Evolution of Collaboration within the US Long Term Ecological Research Network

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The US Long Term Ecological Research (LTER) program began in 1980 with the mission of addressing long-term ecological phenomena through research at individual sites, as well as comparative and synthetic activities among sites. We applied network science measures to assess how the LTER program has achieved its mission using intersite publications as the measure of collaboration. As it grew, the LTER program evolved from (a) a collection of independent sites (1981–1984) to (b) multiple ephemerally connected groupings with a gradual increase in collaboration (1985 to about 1998) to (c) a largely collaborative, densely connected network (from approximately 1999 on). Some sites demonstrated "preferential attachment" by contributing more to the evolution of network cohesion than others. Collaborative efforts of LTER scientists included cross-site measurements and comparisons, information technology transfer, documentation of methodologies, and synthesis of ecological concepts. Network science provides insights that not only document the evolution of research networks but also may be prescriptive of mechanisms to enhance this evolution.

Keywords: centrality, homophily, LTER, preferential attachment, social network analysis

A growing number of ecological programs around the world have been founded on the recognition that many ecological processes occur at, or are driven by, factors at long temporal and large spatial scales (e.g., the International Long Term Ecological Research Network; *http://ilternet.edu*). Networks of sites foster evaluation of processes at these large scales and comparison and synthesis of their patterns and responses (Callahan 1984, Hobbie et al. 2003). Formal association in a network is expected to promote standardization of activities and shared opportunities for common research; therefore, networks might begin as a loose aggregation of research sites but should evolve greater network cohesion as more cooperation and interdependence develop. Collaboration among sites within national programs should increase over time, and collaboration among national programs is ultimately expected to increase (Christian et al. 1999). Here we use tools of social network analysis (Borgatti et al. 2009) to assess the evolution of research cooperation among sites within one national program.

The US Long Term Ecological Research (LTER) Network, created by the National Science Foundation (NSF) in 1980 to encourage long-term and comparative research on ecological processes (Callahan 1984), has grown from 6 to 26 sites, and has added a central coordinating office (the LTER Network Office). The US LTER Network is the oldest such network (Gosz et al. 2010) and has perhaps had the most cumulative financial support of any national program. The program has produced more than 10,000 publications (Hobbie et al. 2003) that initially emphasized site findings; however, intersite collaboration has gradually become more central to the broader mission of the LTER program (USLTER 2007). Decadal reviews of the program have emphasized the importance of cross-site and networkwide collaboration and synthesis. Analyzing the evolution of the US LTER Network and correlative information has helped us isolate variables important for collaboration and those that may foster a cohesive and productive consortium.

Collaboration among scientists may take different forms, some of which are more easily tracked than others. Collaboration across sites may occur through simple communication and sharing of ideas; it may involve exchanges of scientists, students, or even equipment among sites. But collaboration and cooperation can be more easily tracked by the documents that arise from those activities, such as proposals or publications. Proposals, however, often are not tracked as effectively as publications. Moreover, publications are frequently a primary outcome of other forms of interaction, including joint proposals. Therefore, we have used joint publications among sites as the metric of collaboration; our analysis traces the annual patterns of publications by researchers within the LTER Network as grouped by the site.

We used social network analysis to assess patterns of cross-site publication. Social network analysis has become a valuable tool in the evaluation of social interactions among people and larger groupings (Borgatti et al. 2009), and it

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can provide insights into how groups of scientists, artists, and members of other vocations cooperate, and how traits of both individuals and groups promote or deter high levels of collaboration, functionality, and performance (Guimera et al. 2005). We applied both visualization and quantitative analysis techniques to describe the evolution of networks of collaboration, and attempted to understand involvement of the network principles of homophily ("birds of a feather flock together") and preferential attachment ("the rich get richer"; see box 1 for more detailed definitions.).

