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Providing Information on Environmental Change: Data Management, Discovery and Access in the UK Environmental Change Network Data Centre

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Abstract

Development of a clearer understanding of the causes and consequences of environmental change is an important issue globally. The consequent demand for objective, reliable and up-to-date environmental information has led to the establishment of long-term integrated environmental monitoring programmes, including the UK's Environmental Change Network (ECN). Databases form the core information resource for such programmes. The UK Environmental Change Network Data Centre manages data on behalf of ECN (as well as other related UK integrated environmental monitoring networks) and provides a robust and integrated system of information management. This paper describes how data are captured – through standardised protocols and data entry systems – as well more recent approaches such as wireless sensors. Data are managed centrally through a database and GIS. Quality control is built in at all levels of the system. Data are then made accessible through a variety of data access methods – through bespoke web interfaces, as well as third-party data portals. This paper describes the informatics approach of the ECN Data Centre which aims to develop a seamless system of data capture, management and data access interfaces to support research.

Keywords

Database; data management; data access; data quality; informatics; integrated environmental monitoring; environmental change

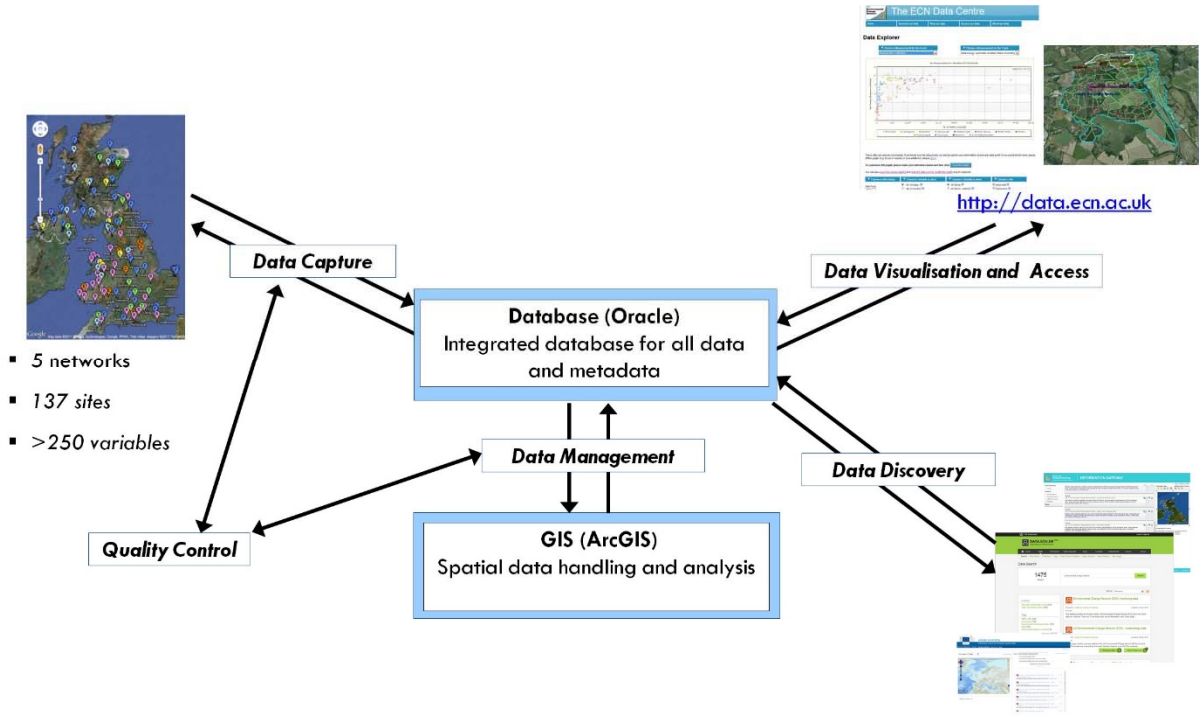
1. Introduction

There is a growing need to improve scientific understanding of the causes and consequences of environmental change in order to inform mitigation and adaptation strategies. The routine collection of data from integrated environmental monitoring programmes can provide a wealth of scientific information and it is of prime importance that these data are made quickly available for research and policy decisions. To address this challenge within the UK, in 1992, the Environmental Change Network (ECN) was set up as the UK's long-term integrated environmental monitoring programme. It consists of 12 terrestrial and 45 freshwater sites throughout the UK, selected to cover the main range of environmental conditions present in the UK, where both biological and physical aspects of the environment are intensively monitored (Sier and Monteith, this issue). The monitoring programme covers a wide range of physical, chemical and biological 'driver' and 'response' variables, identified as being important for the assessment of environmental change. Measurements are made in close proximity at each site, using protocols incorporating standard

