Building EDENs: The Rise of Environmentally Distributed Ecological Networks

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Environmentally distributed ecological networks (EDENs) are growing increasingly important in ecology, coordinating research in more disciplines and over larger areas than ever before, while supplanting post hoc syntheses of uncoordinated research. With the rise of multiple broadly focused, continental-scale EDENs, these networks will be directing an increasingly large proportion of resources in ecology, which warrants a review of their use. EDENs have become important for monitoring populations and ecosystems across regions, focusing on everything from butterflies to soil carbon. They are also pivotal for testing the generality of ecological relationships, testing ecological responses to experimental manipulations across space, ensuring uniform methodology, and compressing the lead time for syntheses. We identify 10 major steps to running EDENs and discuss four avenues of growth for EDENs in the near future.

Keywords: EDENs, ecological networks, monitoring

Analyses along environmental gradients are a fundamental pillar of ecology, providing unique insights into the controls on the abundance of species and into ecosystem processes. As the scope and scale of ecological questions regarding gradients develop, scientists and policymakers increasingly rely on coordinated research utilizing what we refer to as environmentally distributed ecological networks (EDENs) to understand populations and ecosystems and provide information for policy decisions (Vaughan et al. 2001). EDENs are sets of sites where the same ecological measurements are made by multiple users in a coordinated fashion. Throughout this article, we use "EDEN" as a collective term for networks that carry out surveying and monitoring efforts in population and ecosystem ecology and in cross-site, coordinated experiments.

Today, EDENs' data gathering ranges from one-time measurements to decades of annual monitoring, and from tens of kilometers to global in scale. EDENs can be institutionalized or ad hoc, can move biological material as well as data, can include tens of thousands of individuals, and can focus on understanding both populations and ecosystems. The use of EDENs has been growing rapidly in many disciplines, and multiple continental-scale EDENs with broad mandates are currently under development. These include the National Ecological Observatory Network, or NEON, in the United States; the Tropical Ecology, Assessment, and Monitoring, or TEAM, network in South America; the Australian Research Council's Earth System Science, or ESS, network; the

South African Environmental Observatory Network, or SAEON; and the Africa Earth Observatory Network, or AEON. Of late, there have even been calls for global EDENs to monitor aspects of biodiversity (Pereira and Cooper 2006).

Though the importance of EDENs is increasing, involving the research of a large number of scientists over broad regions, there has been little formal study into how EDENs are constructed and function, or into their benefits to ecological understanding. The purpose of this overview is to show the increasing utility of EDENs, to demonstrate the breadth of their application, and to begin to codify the ways in which they are organized and utilized. We first discuss some common arguments associated with cross-site research and the use of

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EDENs. Second, we describe the basic types of EDENs in population and ecosystem ecology, distinguish between observational and experimental EDENs, and outline important EDEN findings. Third, we outline the organizing principles of EDENs, including 10 steps associated with setting up and running an EDEN. Last, we discuss some potential avenues for future growth for EDENs.

Arguments surrounding EDENs

Understanding the importance of EDENs for ecology begins with understanding the importance of distributing measurements across space. First, testing relationships across multiple sites and regions is necessary for establishing the generality of a particular relationship with data from different sites used as replicates. Second, when measurements are arrayed across environmental gradients, ecological responses to environmental variables can be tested. Third, working across multiple sites increases statistical power. Weak patterns are more likely to be discovered as the number of sites examined increases. Fourth, although experiments might be considered the cleanest tests of relationships between environmental drivers and ecological responses, some environmental gradients cannot be replicated experimentally, and some hypotheses are best tested over spatial gradients. In other instances, space is used as a substitute for time because some temporal sequences are too long for repeated sampling at an individual site to be feasible. EDENs can help link together research conducted at different scales by providing the contextual framework of long-term ecological change, within which often short-term, specific research projects provide detailed information. The results obtained by EDENs can confirm the patterns of results from research carried out at a smaller scale and can contextualize the magnitude of long-term changes. Finally, sampling across space is necessary for monitoring ecological patterns where spatial relationships and distributions are necessary (e.g., for generating maps of species ranges or abundances).

Once it is established that it is appropriate to sample across space, sampling can be undertaken either by a given individual, by multiple individuals in an uncoordinated manner, or by multiple, coordinated individuals working through an EDEN. There are three specific advantages of EDENs: (1) Techniques and effort density can be standardized from the outset, (2) spatial distributions of sites can be selected a priori, and (3) data can be collected synchronously over large spatial scales, something that might not be possible for a single individual or uncoordinated group of individuals. EDENs also allow less specialized (and often free) labor to be harnessed while taking advantage of economies of scale in sample processing and data analysis. For example, over 50,000 individuals volunteer annually for the Audubon Christmas Bird Count (CBC) in North America, and over 14,000 volunteers provide 140,000 hours of surveying annually for projects associated with the United Kingdom's Tracking Mammals Partnership (Battersby 2005).

Some of the perceived disadvantages of EDENs parallel those discussed in debates over long-term research in the 1980s (Likens 1989, Krebs 1991), and can be addressed using these debates as a guide.