Organizing the database

Data used in this analysis were taken from the LTER all-site bibliography (*http://search.lternet.edu/biblio*), which is the best accounting of LTER publications between 1981 and 2006. The bibliography results from reporting by individual sites, rather than by authors; authors report at the site level. To ensure consistency among sites, we restricted the data from more than 15,000 citations to include only journal articles, edited book chapters, books, or conference proceedings. With this restriction, the data set contained more than 10,000 citations for 1122 unique authors from 25 LTER sites (the Moorea Coral Reef LTER had just been selected and was not included in the bibliography at the time of this analysis) and the LTER Network Office (table 1). These data were managed through identification of a particular publication, author, and site combination and each publication was assigned an accession number.

Difficulties in developing the final data set included duplicates from multisite reporting of joint publications, movement among sites by authors, authors affiliated with multiple sites, and the absence of author or affiliation information. To eliminate duplicates resulting from multisite reporting, we used a heuristic algorithm that compared publication year, journal, and first author, and we performed a weighted calculation of similarity in title. Each record classified as unique by this process was given a specific accession number. For each record, we made an effort to identify all authors within the LTER Network personnel database and link them individually to the unique publications in the resultant bibliographic data set. We contacted authors with a targeted Web application and encouraged them to verify their publications and identify at which site the work was done. About 500 of the 1122 authors responded. We manually verified highly published authors and known multisite authors. We visually scanned publication data for duplicates, and deleted many of them on the basis of similarity of title recorded by different LTER authors. Records for authors who we were unable to verify through the Web application were associated with their most recent site affiliation. A number of authors made the valid statement that they were "primarily" associated with more than one LTER sites; they verified their publications on the basis of where the work was performed and not where they were located. It is possible that individual authors were at LTER sites but left before the personnel database was constructed in the early 1990s; therefore, there may be cross-site papers that could not be identified from the existing author records.

Constructing and analyzing networks

We used UCINET (Analytic Technologies), a software program for social network data analysis. We use the vocabulary of network science in this article, and provide a glossary of social network science in box 1 for biologists unfamiliar with the lexicon. We organized the data into a series of annual, two-mode matrices of accession numbers (i.e., database publication number) along rows, and sites along columns. Network relations among LTER sites were produced by calculating the number of shared authors across sites for a given paper in a given year. This process yielded a series of annual one-mode affiliation networks that were visualized using Netdraw in UCINET with spring embedding

Box 1. Definitions for some social network terms.

Degree centrality: the number of edges a node has, or the number of nodes adjacent or directly attached to any given node. In this case, it represents the number of other Long Term Ecological Research (LTER) sites with coauthored publications to a site.

Density: the ratio of the number of observed dyadic (nodal pairs) connections in a network to the total number of possible dyadic connections. The density runs from 0, where no nodes are connected, to 1, where every node in the network is connected to every other node in the network. This is often referred to as connectance in network ecology.

Dichotomized matrix: a binary matrix (with one for any joint publication between sites and zero for none).

Edge: a line connecting two vertices or nodes in a network or graph. Edges can be valued (e.g., number of joint publications among LTER sites) or binary (e.g., presence or absence).

Homophily: the tendency of nodes in a network to associate with other nodes of a similar kind (i.e., "birds of a feather flock together"); in this case, the tendency of sites of similar ecosystem classes.

Networks over time: comparison of a series discrete networks over some time period.

Node: a vertex in a graph or network. It can be people, organizations, countries, species, and so on (individual LTER sites here).

Spring embedder: a series of algorithms for visualizing a network or graph in which the nodes are thought of as steel rings and the edges are thought of as springs in which the final visualized network involves mechanical forces of both attraction and repulsion. The goal is to minimize the overall distance between nodes.

Two-mode network: a two-mode network involves nodes in which the row entries are different from the column entries (e.g., LTER sites by publications). This differs from a one-mode network, where row and column entries are the same (e.g., LTER site by LTER site).

Table 1. US Long Term Ecological Research sites and information used for analysis of the evolution of the network of collaboration based on intersite, joint publications.