quality control procedures (Sykes and Lane, 1996; Sykes *et al*., 1999); the protocols are also available online (http://www.ecn.ac.uk/measurements). The ECN programme is sponsored by a consortium of fourteen UK Government departments and agencies (see acknowledgements) with an interest in the environment, who contribute to the programme through funding either site monitoring or network co-ordination activities.

Databases form the core information resource for long-term monitoring programmes such as ECN. Long-term environmental research databases must be reliable and stable in terms of data quality, secure over a long time span, accessible (but with access controls), and should facilitate spatio-temporal analyses of multiple variables at a range of scales. The use of reliable and well-supported database software is of paramount importance for long-term security; the ECN Data Centre uses the Oracle Relational Database Management System. When ECN was established in 1992, its sponsors agreed that a centrally managed database, with remote access links, was the model most appropriate to ensure a fully integrated system with the required data quality standards, i.e. those specified in the ECN protocols (Sykes and Lane, 1996; Sykes *et al*., 1999). Today, the remit of the ECN Data Centre has expanded to include not only the management of ECN data, but also that of other related integrated environmental monitoring networks, including the Environmental Change Biodiversity Network (ECBN), the UK Lake Ecological Observatory Network (UKLEON) and the Upland Waters Monitoring Network (UWMN). The ECN Data Centre manages an integrated information resource (figure 1), storing all data and metadata collected at the 137 sites within these networks. Data from all networks are held in standardised structures in order to support the cross-disciplinary analyses necessary for environmental change research (documentation for these data structures is available online - http://data.ecn.ac.uk/database_documentation/index.asp). Data are regularly sent in from sites and are quality assured - before being lodged in the database.

Figure 1: Overview of the ECN Data Centre Information System



One of the challenges facing managers of environmental databases is to provide data access mechanisms to suit the requirements of different users, who range from scientists and policy-makers, to students and the general public. These access methods should give sufficient guidance to users unfamiliar with the structure of the data (i.e. provide comprehensive metadata to ensure the data are understandable); whilst at the same time providing users with sufficient flexibility in data query and presentation. ECN was an early adopter of Internet-based data access (Brocklebank *et al.*, 1996, Rennie *et al*., 2000) and it was one of the few direct data access portals available at that time. The ECN Data Centre continues to provide this access on the website (http://data.ecn.ac.uk) *via* a number of targeted data products.

ECN is the UK node in a global system of long-term, integrated environmental research networks and is a member of LTER-Europe (the European Long-Term Ecosystem Research Network - http://www.lter-europe.net/) and ILTER (International Long Term Ecological Research - http://www.ilternet.edu/). The ECN Data Centre provides information to both these networks and also provides metadata to a number of other national and international data portals to ensure the data are discoverable by users (see section 4.3 for details).

This paper describes the informatics approach of the ECN Data Centre which aims to develop a seamless system of data, information and software tools to support research by taking a holistic view of programme requirements from data capture and management, through to data delivery and analysis. In so doing, it also complements the other papers in this special issue by providing an insight into the origin and management of the datasets being discussed.