A major potential point of contention is the argument that collecting spatially distributed data is antithetical to the hypothetico-deductive method, in which hypotheses are first proposed and then tested on the basis of observed data. Counter to this argument, first, hypotheses can be generated a priori for EDENs just as they can for long-term data and experiments. Second, data collection without a priori hypotheses does not preclude hypothesis testing at a later time. Although sampling designs might not be optimized for the eventual analyses, data can be collected and hypotheses developed without a priori knowledge of relationships of predictor and response variables. Hypotheses also can be developed by examining patterns in a subset of the data and then tested independently on the full data set. Finally, observation is the first part of the scientific method. Even if there are no a priori hypotheses to be tested, this does not invalidate the utility of large-scale observation that can generate hypotheses to be tested later.

It also can be argued that EDENs are too costly, although such arguments are rarely accompanied by criteria by which to evaluate the costs and benefits of competing allocations of scarce research dollars. Considering the extensive data they provide, many EDENs are run on a very economical budget, especially those that incorporate a large number of volunteers. For example, the United Kingdom's National Bat Monitoring Programme (NBMP) delivers status and trend information for UK bat species, a difficult group to survey because of their ecology yet a high-priority group in terms of conservation. The annual running costs of the NBMP, which uses volunteers, are approximately $200,000, whereas the estimated cost of using professionals to collect the same data is more than $1,100,000 (Battersby 2005). Moreover, the examples provided below demonstrate the utility of extant EDENs in the development of ecological understanding.

EDENs that measure populations and ecosystems

EDENs vary greatly in their structure, depending on the intended purposes of the network (figure 1). In general, EDENs can be categorized as observational or experimental in nature, and as having a focus on populations or on ecosystem properties.

Observational EDENs record data with minimal interference and with no experimental manipulations at a given site. Observational EDENs that measure populations have a long history in ecology. For example, in 1900, the Audubon CBC quantified bird abundances at more than 25 sites from New Brunswick to California, and in the 1930s, groups of schoolchildren were organized to survey the land cover of Great Britain (Stamp 1948). EDENs have been created to survey or monitor populations of a wide variety of organisms. Birds, dormice, deer, butterflies, moths, crop pests, stream macroinvertebrates, flying insects, fish, coral reefs, worms, bats,

frogs, microbes, plants, forest trees, plant pollen, and mushrooms have been the subjects of recent individual EDENs. Below, we provide representative examples of the main aims of population EDENs, which include determining species' ranges and abundances and changes in ranges and abundances of species over time. We highlight the results of these examples separately (table 1).

The simplest population EDENs are coordinated surveys to examine the distribution of organisms over large spatial scales. For example, the Protea Atlas was coordinated by the South African National Botanical Institute to map the distribution of Proteaceae species in southern Africa (Gelfand et al. 2005). For the atlas, more than 400 contributors generated a quarter-million species records from more than 60,000 sites in southern Africa from 1991 to 2000. Other surveys have been coordinated to examine the geographic patterns of abundance in addition to delimiting geographic ranges. The annual Fourth of July Butterfly Count produced indices of abundance and richness estimates of butterflies for over 500 sites in North America (Kocher and Williams 2000). In an analogous survey of abundances, instead of waiting for multiple researchers to begin to develop local data sets that could be compiled to explore continental-scale patterns, Fierer and Jackson (2006) established a network of contributors who collected samples of surface soils from 98 sites in North and South America, which were sent to a central facility for ribosomal DNA fingerprinting of microbial assemblages. With less than an hour of volunteered time and a $25 shipping cost for each site, Fierer and Jackson's logistical planning compressed the lead time to developing broader syntheses associated with novel techniques.

When repeated in a standardized way, surveys become surveillance. Some EDENs quantify the changes in range and abundance of populations over time while seeking to identify the drivers of observed changes. The Tracking Mammals Partnership in the United Kingdom involves 24 organizations cooperating on 17 surveillance projects that focus on either single or multiple mammal species across the country, including urban areas. Volunteers from the partnership cover more than 16,500 sites (Battersby 2005) and have surveyed 37 mammal species, or 57% of the terrestrial mammal species in the United Kingdom. Also in the United Kingdom, EDENs have allowed comparisons of countrywide surveys of butterflies and plants, separated by at least 20 years, to examine changes in abundance and range over long time frames (Thomas et al. 2004).

