P. Larsson, M. Mallaun, O.
720  Michelsen, D. Moiseev, P. Moiseev, U. Molau, A. Merzouki, L. Nagy, G. Nakhutsrishvili, B.
721  Pedersen, G. Pelino, M. Puscas, G. Rossi, A. Stanisci, J.-P. Theurillat, M. Tomaselli, L. Villar, P.
722  Vittoz, I. Vogiatzakis, G. Grabherr, Continent-wide response of mountain vegetation to
723  climate change, Nature Clim. Change, 2 (2012) 111-115. DOI: 10.1038/nclimate1329

724  H. Haberl, V. Winiwarter, K. Andersson, R.U. Ayres, C. Boone, A. Castillo, G. Cunfer, M. Fischer-
725  Kowalski, W.R. Freudenburg, E. Furman, R. Kaufmann, F. Krausmann, E. Langthaler, H. Lotze-
726  Campen, M. Mirtl, C.L. Redman, A. Reenberg, A. Wardell, B. Warr, H. Zechmister, From LTER
727  to LTSER: conceptualizing the socioeconomic dimension of long-term socioecological
728  research, Ecology and Society, 11(2) (2006) 13. [online] URL:
729  http://www.ecologyandsociety.org/vol11/iss2/art13/

730  O.W. Heal and D.F. Perkins (eds.). Production Ecology of British Moors and Montane
731  Grasslands. Ecological Studies 27. Springer-Verlag Berlin Heidelberg. 1978. 428pp. DOI:
732  10.1007/978-3-642-66760-2

733 C. Huntingford, P. Friedlingstein, More frequent moments in the climate change debate as
734 emissions continue, Environmental Research Letters, 10 (2015) 121001. DOI: 10.1088/1748-
735 9326/10/12/121001

736 E.-S. Kim, Development, potentials, and challenges of the International Long-Term Ecological
737 Research (ILTER) Network, Ecological Research, 21 (2006) 788-793. DOI: 10.1007/s11284-006-
738 0049-1

739 S.C. Maberly, J.A. Elliott, Insights from long-term studies in the Windermere catchment:
740 external stressors, internal interactions and the structure and function of lake ecosystems,
741 Freshwater Biology, 57 (2012) 233-243. DOI: 10.1111/j.1365-2427.2011.02718.x

742 B. Martay, D.T. Monteith, M.J. Brewer, T. Brereton, C.R. Shortall, J.W. Pearce-Higgins, An
743 indicator highlights seasonal variation in the response of Lepidoptera communities to
744 warming, Ecological Indicators. DOI: 10/1016/j.ecolind.2016.01.057

745 L. May, B.M. Spears, A history of scientific research at Loch Leven, Kinross, Scotland,
746 Hydrobiologia, 681 (2012) 3-9. DOI: 10.1007/s10750-011-0929-4

747 G. Milligan, R. Rose, R.H. Marrs, Winners and losers in a long-term study of vegetation
748 change at Moor House NNR: effects of sheep-grazing and its removal on British upland
749 vegetation, Ecological Indicators. DOI: 10.1016/j.ecolind.2015.10.053

750 G. Mills, F. Hayes, S. Wilkinson, W.J. Davies, Chronic exposure to increasing background
751 ozone impairs stomatal functioning in grassland species, Global Change Biology, 15 (2009)
752 1522-1533. DOI: 10.1111/j.1365-2486.2008.01798.x

753 S.K. Min, X.B. Zhang, F.W. Zwiers, G.C. Hegerl, Human contribution to more-intense
754 precipitation extremes, Nature, 470 (2011) 378-381. DOI: 10.1038/nature09763

755 M. Mirtl, Introducing the Next Generation of Ecosystem Research in Europe: LTER-Europe's
756 Multi-Functional and Multi-Scale Approach, in: F. Müller, C. Baessler, H. Schubert, S. Klotz
757 (Eds.) Long-Term Ecological Research, Springer Netherlands, 2010, pp. 75-93. DOI:
758 10.1007/978-90-481-8782-9_6

759 D.T. Monteith, P.A. Henrys, L. Banin, R.I. Smith, M.D. Morecroft, T. Scott, C. Andrews, D.A.
760 Beaumont, S. Benham, V. Bowmaker, S. Corbett, J. Dick, B. Dodd, N. Dodd, C. McKenna, S.D.
761 McMillan, D. Pallett, G. Pereira, S.C. Rennie, R. Rose, S.M. Schäfer, L. Sherrin, A. Turner, H.
762 Watson, J. Poskitt, S.Y. Tang, Trends and variability in weather and atmospheric deposition at
763 UK Environmental Change Network sites (1993 -2012), Ecological Indicators. DOI:
764 10.1016/j.ecolind.2016.01.061