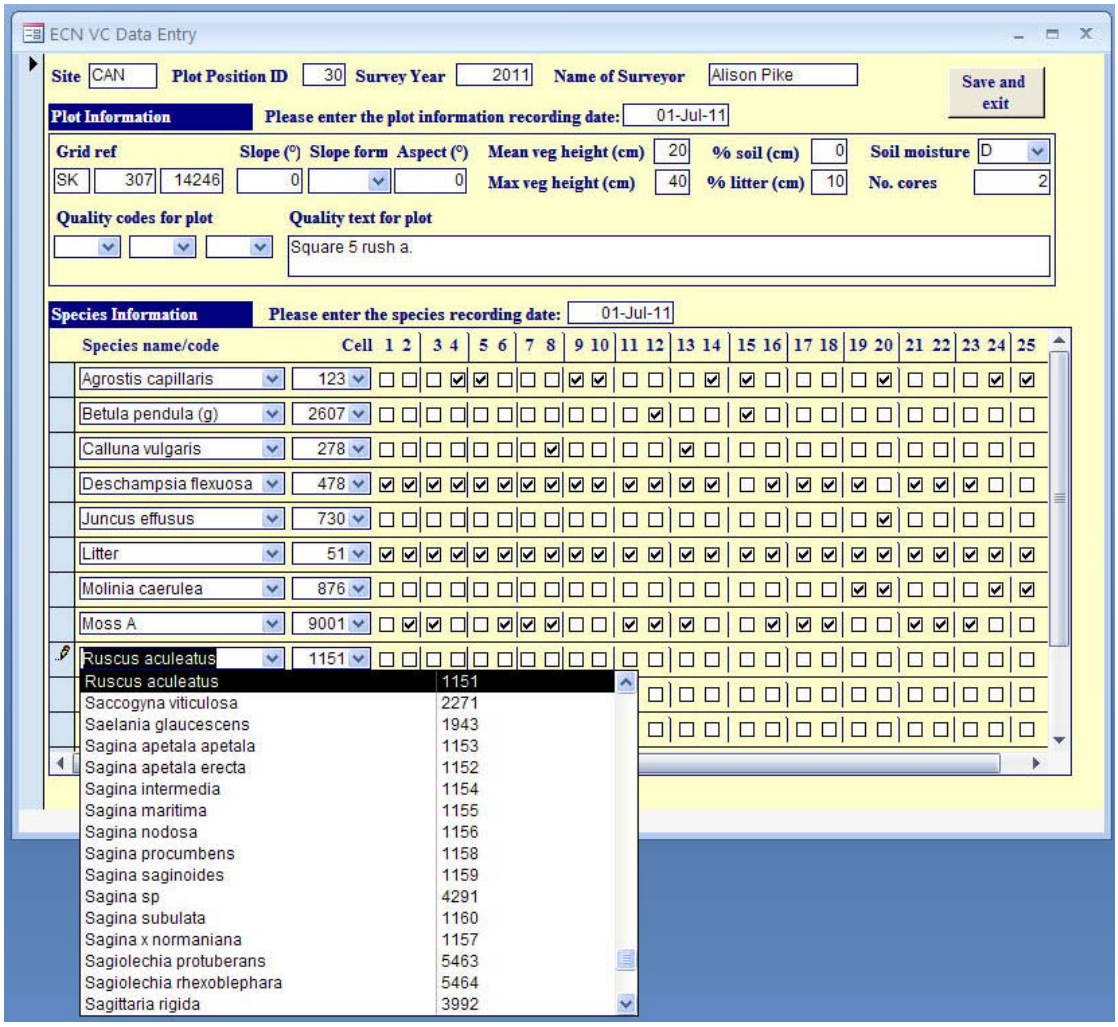
2. Data Capture

At the start of ECN, working groups comprising scientists and statisticians representing a range of environmental disciplines agreed on a list of environmental variables to be monitored. Ever since, data collection and handling procedures have been co-ordinated and standardised across the sites through reference to published protocols (Sykes and Lane, 1996; Sykes *et al*., 1999); which are also available online (http://www.ecn.ac.uk/measurements). These are designed to ensure consistency in measurement methods and data handling over time and across all of the sites. Data requirements are an integral part of these protocols and include specifications of variables, units, reporting precisions, dimensions, resolutions, reference systems and quality assurance procedures which have been used to design the database, construct standard formats for data transfer and standard field forms for each dataset. Wherever possible and appropriate, existing data capture techniques (e.g. Breeding Bird Survey (http://www.bto.org/volunteer-surveys/bbs), Rothamsted Light trap network (http://www.rothamsted.ac.uk/insect-survey), Butterfly Monitoring Scheme (http://www.ukbms.org/)) and common coding schemes (e.g. Biological Records Centre (butterflies, carabid beetles, vegetation - http://www.brc.ac.uk/), British Trust for Ornithology (birds - http://www.bto.org/) have been adopted to maintain ECN's comparability with other sectoral networks. These networks often have a narrower focus than ECN but a much wider geographical spread of sampling. In some circumstances, therefore, ECN can act as a 'bridge' to facilitate interoperability between these sectoral networks.