Observational EDENs have also been used to survey and monitor ecosystem parameters, such as soil carbon, ecosystem carbon exchange, leaf longevity, atmospheric deposition, and the decomposition of plant biomass. The history of ecosystem EDENs might not be as long as that of population
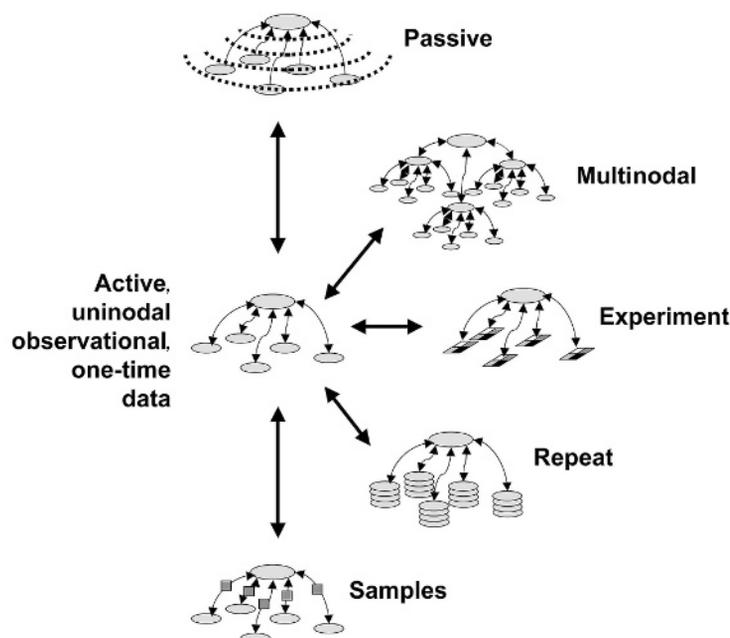

Figure 1. Axes of environmentally distributed ecological networks (EDENs). The form of EDENs extends beyond the scale and density of the network, and beyond the intensity of investigation at any one site. At the center of multiple axes, EDENs are coordinated actively, as a single node determines the one-time collection of data at individual sites; the topology of the network can also be generated passively as a general call for data or samples is announced and individuals volunteer their sites. When local control and decisionmaking are needed beyond what can be efficiently organized from a central site, multinodal networks are used; this approach is more likely to be taken with increasing spatial scale and site density. In addition to surveys or monitoring, networks can be arranged around site-level manipulative experiments, as exemplified by ITEX (International Tundra Experiment) and BIODEPTH (Biodiversity and Ecological Processes in Terrestrial Herbaceous Ecosystems). EDENs can also use repeat sampling, emphasizing the ability to return to individual sites. Finally, some networks are structured to move samples, rather than just data, and this requires additional logistical planning.

EDENs, but coordination of ecosystem research across sites has nonetheless been occurring for decades. Following the International Geophysical Year in 1957–1958, the decade-long International Biological Program (1964–1974) coordinated measurements associated with the productivity of ecosystems throughout the world, and is still a unique source for comparative data for ecosystem properties (Golley 1993). Observational EDENs that measure ecosystem variables tend to be more intensive and less extensive than those that measure populations, and are more likely to be used for testing the generality of fundamental principles than for quantifying spatial relationships.

The simplest reason for using EDENs to measure ecosystem variables is to provide independent replicates to test the generality of principles concerning controls of ecosystem

Table 1. Major findings of selected environmentally distributed ecological networks.

Project	Findings
Protea Atlas Project (South Africa)	The project improved maps of species distributions; participants discovered eight new species in the Proteaceae family and rediscovered two species that were thought to be extinct (Gelfand et al. 2005).
Bacterial biodiversity survey (North America)	Across sites, bacterial richness and diversity increased with increasing soil pH, peaking near a pH of 7, with the relationship holding across and within vegetation types. In contrast to patterns observed for plants and animals, there was no latitudinal diversity gradient for bacteria (Fierer and Jackson 2006).
Fourth of July Butterfly Count (North America)	Eight years of surveys revealed that butterfly species richness decreases with increasing latitude, while abundances increase (Kocher and Williams 2000).
Tracking Mammals Partnership (United Kingdom)	Most species surveyed increased in abundance over the past decade, with species such as the water vole and common dormouse declining (Battersby 2005).
Countrywide surveys of butterflies and plants (United Kingdom)	Although 72% of all native plant species increased in abundance over a two-decade period, 78% of all butterfly species decreased (Thomas et al. 2004).
Wardle chronosequences (global)	With successional time, phosphorus limitation increases, causing tree basal area to decrease, the ratio of nitrogen to phosphorus in litter and soil organic matter to increase, and the microbial community to decline in biomass while shifting in dominance from bacteria to fungi (Wardle et al. 2004).
Long-term Intersite Decomposition Experiment, Canadian Intersite Decomposition Experiment (North America)	Decomposition increases with increasing temperature and precipitation; the resulting changes in substrate quality have significant effects independent of climate (Gholz et al. 2000, Trofymow et al. 2002).
Lotic Intersite Nitrogen Experiment (North America)	In a comparison across sites and sampling dates, uptake of the labeled inorganic nitrogen was shown to be fastest when discharge was the least and, in general, ammonium (NH_4^+) cycled 5 to 10 times more tightly in streams than nitrate (NO_3^-) (Peterson et al. 2001).
National Atmospheric Deposition Program (North America)	From 1985 to 2002, NO_3^- deposition decreased in the US Northeast and increased in the west-central states, while NH_4^+ deposition increased in the mid-continental United States (Lehmann et al. 2005).
Alpine Pals montane stress gradient (global)	At lower elevations, where the physical environment is less harsh, plant removal resulted in an increase in growth of neighboring plants. At higher elevations, where temperatures are lower and winds are greater, plant removal resulted in a decrease in the growth of neighbors (Callaway et al. 2002).
International Tundra Experiment (global)	Reproductive responses of warmed vegetation lagged behind growth responses at all sites; growth responses were greater in warmer sites, and reproduction increased more in colder sites.
Biodiversity and Ecological Processes in Terrestrial Herbaceous Ecosystems (Europe)	Across the relatively broad climate gradient, aboveground biomass declined with declines in diversity, but there was no evidence that climate affected the relationships between diversity and productivity.
UK Acid Waters Monitoring Network	Over the past 150 years, there has been a gradual acidification of lakes that began to reverse only in the early 1990s as lake pH recovered along with less acid-resistant diatoms and trout (Monteith et al. 2005).
Countryside Survey (United Kingdom)	In a comparison of results in 1998 with those in 1990 (or 1978 for a smaller subset), eutrophic plants were found to increase in abundance in inherently low-fertility upland and lowland sites, while the composition of assemblages of already high fertility sites remained more stable (Smart et al. 2003).