Site name and code	Site biome or ecosystem classification	Classification for homophily analysis (code)	Year site began	Publications used, including multisite	Number of years with high degree centrality
Coweeta (CWT)	Eastern deciduous forest	Forest	1980	567	7
HJ Andrews Experimental Forest (AND)	Temperate coniferous forest	Forest	1980	685	13
Konza Prairie Biological Station (KNZ)	Tallgrass prairie	Grassland and desert	1980	325	0
Niwot Ridge (NWT)	Alpine tundra	Landscape and lake	1980	344	4
North Temperate Lakes (NTL)	North temperate lakes	Landscape and lake	1980	484	2
Cedar Creek Ecosystem Science Reserve (CDR)	Oak savanna and tallgrass prairie	Grassland and desert	1981	52[a]	0
Jornada Basin (JRN)	Chihuahuan desert	Grassland and desert	1981	346	3
Short Grass Steppe (SGS)	Shortgrass steppe	Grassland and desert	1981	543	11
Bonanza Creek Experimental Forest (BNZ)	Taiga boreal forest and floodplain	Forest	1987	444	2
Hubbard Brook Experimental Forest (HBR)	Eastern deciduous forest	Forest	1987	780	9
Kellogg Biological Station (KBS)	Row-crop agriculture	Agricultural and temperate deciduous forest	1987	128	2
Virginia Coast Reserve (VCR)	Coastal barrier islands	Coastal marine	1987	266	2
Harvard Forest (HFR)	Eastern deciduous forest	Forest	1988	153	2
Luquillo Experimental Forest (LUQ)	Tropical rainforest	Forest	1988	509	7
Sevilleta National Wildlife Refuge (SEV)	Great Plains grassland, Chihuahuan Desert, Colorado Plateau shrub-steppe	Grassland and desert	1988	248	4
Arctic (ARC)	Arctic tundra and lakes	Landscape and lake	1988	270	11
Palmer Station (PAL)	Polar marine	Marine	1992	166	0
McMurdo Dry Valleys (MCM)	Polar desert	Landscape and lake	1993	72	0
Baltimore Ecosytems Study (BES)	Eastern deciduous forest and suburban	Urban and landscape	1997	141	0
Central Arizona – Phoenix (CAP)	Sonoran Desert scrub and urban	Urban and landscape	1997	148	1
Plum Island Ecosystems (PIE)	Atlantic coastal estuary	Coastal marine	1998	43	0
Florida Coastal Ecosystems (FCE)	Freshwater marsh and estuarine mangroves	Coastal marine	2000	120	0
Georgia Coastal Ecosystems (GCE)	Salt marsh and estuary	Coastal marine	2000	219	0
Santa Barbara Coastal (SBC)	Kelp forests, coastal ocean, and watersheds	Coastal marine	2000	12[a]	0
California Current Ecosystem (CCE)	Pacific pelagic coastal upwelling zone	Marine	2004	20	0
LTER Network Office (LNO)	Not applicable	Not applicable	1997	26	0

a. Not all data were available in the database at time of analysis.

(see box 1) to establish positions of nodes and edges in the visualization (Borgatti et al. 2002). We used two measures of network collaboration to characterize cross-site cooperation over time. The first was the number of network components in a given year (i.e., the number of sets of nodes [i.e., sites] in which each node can reach each other node on some path, no matter the length). If all sites can reach all other sites by some path, then the network forms a single network component.

The second measure we used was degree centrality, calculated by the number of other sites with which any particular site collaborates. There are several kinds of centrality used in social network analysis; all provide a measure of the importance or power of a node relative to other nodes. We use degree centrality as a measure of the importance of a site in the context of collaborations. To determine degree centrality, we converted interaction matrices to binary form, indicating that collaboration between two sites occurred, but not the number of coauthorships involved. The annual number of collaborating sites for each site represented the site's degree centrality. We then calculated the annual average degree centrality for each affiliation network across all of its sites.