ECN, and the other contributory networks, collect a wide range of physical, chemical and biological measurements, using a variety of data collection methods e.g. automatic loggers and surveying in the field by site managers. Data capture methods include manual recording (i.e. a site manager recording data in the field onto forms or maps) and automated methods (e.g. the data loggers of Automatic Weather Stations or river gauging stations). The frequency of data capture varies from meteorological and hydrological logger data measured every fifteen minutes to soil surveys conducted every 20 years.

Data are checked and formatted by data providers prior to being submitted by email (in standardised, comma-separated files). Detailed data transfer documentation for each protocol guides the preparation of these files, to ensure comparability of data across sites and over time. The documentation includes rules for handling missing values and data quality information. To further aid site managers, bespoke data entry templates have been developed, using MS Access, to improve data handling efficiency (figure 2). These ensure that quality-checked, standardised and formatted data are submitted, and incorporate quality checking procedures. The design of the templates takes into account ease of use, with the main emphasis being on minimising error. The use of the templates in the field is encouraged where sites have access to robust field computers. This type of data entry software is particularly useful where numeric coding systems for species are in use; numbers are less memorable and mistakes in one digit of a code can produce serious errors. For example, the software uses drop-down lists of codes (which are dynamically linked with a list of the species names) so that the codes can be cross-checked against the species name to ensure that the correct code is chosen.

Figure 2: Screenshot from the Data Entry Templates (developed using MS Access)



3. Data Management

The ECN Data Centre manages an integrated information resource, comprising all data and metadata collected by ECN and the other contributory networks. Data are held in standardised structures that enhance the potential for cross-disciplinary analyses. The database uses the Oracle Relational Database Management System (RDBMS), with links to ArcGIS for spatial data handling. This was designed in-house to serve the particular needs of the ECN community. The core database stores raw data at the resolutions specified in the protocols. An associated, and regularly updated, summary database consists of monthly, quarterly, and/or annual summaries of these data using summary statistics appropriate to each measurement, as advised by experts. Documentation for the database is available online (http://data.ecn.ac.uk/database_documentation/index.asp).

The database is complex due to the heterogeneous nature of the data being collected, in terms of the core measurements covered (from vertebrate populations to water quality), the formats involved (from field data to satellite imagery) and the temporal and spatial scales covered by the protocols. The spatial dimension of ECN sampling can relate to a point (e.g. automatic weather station), line (e.g. butterfly transect) or an area (e.g. land cover). The time dimension can relate to an instant in time (e.g. temperature at 9:00) or may be summary or cumulative data for time periods

(e.g. average wind speed, number of invertebrates trapped) which may or may not be contiguous. Consequently an extensive metadatabase, describing the data and their proper use, is also required.

Metadata are an essential part of any database. Metadata can be regarded as a continuum of characteristics from general information about a dataset to specific details about a data item or object within that dataset, with data quality as an important component. They provide information about data availability, appropriate use, access and transfer methods essential for the integration of datasets and for efficient maintenance and use of data resources. The boundary between data and metadata is not necessarily clear-cut; metadata for one purpose might be regarded as data for another.

The ECN Data Centre metadatabase has a small set of core metadata tables that form the principle link between the data and metadata. These provide the essential metadata for each dataset e.g. measurement descriptions, site information, sampling protocols, physical location of sampling, data ownership and responsibility etc. Associated with these core tables are ancillary metadata tables which hold linked information on units of measurement, quality criteria, quality codes and text relating to sampling occasions, instrument and sampling details, units of measurement and data dictionaries (e.g. species coding lists). Details of any deviation from the protocol specification, together with quality codes and text describing factors affecting sampling are also stored in these associated metadata tables, along with laboratory methods and associated detection limits. All metadata are linked directly with the data to which they relate and are provided to users with each data request. Discovery metadata are also available (for more details see section 4.3).