processes. To test hypotheses regarding the consequences of increasing phosphorus limitation with ecosystem development, Wardle and colleagues (2004) used a global-scale EDEN to sample soil and vegetation properties across six chronosequences distributed across boreal, temperate, and tropical portions of the globe. Their study did not attempt to explain nonstationarity in relationships with environmental covariates.

Other ecosystem EDENs can generate multidimensional gradients to test the primary and interactive roles of state factors on ecosystem function. For example, beginning in 1990, large-scale coordinated studies were undertaken to understand the relationships between climate and decomposition rates. Across North and Central America, the Long-term Intersite Decomposition Experiment Team, or LIDET (Gholz et al. 2000), deployed mesh bags containing common root and leaf litters to examine decomposition at 28 midlatitude sites; the Canadian Intersite Decomposition Experiment, or CIDET, extended relationships between climate and decomposition into higher latitudes for 21 forest and wetland sites in Canada (Trofymow et al. 2002); and another decomposition survey has just concluded among 21 tropical ecosystems (Jennifer Powers, Department of Plant Biology, University of Minnesota, Saint Paul, personal communication, 1 November

2006). Analogous to decomposition experiments using natural gradients of climate, the Lotic Intersite Nitrogen Experiment, or LINX, utilized spatial variation in stream characteristics to test general principles of nitrogen cycling in streams. Nitrate and ^{15}N-labeled ammonium were added to 12 headwater streams across the United States that varied in their discharge and in the biomes they ran through (Peterson et al. 2001).

As with populations, surveillance of ecosystem properties over time can be used to understand long-term changes over broad spatial scales. For example, the US National Atmospheric Deposition Program (NADP) has been contracting out weekly rainwater collection to multiple sites (now over 200) since 1978. Samples are sent to a central laboratory to measure rainwater chemistry variables such as pH and inorganic nitrogen concentrations (Lamb and Bowersox 2000).

Both population and ecosystem EDENs have extended beyond range mapping and surveillance to coordinated, replicate experimental manipulations over large spatial scales. One experimental EDEN showed the importance of facilitation in stressful habitats by removing plants and assessing the response in the growth of neighboring plants in paired sites in 11 mountain ranges across four continents (Callaway et al. 2002). Also investigating the role of temperature in plant

growth, the International Tundra Experiment, or ITEX (Arft et al. 1999), a circumboreal EDEN, tested the consequences of higher temperatures in the Arctic with field warming experiments. Among 13 sites distributed across the Holarctic, open-top chambers were installed to passively warm the native vegetation. Other experimental EDENs have extended beyond simple manipulations of extant vegetation or state factors. For example, in the BIODEPTH (Biodiversity and Ecological Processes in Terrestrial Herbaceous Ecosystems) experiment (Hector et al. 1999), conducted at eight field sites in Europe, herbaceous communities of different diversity and composition were synthesized to test the consequences of declining plant diversity on productivity and other ecosystem properties.

EDENs, climate, and climate change

Although EDENs are not necessarily established to answer a specific question, EDENs whose sampling has been repeated over time have been key in providing data to help understand the effects of climate and climate change on populations and ecosystems. Interannual surveys have shown the consequences of short-term variation in climate on populations. The British Trust for Ornithology Heronries Census has monitored grey herons annually since 1938 and counted over 10,000 heronries in 2003. The long-term data show that herons suffer large population declines after hard winters across Great Britain (Marchant et al. 2004). Data from 1350 sites of the Wisconsin Frog and Toad Survey, sampled over 18 years, led to the inference that low rainfall caused declines in amphibian populations; but for amphibians, as opposed to herons, there was a lag of one to four years after the severe weather, with species differences in the lag dependent on their time to maturity (Trenham et al. 2003). A widespread and long-running survey of moth populations in the United Kingdom detected declines in a range of species, associated at least in one species with large-scale climatic patterns in the Atlantic basin (Conrad et al. 2003).