765 D.T. Monteith, J.L. Stoddard, C.D. Evans, H.A. de Wit, M. Forsius, T. Hogasen, A. Wilander, B.L.
766 Skjelkvale, D.S. Jeffries, J. Vuorenmaa, B. Keller, J. Kopacek, J. Vesely, Dissolved organic

767  carbon trends resulting from changes in atmospheric deposition chemistry, Nature, 450
768  (2007) 537-540. DOI: 10.1038/nature06316

769  C.S. Moody, F. Worrall, T.P. Burt, Identifying DOC gains and losses during a 20-year record in
770  the Trout Beck catchment, Moor House, UK, Ecological Indicators. DOI:
771  10.1016/j.ecolind.2015.11.033

772  M.D. Morecroft, C.E. Bealey, D.A. Beaumont, S. Benham, D.R. Brooks, T.P. Burt, C.N.R.
773  Critchley, J. Dick, N.A. Littlewood, D.T. Monteith, W.A. Scott, R.I. Smith, C. Walmsley, H.
774  Watson, The UK Environmental Change Network: Emerging trends in the composition of
775  plant and animal communities and the physical environment, Biological Conservation, 142
776  (2009) 2814-2832. DOI: 10.1016/j.biocon.2009.07.004

777  M.D. Morecroft, C.E. Bealey, M.E. Taylor, W.A. Scott, Interannual variability, stability and
778  resilience in UK plant communities, Ecological Indicators. DOI: 10.1016/j.ecolind.2015.11.040

779  M.D. Morecroft, L. Speakman, Terrestrial Biodiversity Climate Change Impacts Summary
780  Report, Living With Environmental Change, 2013.

781  F. Müller, C. Baessler, H. Schubert, S. Klotz (Eds.), Long-Term Ecological Research: Between
782  Theory and Application, 1 ed., Springer Netherlands, Netherlands, 2010. DOI: 10.1007/978-
783  90-481-8782-9

784  D. Pallett, O.L. Pescott, S.M. Schäfer, Changes in plant species richness and productivity in
785  response to decreased nitrogen inputs in grassland in southern England, Ecological
786  Indicators. DOI: 10.1016/j.ecolind.2015.12.024

787  T.W. Parr, A.R.J. Sier, R.W. Battarbee, A. Mackay, J. Burgess, Detecting environmental change:
788  science and society—perspectives on long-term research and monitoring in the 21st century,
789  Science of The Total Environment, 310 (2003) 1-8. DOI: 10.1016/S0048-9697(03)00257-2

790  H. Pauli, M. Gottfried, S. Dullinger, O. Abdaladze, M. Akhalkatsi, J.L.B. Alonso, G. Coldea, J.
791  Dick, B. Erschbamer, R.F. Calzado, D. Ghosn, J.I. Holten, R. Kanka, G. Kazakis, J. Kollár, P.
792  Larsson, P. Moiseev, D. Moiseev, U. Molau, J.M. Mesa, L. Nagy, G. Pelino, M. Puşcaş, G. Rossi,
793  A. Stanisci, A.O. Syverhuset, J.-P. Theurillat, M. Tomaselli, P. Unterluggauer, L. Villar, P. Vittoz,
794  G. Grabherr, Recent Plant Diversity Changes on Europe's Mountain Summits, Science, 336
795  (2012) 353-355. DOI: 10.1126/science.1219033

796  J.W. Pearce-Higgins, M.J. Brewer, D.A. Elston, B. Martay, G.D. Powney, I. N.J.B., D.T. Monteith,
797  P.A. Henrys, I.P. Vaughan, S.J. Ormerod, S. Green, F.K. Edwards, A. Johnston, J.R. Bell, R.
798  Harrington, T.M. Brereton, K.E. Barlow, R.W. Battarbee, E.M. Shilland, BICCO-Net II: Final
799  report to the Biological Impacts of Climate Change Observation Network (BICCO-Net)
800  Steering Group. 2015. DOI: 10.13140/RG.2.1.4108.3920

801 C.M. Perrins, K.J. Kirby and N. Fisher. Wytham Woods: Oxford's Ecological Laboratory. Oxford
802 University Press, 2010. ISBN: 978-0-19-954320-5

803 M.J.O. Pocock, H.E. Roy, C.D. Preston, D.B. Roy, The Biological Records Centre: a pioneer of
804 citizen science, Biological Journal of the Linnean Society, 115 (2015) 475-493. DOI:
805 10.1111/bij.12548

806 G. Pozsgai, J. Baird, N.A. Littlewood, R.J. Pakeman, M.R. Young, Interspecific networks in
807 ground beetle (Coleoptera: Carabidae) assemblages, Ecological Indicators. DOI:
808 10.1016/j.ecolind.2015.11.031