Incoming data are quality assured before being lodged in the database using data loading, transformation and validation procedures that have been developed and documented for each measurement. These verification steps include numeric range checks (i.e. checking if a value falls within a specified range), categorical checks (e.g. checking that a species code appears on the standard code list), formatting (i.e. that the dataset conforms to the specified data format) and logical integrity checks (i.e. checking the data make sense e.g. that the dates in one dataset match those in a related dataset). Appropriate range settings for ECN variables have been selected following discussion with specialists in each field. Where data fall outside these ranges, a cautious approach has been adopted towards discarding data on the principle that apparent errors may be valid outliers. Such values are discarded only if there is a clear explanation, e.g. an instrumentation error, and corrections are made where possible. If the reason is unclear, then the values will be stored, but qualified in the metadatabase using pre-defined quality codes or free-text descriptions. Data providers also use these codes or free text to describe factors affecting sampling outside their control, instrument damage or site management effects. The verification checks are important "first-pass" procedures, but are relatively coarse and may fail to identify erroneous data within the valid range. More subtle problems are investigated through multivariate or time-series checks, based on known processes or expected patterns in the data. Periodically, quality assessment exercises are run by appropriate experts to check, for example, consistency in species identification across sites. In ECN, where the measured feature can be kept (e.g. archived invertebrate samples) or re-visited (e.g. vegetation plots), the accuracy of identification has, where possible, been assessed at a later date through sub-sampling by an independent expert (e.g. Scott and Hallam, 2003).

Where it is necessary to change a data record already lodged in the database, details of the correction are logged in the metadatabase. All data records in the database have a time-stamp which is updated when a data record is edited, while the original data record is retained in an archive table with its original time-stamp. This allows the dataset to be reconstructed as it was at any point in time i.e. if a user needs to access the dataset provided previously, this can be reconstructed (using the time-stamps and archive tables) if necessary.

The time taken to process datasets is strongly affected by the type and number of errors they contain; whilst the detection and reporting of errors is automated, finding appropriate solutions is often a manual process and can be time-consuming. More direct methods of remote data submission by data providers directly to the database – with appropriate quality assurance procedures built in – are currently being developed to improve the efficiency and speed of data ingestion. An automated data harvesting system is therefore under development that uses web accessible services. This will allow data providers to upload data directly to a temporary area of the ECN database and will incorporate user authentication, data upload and visualisation, dataset quality assurance and outlier detection methodologies by modelling data against previously verified data.

Database security is an important consideration, to avoid corruption or loss of data through system faults and to protect against unauthorised access. Incremental back-ups of the database are made daily, a full back-up is made weekly, and monthly back-ups are kept for one year, off-site. Storage media are renewed regularly. Access controls and security monitoring software are in operation to prevent unauthorised use.

4. Data Visualisation and Access

Environmental monitoring programmes can be costly, and their full benefit may only be fully realised through making data openly available. There are now few technological barriers to making data, metadata and interpretations available *via* the Internet to inform environmental research and policy development. Indeed the ubiquitous nature of the Internet has meant that awareness of environmental data sources and expectations of users have risen accordingly. Remote use by third parties, however, means users have fewer opportunities for personal contact with data providers, making it essential that systems are tailored to provide appropriate metadata to ensure users understand the data. Such developments depend on the availability of skilled staff and on the willingness of data providers to co-operate in allowing access to data.

Provision of easy access to data has always been central to ECN's strategy to provide a resource for environmental research, policy purposes and public information. The data are used by a diverse community of science, policy and public users. A particular challenge is to provide data access methods to suit these users, which can give sufficient guidance and information whilst at the same time providing flexibility in data query and presentation. The ECN Data Centre addresses this through targeted data exploration interfaces (see 4.1) on the website (http://data.ecn.ac.uk) and by making discovery metadata available on a variety of national and international data portals (see 4.3).