Other long-running or repeated surveys have revealed the consequences of climate change for populations (Hughes 2000, Walther et al. 2002). Plant phenology EDENs, critical to understanding primary production and coordination among organisms across trophic levels (Menzel 2002, Sparks and Menzel 2002), have shown that spring comes increasingly early to northern Europe, causing birds to lay their eggs earlier (Crick 2004). Recent surveys have also found that the more northerly a bird's distribution in France, the more it has declined since 1989 (Julliard et al. 2004), a trend that is probably associated with warming. Spring has also come earlier in the northern United States, reflected in earlier bloom dates for lilac and honeysuckle and in earlier peaks in spring streamflow (Schwartz and Reiter 2000, Cayan et al. 2001).

Monitoring in the United Kingdom has shown that the effects of climate change on butterfly populations are not simple. Many butterfly species in the United Kingdom have extended their northern range limits, but many other butterfly species that would be expected to respond positively to climate

change have declined as a result of habitat modification (Warren et al. 2001). Butterflies that are habitat specialists were hit the hardest by habitat modification, whereas mobile generalist butterflies showed the greatest population increases. This kind of information is vital for planning effective long-term conservation management for different species groups, and it is unlikely that it would have been obtained through uncoordinated sampling or experimental research methods.

Although there has been less investigation into the effects of climate on ecosystems than on populations, EDENs have revealed how climate and climate change have affected some ecosystems. Multiple regional eddy flux networks intensively measure ecosystem-level carbon, water, and energy balance at individual sites; taken together, these networks are global in extent. The European carbon balance network, CarboEurope, analyzed carbon balance data from 15 sites in Europe and showed that continental-scale drought in 2003 caused a reversal of net ecosystem carbon storage, releasing 0.5 Pg carbon per year over Europe as gross primary production fell by 30% (Ciais et al. 2005). To similar ends, surface soils in over 2000 English and Welsh sites were resampled between 1994 and 2003, approximately 20 years after they were first sampled, generating an unbiased map of soil carbon change across a large number of habitat classifications (Bellamy et al. 2005). The resampling revealed that warming has caused significant soil carbon loss in the United Kingdom over the past 20 years, a loss that may be equivalent to 10% of the carbon from the country's industrial emissions during that period.

Organizing EDENs

The magnitude of effort that can be harnessed by EDENs provides unparalleled power to answer ecological questions that cannot be addressed through other means. As more scientists gain experience in setting up and running EDENs, the organization and coordination of the networks improve greatly. In some countries, notably the United States and the United Kingdom, EDENs are organized to a very high level, with regulatory systems in place for data collection, data analysis, and reporting. These EDENs are carefully planned and managed and go through a structured process that includes identifying the questions that need to be answered; running pilot projects to develop methods and test the feasibility and statistical power of the EDEN; assembling the network using central or distributed coordination to recruit and train the surveyors; data management, including collection, collation, validation, and archiving; statistical analysis to provide robust results; and dissemination of results through reports, scientific papers, and feedback to the networks of surveyors. These steps are detailed below.

Identifying questions. The first step in developing a successful EDEN is to identify the main questions that the network is to answer. The specific questions dictate the extent and intensity of the EDENs and their temporal scope. As EDENs are a response to the need for coordinated research across sites,

the benefits to coordinating multiple investigators should outweigh the organizational costs. EDENs are best utilized as the number of sites and the distances across sites increase and as the time frame over which measurements should be measured decreases.

Running pilot projects. After identifying questions, pilot projects must be run to test the feasibility of the EDEN. Pilot projects should ensure that data collection is repeatable over time and across sites, check that methodologies are successful and appropriate for the participants, and identify the training required for participants. Pilot projects must also include power analyses to determine the number of sites required for a given methodology to provide sufficient confidence in estimates. Pilot projects are often run at the full spatial extent of the desired network.

Assembling the network. Once an EDEN's planners show that their methodologies are successful and the network size allows for sufficient statistical power, the EDEN must be assembled (figure 1). Network assembly involves three main endeavors. First, the nodal structure of the networks must be established. Some networks can have a single coordinating site, while others need nodes that coordinate regional or local activities. Establishing decentralized nodes becomes more beneficial as the size of an EDEN and the need for regional or local control increase. Once nodal structure is determined and the nodes put in place, networks can be assembled either actively or passively. Passive assembly involves self-selection of individuals and sites, with minimal training. Active assembly generally occurs within a given organization in which command coordination is feasible, and sites and individuals are selected. Participant motivation must be actively considered, as the participants and the goals of an EDEN must be aligned for success, especially for EDENs that rely on a large number of volunteers across many years.

Training participants. For any network, some degree of training is always required. In some EDENs, training involves simple instructions that might include photographs or recordings of calls; in others, it include workshops for skill development and methodology implementation. Training sessions often include tests at the end of the session to ascertain proficiency and certify the participant's skills.

Collecting data and samples. Once participants are trained, they must be deployed to collect data or samples. Data are generally collected on paper, although some networks collect data electronically. Examples of samples collected by EDEN participants include rainwater for the NADP and hazelnuts for the United Kingdom's Great Nut Hunt; the latter are examined to see whether they have been opened by dormice, and used to generate maps of the dormouse's distribution.