809 G. Pozsgai, N. Littlewood, Ground beetle (Coleoptera: Carabidae) population declines and
810 phenological changes: Is there a connection?, Ecological Indicators, 41 (2014) 15-24. DOI:
811 10.1016/j.ecolind.2014.01.029

812 S.C. Rennie, Providing Information on Environmental Change: Data Management, Discovery
813 and Access in the UK Environmental Change Network Data Centre, Ecological Indicators. DOI:
814 10.1016/j.ecolind.2016.01.060

815 R. Rose, D.T. Monteith, P.A. Henrys, S.M. Smart, C.M. Wood, M. Morecroft, C. Andrews, D.A.
816 Beaumont, S. Benham, V. Bowmaker, S. Corbett, J. Dick, B. Dodd, N. Dodd, M. Flexen, C.
817 McKenna, S.D. McMillan, D. Pallett, S.C. Rennie, S.M. Schäfer, T. Scott, L. Sherrin, A. Turner, H.
818 Watson, Evidence for increases in vegetation species richness across UK Environmental
819 Change Network sites linked to changes in air pollution and weather patterns, Ecological
820 Indicators. DOI: 10.1016/j.ecolind.2016.01.005

821 RoTAP, Review of Transboundary Air Pollution (RoTAP): Acidification, Eutrophication, Ground
822 Level Ozone and Heavy Metals in the UK. Contract Report to the Department for
823 Environment, Food and Rural Affairs, Centre for Ecology & Hydrology, 2012. URL:
824 http://www.rotap.ceh.ac.uk/sites/rotap.ceh.ac.uk/files/CEH%20RoTAP.pdf

825 E.C. Rowe, S. Jarvis, J. Hall, D.T. Monteith, P.A. Henrys, C.D. Evans, S.M. Smart,
826 Operationalising a metric of nitrogen impacts on biodiversity for the UK response to a data
827 request from the Coordination Centre for Effects. Final report on Defra project AQ0832, "A
828 metric for assessing changes in biodiversity for the UK's response to a data request under
829 the Convention on Long-range Transboundary Air Pollution". CEH project NEC05090. 2014.
830 URL: http://uk-air.defra.gov.uk/library/reports?report_id=864

831 E.C. Rowe, E. Tipping, M. Posch, F. Oulehle, D.M. Cooper, T.G. Jones, A. Burden, J. Hall, C.D.
832 Evans, Predicting nitrogen and acidity effects on long-term dynamics of dissolved organic
833 matter, Environmental Pollution, 184 (2014) 271-282. DOI: 10.1016/j.envpol.2013.08.023

834 K. Sawicka, D.T. Monteith, E.I. Vanguelova, A.J. Wade, J.M. Clark, Fine-scale temporal
835 characterization of trends in soil water dissolved organic carbon and potential drivers,
836 Ecological Indicators. DOI: 10.1016/j.ecolind.2015.12.028

837    M. Scheffer, J. Bascompte, W.A. Brock, V. Brovkin, S.R. Carpenter, V. Dakos, H. Held, E.H. van

838    Nes, M. Rietkerk, G. Sugihara, Early-warning signals for critical transitions, Nature, 461 (2009)

839    53-59. DOI: 10.1038/nature08227

840    W.A. Scott, M.D. Morecroft, M.E. Taylor, S.M. Smart, Countryside Survey - Environmental

841    Change Network link.  CS Technical Report, 2010, pp. 63. URL:

842    http://www.countrysidesurvey.org.uk/sites/default/files/pdfs/reports2007/CS_UK_2007_TR6.p

843    df

844    J. Silvertown, P. Poulton, E. Johnston, G. Edwards, M. Heard, P.M. Biss, The Park Grass

845    Experiment 1856–2006: its contribution to ecology, Journal of Ecology, 94 (2006) 801-814.

846    DOI: 10.1111/j.1365-2745.2006.01145.x

847    J. Storkey, A.J. Macdonald, P.R. Poulton, T. Scott, I.H. Köhler, H. Schnyder, K.W.T. Goulding,

848    M.J. Crawley, Grassland biodiversity bounces back from long-term nitrogen addition, Nature,

849    528 (2015) 401-404. DOI: 10.1038/nature16444

850    M.I. Stutter, D.G. Lumsdon, A.P. Rowland, Three representative UK moorland soils show

851    differences in decadal release of dissolved organic carbon in response to environmental

852    change, Biogeosciences, 8 (2011) 3661-3675. DOI: 10.5194/bg-8-3661-2011

853    J.M. Sykes, A.M.J. Lane, The United Kingdom Environmental Change Network: Protocols for

854    standard measurements at terrestrial sites, The Stationery Office, London, 1996. ISBN: 0-11-