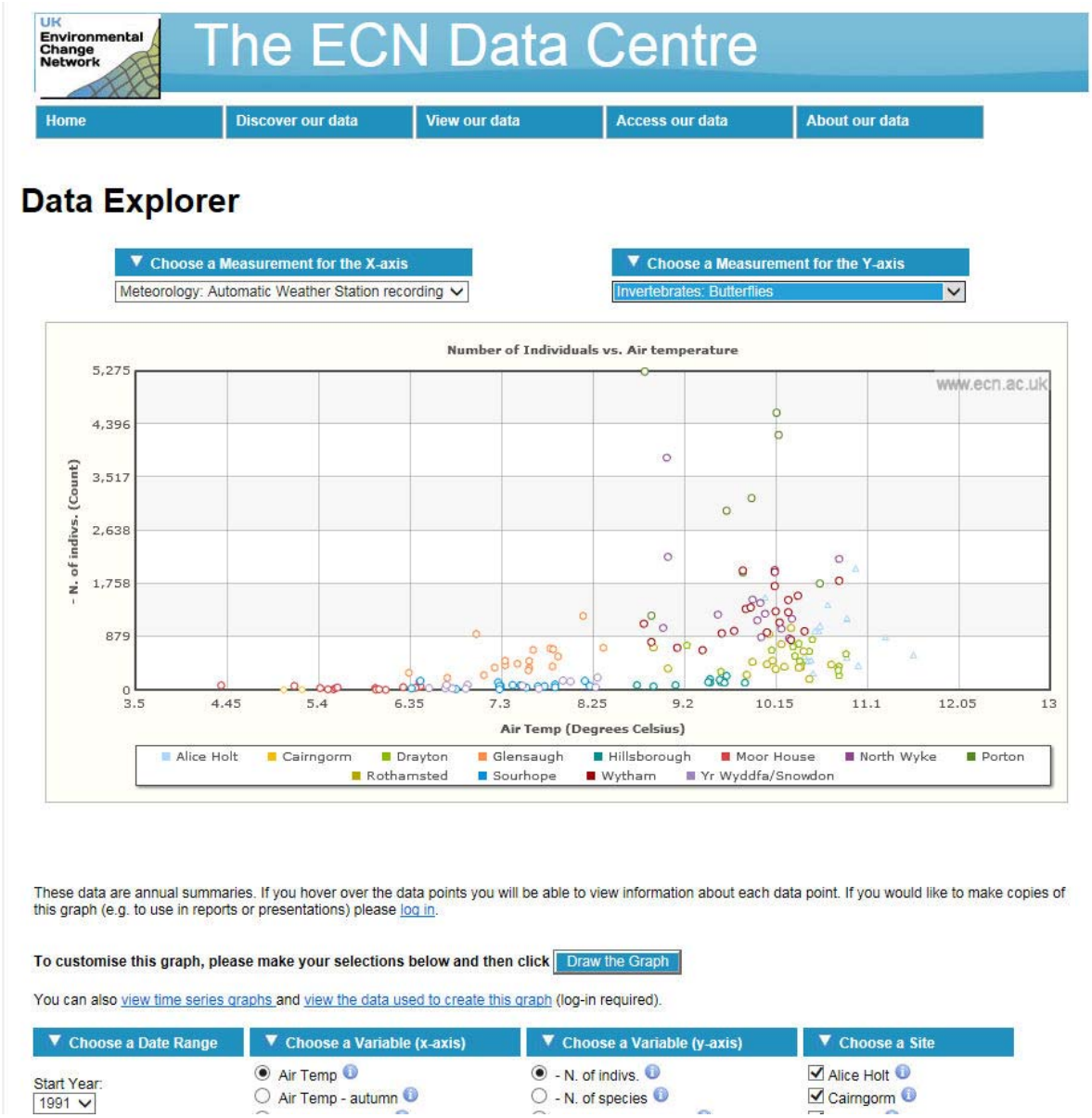
4.1 Data Exploration Interfaces

Raw data is generally preferred for scientific analysis but its use often requires a degree of expertise in data handling and it can be time-consuming to process so may not be suitable for all users. The

ECN Data Centre has, therefore, developed 'tailored' web interfaces to the ECN summary database, which require little or no initial learning process for the user. The data exploration interfaces on the website allow query-based dynamic generation of graphs and tables direct from the database. They have been designed to support a diverse user community. The Data Explorer interface (http://data.ecn.ac.uk/explore/index.asp) allows users to relate ECN terrestrial summary data variables in the form of scatter plots. The plots can be customised – by selecting the sites, variables and date ranges of particular interest. In the case of invertebrate species, data links are provided to the National Biodiversity Network (NBN - http://www.nbn.org.uk) species distribution maps to give a national spatial context to this site-based data. The Time Series Viewer (http://data.ecn.ac.uk/tsv/ECNdb.asp) allows a user to generate time series from the summary data.