Moving data and samples. Once collected, data or samples must be collated for later analysis. For some surveys, data sheets are mailed to a central site, or participants enter data using Web-based forms. For EDENs that have electronic data collection, data are often uploaded directly to a central server. If samples must be moved to central locations, the speed of movement should be considered from the outset. The delivery of NADP rainwater for analysis, for example, is generally expedited, whereas there is little immediacy required for the transport of Great Nut Hunt hazelnuts.

Data quality control. Quality control of data is achieved by training individuals to take high-quality data, calibrating measurements with duplication, and detecting anomalous measurements statistically. For example, the NBMP circulates a small number of frequency division detectors to record bat calls and to assess the accuracy of identification made by volunteers with heterodyne detectors.

Archiving and disseminating data. Like nongeospatial data (Michener et al. 1997), data from EDENs should be archived using best practices for data storage. Because data from EDENs is inherently spatial, GIS (geographic information system) software is a natural solution for archiving and disseminating data. Web-based GIS databases can easily make the information accessible to all network members for modification and addition, and to the general public for educational outreach and publicity.

Analyzing data. Beyond the analyses of any samples collected, statistical analyses and visual representations of data are critical steps for any EDEN. In addition to quality control of data, many of the surveys require analyses of both temporal and spatial patterns. Here again, GIS provides a useful medium for comparing EDEN data with extant data and for integrating site state factors (climate, soil parameters, etc.). Methodologies for both temporal and spatial data investigation should be selected, such as time series analysis and the production of continuous surface maps via spatial interpolation techniques.

Follow-up. If surveys are to be repeated, follow-up exercises are required. Gaps in site distribution need to be filled for subsequent surveys. Feedback should also be provided to participants to help them improve their skills and maintain interest. Occasionally, methodologies need to be altered, but this must be done carefully to maintain comparability across years. Most important, the frequency of follow-up surveys should be tailored to the question being asked and to the temporal frequency of auxiliary data sets.

Comparing two EDENs

Deviations from the basic tenets of running EDENs effectively can greatly diminish the efficacy of the research, as evidenced by a comparison of the two major ornithological EDENs in North America, the Breeding Bird Survey (BBS) and the CBC. The BBS was launched in 1966 by Chandler Robbins and his colleagues at the Migratory Bird Population Station (Sauer et al. 1997) to monitor long-term trends

among breeding birds in the United States and Canada. The design of the BBS focuses on generating scientifically useful data. Today, the survey comprises more than 4000 routes in the continental United States and Canada that are randomized at a given geographic scale, although these are not independent of human population density. Participants (both volunteers and employees of various state and federal organizations) drive a 24.5-mile (39.4-km) route, stopping every half-mile (0.8 km) to survey birds for three minutes, typically during June or early July, depending on latitude. Because an individual route can be completed only by a single person (or perhaps two, if the other person works only as a recorder), the observer effort per route remains constant. The observer must be skilled in the identification of birds primarily by song and chip notes, which requires a higher level of proficiency than visual identification. Although this excludes many active bird-watchers, it reduces observer error. In part as a result of its careful a priori attention to survey methodology, the BBS has produced heavily analyzed data on trends for hundreds of species breeding in North America (see www.pwrc.usgs.gov/infobase/bbsbib/bbsbib.pdf). Although the method does not cover all species equally well (nocturnal birds and those that do not nest in June or early July are particularly poorly covered), the data it generates have been particularly useful in documenting long-term declines in Neotropical migrant land birds and grassland birds (Robbins et al. 1989, Askins 1993). This has led to the establishment of major conservation initiatives and even new nongovernmental organizations (e.g., Partners in Flight) to deal with these issues.

Volunteers for the Audubon Society's CBC survey birds during a 23-day window in December and January. Volunteers travel by foot and by car, recording by sight and sound all observed birds within a circle 15 miles (about 24 kilometers) in diameter. The same circles are censused every year. From its humble origins as an alternative to counter a legacy of killing birds on Christmas morning, the CBC has blossomed into a monumental effort, with approximately 2000 circles surveyed by some 50,000 volunteers. The annual bird count has recently expanded into Central and South America. The CBC generates a tremendous amount of data, and these data have been tapped for publications documenting changes in distribution and abundance, and for a few hypothesis-driven analyses. For example, researchers' understanding of the irruptions in populations of boreal seed-eating birds, which lead to the birds' appearance in areas far south of their typical winter range, has been enhanced by the CBC. With CBC data, no evidence was found to support the notion that feeding stations will alter irruptive patterns (Wilson 1999) or that the prevalence of seed masting, rather than mean January temperatures, correlates with seasonal movements in three species (Smith 1986).

The CBC has also helped in understanding the spread of zoonoses. The spread of *Mycoplasma gallisepticum* among house finches in the United States was documented through population crashes in local CBC results (Hochachka and Dhondt 2000); and as the West Nile virus moved west across

the United States in the early 2000s, CBC data demonstrated that no significant declines were occurring in 10 focal bird species in the northeastern United States (Caffrey and Peterson 2003).