855    702197-0

856    J.M. Sykes, A.M.J. Lane, D.G. George, The United Kingdom Environmental Change Network:

857    Protocols for standard measurements at freshwater sites, Institute of Terrestrial Ecology,

858    Huntingdon, 1999. ISBN: 1 870393 49 X

859    S.J. Thackeray, T.H. Sparks, M. Frederiksen, S. Burthe, P.J. Bacon, J.R. Bell, M.S. Botham, T.M.

860    Brereton, P.W. Bright, L. Carvalho, T.I.M. Clutton-Brock, A. Dawson, M. Edwards, J.M. Elliott, R.

861    Harrington, D. Johns, I.D. Jones, J.T. Jones, D.I. Leech, D.B. Roy, W.A. Scott, M. Smith, R.J.

862    Smithers, I.J. Winfield, S. Wanless, Trophic level asynchrony in rates of phenological change

863    for marine, freshwater and terrestrial environments, Global Change Biology, 16 (2010) 3304-

864    3313. DOI: 10.1111/j.1365-2486.2010.02165.x

865    UK National Ecosystem Assessment, The UK National Ecosystem Assessment: Technical

866    Report, UNEP-WCMC, Cambridge, 2011. URL: http://uknea.unep-

867    wcmc.org/Resources/tabid/82/Default.aspx

868    P. Vihervaara, D. D'Amato, M. Forsius, P. Angelstam, C. Baessler, P. Balvanera, B. Boldgiv, P.

869    Bourgeron, J. Dick, R. Kanka, S. Klotz, M. Maass, V. Melecis, P. Petřík, H. Shibata, J. Tang, J.

870    Thompson, S. Zacharias, Using long-term ecosystem service and biodiversity data to study

871    the impacts and adaptation options in response to climate change: insights from the global

872    ILTER sites network, Current Opinion in Environmental Sustainability, 5 (2013) 53-66. DOI:

873    10.1016/j.cosust.2012.11.002

874    **Web pages**

875    Automatic Urban and Rural Network (AURN). URL: http://uk-

876    air.defra.gov.uk/networks/network-info?view=aurn (visited 22/01/2016)

877    COSMOS-UK: UK Cosmic-Ray Soil Moisture Monitoring Network. URL:

878    http://cosmos.ceh.ac.uk/ (visited 22/01/2016)

879    ECN Data Centre: Home page. URL: http://data.ecn.ac.uk/ (visited 22/01/2016)

880    ECN Data Centre: Data Access page. URL: http://data.ecn.ac.uk/request_form.asp (visited

881    09/02/2016)

882    ECN 'Environmental Change Biodiversity Network (ECBN)' web pages: Information about the

883    monitoring and research network closely linked to ECN. URL: http://www.ecn.ac.uk/what-we-

884    do/science/projects/ecbn (created 18/08/2011; visited 22/01/2016)

885    ECN 'Why it matters' web pages: information about how selected published research relates

886    to environmental and societal issues. URL: http://www.ecn.ac.uk/publications/why-it-matters

887    (created 19/03/2014; visited 22/01/2016)

888    eLTER: European Long-Term Ecosystem and Socio-Ecological Research Infrastructure. URL:

889    http://www.lter-europe.net/elter (visited 22/01/2016)

890    EnvEurope. URL: http://www.enveurope.eu/ (visited 22/01/2016)

891    ExpeER. URL: http://www.expeeronline.eu/ (visited 22/01/2016)

892    International Long-Term Ecological Research Network. URL: http://www.ilternet.edu/ (visited

893    22/01/2016)

894    Long-Term Ecosystem Research Network, Europe. URL: http://www.lter-europe.net/ (visited

895    22/01/2016)

896    National Ecological Observatory Network (NEON). URL: http://www.neoninc.org/ (visited

897    22/01/2016)

898    Rothamsted Insect Survey. URL: http://www.rothamsted.ac.uk/insect-survey/ (visited

899    22/01/2016)

900    Terrestrial Environmental Observatories (TERENO). URL: http://teodoor.icg.kfa-

901    juelich.de/overview-en?set_language=en (visited 22/01/2016)

902    UK Acidifying and Eutrophying Atmospheric Pollutants (UKEAP) network. URL:

903    http://pollutantdeposition.defra.gov.uk/ukeap (visited 22/01/2016)

904     UK Ammonia Network. URL: http://www.pollutantdeposition.defra.gov.uk/ammonia_network
905     (visited 22/01/2016)

906     UK Butterfly Monitoring Scheme. URL: http://www.ukbms.org/ (visited 22/01/2016)

907     UK Environmental Observation Framework: Home page. URL: http://www.ukeof.org.uk/
908     (visited 22/01/2016)

909     UK Lake Ecological Observatory Network (UKLEON). URL: http://www.ceh.ac.uk/our-
910     science/projects/uk-lake-ecological-observatory-network-ukleon (visited 22/01/2016)

911     UK Upland Waters Monitoring Network. URL: http://uwmn.defra.gov.uk/ (visited 22/01/2016)