Both these interfaces are linked dynamically to the database so the most up-to-date data are always available to users. The interfaces work together so a user can switch between them easily. Users can also generate and download tables of data as well as the graphs. Since users are accessing an automated system, they do not have the opportunity for dialogue with the data providers or database staff, and these interfaces have, therefore, been designed to provide all the necessary metadata. Where download facilities have been provided, these metadata are automatically included in the download.

Figure 3: Example Output from the Data Explorer. In this example the log of the total number of individual butterflies counted each year at each ECN site are plotted against the mean annual air temperature.



4.2 Wireless Sensor Networks

Wireless sensor networks have the potential to make collection of monitoring data more efficient and cost-effective – whilst also providing access to more detailed data over significant time periods. The ECN Data Centre has been exploring its potential through involvement in the UK Lake Ecological Observatory Network (UKLEON - http://www.ceh.ac.uk/our-science/projects/uk-lake-ecological-observatory-network-ukleon). UKLEON operates a network of buoys on 11 UK lakes which transmit data via GPRS (a global system for mobile communication) every four minutes – using CSI::XML or TOA5 (for older buoys) standards to facilitate data transmission. Data are received, processed and automatically quality checked, prior to being lodged in the database using a system developed in collaboration between the Centre for Ecology and Hydrology (CEH) Lake Ecosystems Group, the UK Astronomy Technology Centre and the ECN Data Centre. The Data Viewer on the website (http://data.ecn.ac.uk/ukleon) displays data in a format that allows results to be easily visualised and used. The plots are again customisable, allowing a user to select the dates, variables and sites of

interest. The lessons learnt from, and systems developed for, the UKLEON network are now being applied to enhance the data capture capabilities of ECN and the other networks for which the ECN Data Centre has data management responsibility.

4.3 Data Discovery

The website has a Data Discovery Portal providing information on the datasets that are held (http://data.ecn.ac.uk/Data_discovery/search.asp). Datasets can be found using a map-based or keyword search. Overview metadata are provided e.g. locations and the date range of the datasets, as well as more detailed metadata to comply with metadata standards (e.g. UK GEMINI).

The ECN Data Centre also makes metadata discoverable on a number of national and international data discovery portals including the CEH Environmental Information Platform (https://eip.ceh.ac.uk/), Natural Environment Research Council (NERC) Data Discovery Service (http://data-search.nerc.ac.uk/), the UK Government data discovery portal (http://data.gov.uk/), the LTER-Europe (European Long-term Ecosystem Research Network) data portal (http://data.lter-europe.net/deims/) and the European Geoportal (http://inspire-geoportal.ec.europa.eu/). This is made possible through the use of the core CEH metadata standard for discovery metadata (https://wiki.ceh.ac.uk/display/cehigh/CEH+Core+Metadata+Detail), to transfer data to the CEH Environmental Information Data Centre (EIDC). The CEH core metadata standard is compatible with the NERC metadata standard (http://data-search.nerc.ac.uk/documents/nerc_metadatastandard.pdf), UK GEMINI (http://www.agi.org.uk/join-us/agi-groups/standards-committee/uk-gemini), the INSPIRE metadata implementing rules (http://inspire.ec.europa.eu/index.cfm/pageid/101) and ISO 19139 (http://www.iso.org/iso/catalogue_detail.htm?csnumber=32557). Once ECN data are passed to the CEH Environmental Information Platform, using this metadata standard, data can be shared on the data discovery portals listed above to help users find and use the data resources. The details of how EIDC do this are outside the scope of this paper (see http://eidc.ceh.ac.uk/ for more details).