The goals of the CBC are not exclusively scientific; an important component of the program is raising awareness of the need for bird conservation. Yet, although the CBC and the BBS collect a similar amount of data, the CBC has had less scientific and policy impact. Most publications resulting from the CBC have been published in regional or national journals that have little or no peer review (e.g., *American Birds,* which is published by the National Audubon Society). Among the reasons that the CBC has had less of an impact than the BBS might be the scientific and conservation significance of winter versus summer sightings. Yet there are other structural issues that limit the efficacy of CBC data. CBC circles are selected by a local leader, often without reference to habitat types, whereas BBS routes are randomly located at a given scale. The CBC's studies are also hampered by weaknesses such as high variation in the quantity and quality of observers within a given CBC each year. The problem of uneven talents and efforts per observer is exacerbated by a subset of observers who lure additional birds with playback equipment, and by a lack of any associated habitat data (Stewart 1954, Dunn et al. 2005). Recently, the National Audubon Society has recognized the need for greater scientific value from the CBC, and has assembled a panel of 10 scientists to make recommendations for improving the value of the CBC and thus enhancing the reputation and value of what might be the world's largest and longest-running EDEN (Dunn et al. 2005).

The future of EDENs

As mentioned earlier, justifying the creation of EDENs depends on comparisons of the relative value of different scientific inquiries, the accounting of which is beyond the scope of this article. Determining the specifics of how EDENs should grow requires similar analyses. In general terms, however, EDENs would benefit from growing in four major areas.

First, future growth and development clearly could come from expanding EDENs into new geographical areas, allowing ecological relationships to be tested across novel environmental gradients and extending maps of ecological properties to new areas. Although the United Kingdom and the United States have a long history of using EDENs to answer questions, there are very few operational EDENs in South America, Australia/New Zealand, Asia, or Africa. Extant networks can also be improved by increasing the density of sampling sites and by enhancing coordination where administration is balkanized. For example, many states in the United States survey populations of plants and animals, but interstate comparisons are rare; coordinating these statewide efforts would create an opportunity for broader syntheses.

Second, EDENs could advance simply by measuring more variables. Even in regions rich with EDENs, many organisms and ecosystem properties are poorly represented. This
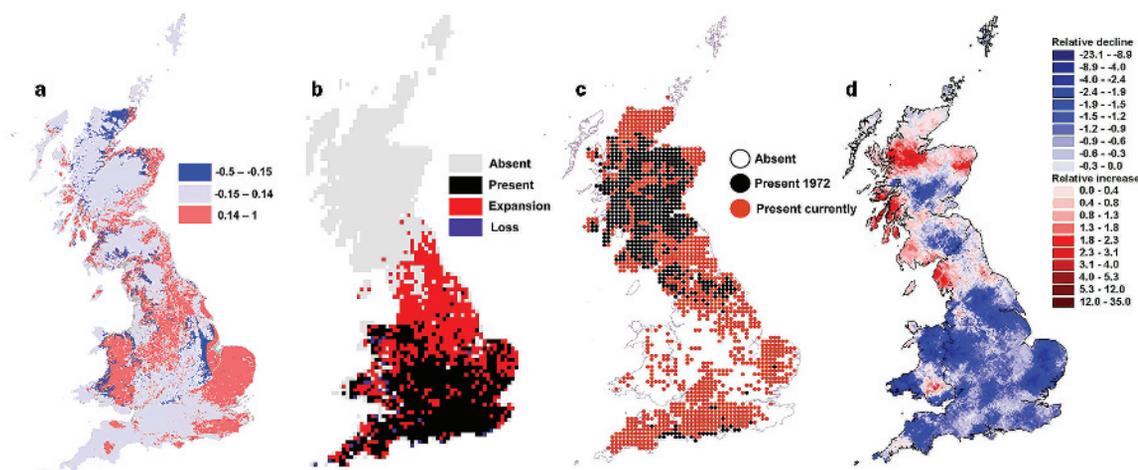
Figure 2. Changes in animal and plant populations of Great Britain, derived from environmentally distributed ecological network (EDEN) data. As multiple EDENs are established over the same regions, the rectification of multiple data sets makes it possible to compare the responses of different organisms and ecosystem parameters to different ecological drivers. In Great Britain, massive, parallel long-term studies have allowed researchers to track the changes of multiple ecological parameters over time. (a) Changes in the abundance of stinging nettle (Urtica dioica) from 1978 to 1998, documented by the Countryside Survey, have been associated with increases in fertility in uplands. (b) Increases in the comma butterfly (Polygonia c-album) from 1970 through 1982 and from 1995 through 1999 have been attributed to warming, but it should be noted that the butterfly also feeds on U. dioica. (c) General increases in roe deer (Capreolus capreolus) distributions from 1972 to the present are associated with expansion from geographically limited introductions. (d) Willow warblers (Phylloscopus trochilus) have increased in abundance from 1994 to 2003 in Scotland, while declining throughout much of Wales and England. Maps provided by (a) Simon Smart, Center for Ecology and Hydrology; (b) Butterfly Conservation and Center for Ecology and Hydrology; (c) Tracking Mammals Partnership (Ward 2005); and (d) Stuart Newson, British Trust for Ornithology.

cannot be ascribed to the lack of appropriate technology, as there are many organisms and ecosystem parameters that can be measured extensively with current technology. For example, there are no national efforts in the United States to survey small mammals, as there are in the United Kingdom; and no EDEN anywhere directly measures soil nitrogen availability, although that is a critical link in understanding the responses of ecosystems to global change factors such as elevated carbon dioxide (Luo et al. 2004).