ECN is a participant in eLTER, a European Horizon 2020 project, involving LTER-Europe partners in collaboration with the European Critical Zone Observatory community (http://www.lter-europe.net/projects/eLTER). One of its aims is to streamline the design of the European network of LTER (Long-term Ecosystem Research) sites and socio-ecological platforms. It will also develop an organisational framework for the distributed data sources across Europe and enable virtual access to LTER data. The ECN Data Centre provides the UK node of this data integration platform, which will deliver a common data policy, data sharing agreements and data exchange across Europe. Through the eLTER project, ECN data will be made accessible through a range of new web services. These will be compatible with other data and services from the LTER network, provided via a standard eLTER infrastructure and loaded with data from the ECN summary database in the first instance. This should enable increased access to the broad range of data collected by ECN and create added value through greater compatibility with a wide range of other European monitoring sites. eLTER is a 4 year project running from June 2015 to May 2019.

4.4 Licensing and Digital Object Identifiers

ECN data are owned jointly by their originating sponsoring organisation and NERC. The ECN sponsors have agreed a system of data access whereby summary data are freely available, primarily

through the website (http://data.ecn.ac.uk), while raw data are available, under licence. Data are made available under the terms of the NERC data policy – whereby data are made openly available for others to use for free (unless the request is particularly complex or there are third-party licensing arrangements involved).

Increasingly, the ECN Data Centre is making use of Digital Object Identifiers for the citation of data. DOIs (Digital Object Identifiers) allow datasets to be cited, increasing their traceability and impact, and enabling the contribution of individuals involved in data management and collection to be formally acknowledged for their work. DOIs for the ECN terrestrial datasets have been minted to mark the recent 20-year anniversary of ECN data collection (Rennie *et al*., 2015a-n; Rennie, 2012) and a number are cited in various other papers in this special issue. This is being facilitated through the CEH Environmental Information Data Centre, which makes data available via a discovery catalogue (https://eip.ceh.ac.uk/). The catalogue is kept up to date with UK and European standards (UK GEMINI and INSPIRE), and a map viewer for visualising and evaluating data – ensuring that ECN meets its obligations under the INSPIRE directive. Access to the data is through an open non-exclusive, non-transferable, royalty free licence.

5. Concluding Remarks

The complexity and scope of environmental change research demands a comprehensive and integrated approach to science and information management that breaks down the barriers between disciplines, roles and technologies. The promotion of data and information management at the core of much of this research places demands on data managers and information system developers. They must not only design systems to capture, manage and provide access to data within one particular database but should also ensure that resource can be used in combination with other resources, using Internet-based technologies. They must understand enough about each topic area being monitored to build appropriate data models and structures, and cater for the increasingly complex needs of scientists. They are also responsible for quality assurance throughout the information system.

Since its launch in 1992, ECN has placed information management at the heart of its science strategy. The size and scope of the programme has demanded an integrated information management system to store all data and metadata collected by the organisations that supply data to it. Quality control is central to this system. As this paper has shown, this approach considers all aspects of information handling, catering for information requirements from data capture through to access and interpretation. This has meant co-ordinating procedures across the network of organisations that operate data capture protocols and laboratory analyses at their respective sites, and across the range of remote users requiring data access. The data are made available through a number of different data access methods, including a bespoke website and through a number of national and international data portals to ensure the data are accessible to users.

The ECN Data Centre manages data for several UK integrated environmental monitoring networks. This strengthens the work of individual networks by presenting them in context with data from the other networks. It provides a resource for science - rigorous data standards are applied across the networks which allows data to be easily integrated and queried. It also makes development work more cost-effective; systems developed for one network can be reused or adapted for the other networks (e.g. wireless sensor networks). Finally it allows for the UK's integrated monitoring data to

be more easily integrated with data from other national sectoral networks and also with other long-term ecological data from international networks e.g. in the recently established EU Horizon 2020 eLTER project.

Information management systems, like that of the ECN Data Centre, continue to evolve as new technologies emerge and user requirements change. Current development plans for the ECN Data Centre have been highlighted throughout this paper but to summarise they include:

- Development of automated data harvesting system to ensure data upload is efficient and accurate (described in section 3).
- Development of wireless sensor networks to provide access to more detailed data over significant time periods in a cost-effective manner (described in section 4.2).
- Use of data standards and web services to provide increased access to ECN datasets and create added value through greater compatibility with a wide range of other national and international monitoring networks (described in section 4.3).
- Provision of citation methods for ECN datasets to improve the traceability of data used in publications, increase the impact of datasets and provide recognition of individuals involved in the data management and collection (described in section 4.4).

6. Acknowledgements

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