Third, EDENs could advance through the coregistration (matching) of multiple drivers and responses (Smart et al. 2003). Coregistering data allows better rectification of patterns and facilitates the identification of ecological drivers. For example, linking patterns of atmospheric deposition, limnology, and paleolimnological reconstructions has yielded synergies in the United Kingdom when investigating atmospheric pollution of lakes. The UK Acid Waters Monitoring Network examined the effects of changes in deposition, measuring aquatic chemistry and biology in 11 lakes and 11 streams several times each year (Monteith and Evans 2005), but also pairing lake data with proxy records from sediment cores to extend records back 150 years (Battarbee et al. 2005). In another example, the Countryside Survey of Great Britain sampled plant species abundance in over 9000 plots stratified

by land class type, which included climate, topography, soils, and geology (Firbank et al. 2003, Smart et al. 2003, 2005).

Although coregistration of different types of field-collected data will continue to be important, recent advances in satellite and airborne remote sensing data have demonstrated the utility of marrying remote sensing with the "local sensing" provided by EDENs. Quantitative ecological and biogeochemical information can now be obtained from remotely sensed surface reflectivity and emissivity signatures (Wessman 1992, Schimel 1995). Remotely sensed data have the important properties of being both extensive and continuous over space and can therefore be compared against EDEN data. Three applications are apparent: (1) EDEN data can be used across a wide range of environments to validate model results based on remote sensing (e.g., to validate net primary production models using distributed eddy covariance flux towers; Turner et al. 2006). (2) Remote sensing data can be used to extend ecological parameters from distributed field sites to create continuous maps (e.g., forest canopy greenness can be related to bird species richness; Seto et al. 2004, Foody 2005). (3) Remote sensing can provide auxiliary data to help identify ecological drivers that cannot be, or are too expensive to be, measured in the field (e.g., the relationship between vegetation stability, measured using remote sensing, and biodiversity; Fjeldsa et al. 1997, Oindo 2002).

Finally, as data sets grow in extent and temporal span and as multiple data sets become coregistered, new statistical techniques need to be developed to analyze the data. New statistics are being developed to estimate population size better by coupling extensive and intensive surveys (Pollock et al. 2002). Geographical weighted regression has been developed to incorporate scale dependence and spatial nonstationarity in relationships between drivers and responses (Foody 2004). Similar techniques are needed to analyze spatial nonstationarity in time series.

With many options for directing distributed ecological research, modeling the future for EDENs after their present use in the United Kingdom would not be a bad goal. As a result of institutionalizing national EDENs and coordinating them at the highest level, the effects of habitat and climate change on multiple taxa (figure 2) and soil resources (Bellamy et al. 2005) are now better understood for the United Kingdom than for any other place on Earth. The economical use of volunteers provides benefits beyond inexpensive data collection: EDENs help to create an educated populace, and single-factor gradient approaches can evolve into more complex, multifactor distributed networks. The power of EDENs, like that of the supercomputers and distributed computing that have surpassed powerful individual mainframes, rests in their ability to be more extensive than intensive. Tapping this power in more places should be a critical goal for ecological research.

Acknowledgments

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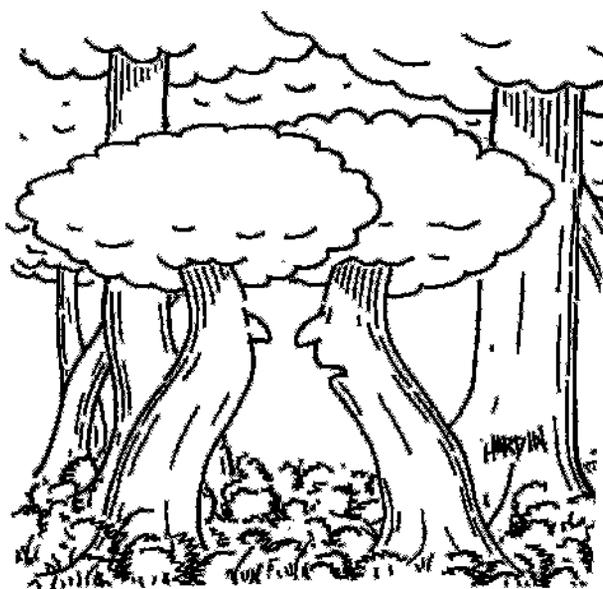
"I'm afraid I'll fall and no one will hear me."