We assessed homophily (the tendency for links to form between sites as a result of habitat similarity) that may promote cohesion within the collaboration networks. Homophily was assessed on an annual basis by testing the null hypothesis that like sites have no better probability of collaborating than unlike sites. Likeness was determined by the self-described site biome or the ecosystem classification, which we further aggregated using our knowledge of the research programs to reduce the number of possible classes (table 1). We applied the E-I index in UCINET for annual data (Borgatti et al. 2002). The E-I index reflects the comparison of the number of external (E, different classes) with internal (I, same class) coauthorships relative to the total number of possible coauthorships. It can range from -1 to $+1$, with -1 indicating complete homophily and $+1$ indexes complete heterophily. Comparisons of E-I indexes across networks are sensitive to several aspects of network structure. Therefore, we also controlled for the number of site types and density or connectance through E-I rescale to normalize the differences over time.

We assessed preferential attachment (i.e., the tendency for central nodes to accrue more ties as a network evolves, as in "the rich get richer") using degree centrality as described above. Degree centrality may reflect preferential attachment if sites with high centrality, or numerous collaborations, continue to maintain or increase collaborations as the network evolves. Using the binary form of annual matrices, we determined which three sites collaborated the most with others in each year. If more than three sites had similarly high degrees of centrality, more than three were included for that year. The result should represent the sites with the most potential for preferential attachment. This potential would be realized if a frequently central site during early years increased in frequency in later years. The percentage of years a site was in the top three for degree centrality was calculated for pre-2000 and from 2000 on. A high frequency of years with a high degree centrality indicates preferential attachment. Also, a larger percentage post-2000 than pre-2000 reflects evolution of greater preferential attachment over time.

Visualizing collaboration

We evaluated 26 graphs of the networks representing summaries of annual sums of publications by sites (figures 1 and 2). No cross-site publications were identified during the earliest years of the US LTER program (1981–1984), and therefore no networks are shown. The first year with cross-site publications was 1985 (its network is shown in figure 2; all subsequent years are represented in figure 1). In these figures and for all subsequent network analyses, each site within a network is a node represented by a circle. Coauthorship of a publication by scientists from two different sites is represented by a single line or "edge" connecting the two nodes. A publication coauthored by scientists from three different sites is represented by edges connecting each node to the others as a triad. Triads and larger polygons arise through the involvement of three or more sites, either through a single paper or through multiple papers. A component is a set of sites in which every site is connected to every other site by some path of collaborations. A component may be a single unconnected node (as isolated circles for 1985 in figure 2), or the entire group of nodes if they are all connected at least indirectly (e.g., 2003 in figure 2). Thicker lines correspond to more coauthorships between sites (i.e., line thickness proportional to the number of between-site coauthorships up to a maximum of five coauthorships). The evolution of collaboration is evident simply from tracking the time series of graphs in figure 1. It is easy to see how the network becomes more coherent. In the following section, we provide analysis of the evolution of network cohesion, and thereby site collaboration.

Here we highlight years representing significant changes in the pattern of collaboration. Evidence of cross-site collaboration appeared in 1985, when authors from three sites contributed to four joint intersite publications (figure 2). Ephemeral groupings of sites generally formed and disbanded from year to year during the following seven years (figure 1). For example, in 1992, 17 sites were involved in six components, of which three components had three or more collaborating sites (figure 2). The degree of collaboration expanded significantly over the next 11 years, and during the time between 2000 and 2006, all sites joined into single component networks in five of the seven years. The greatest amount of collaboration occurred in 2003, as demonstrated by the density of the network (figure 2). In that year, all sites were linked in a single component. The degree of collaboration remained high through 2006, the last year we analyzed. Thus, over 26 years, the research efforts of LTER scientists expanded from site-specific studies to the production of numerous intersite publications.

Intersite coauthorship can occur for a variety of reasons. We assume that the vast majority of collaborations result from some common scientific interest. However, we cannot rule out that social, financial, and even familial relationships affect

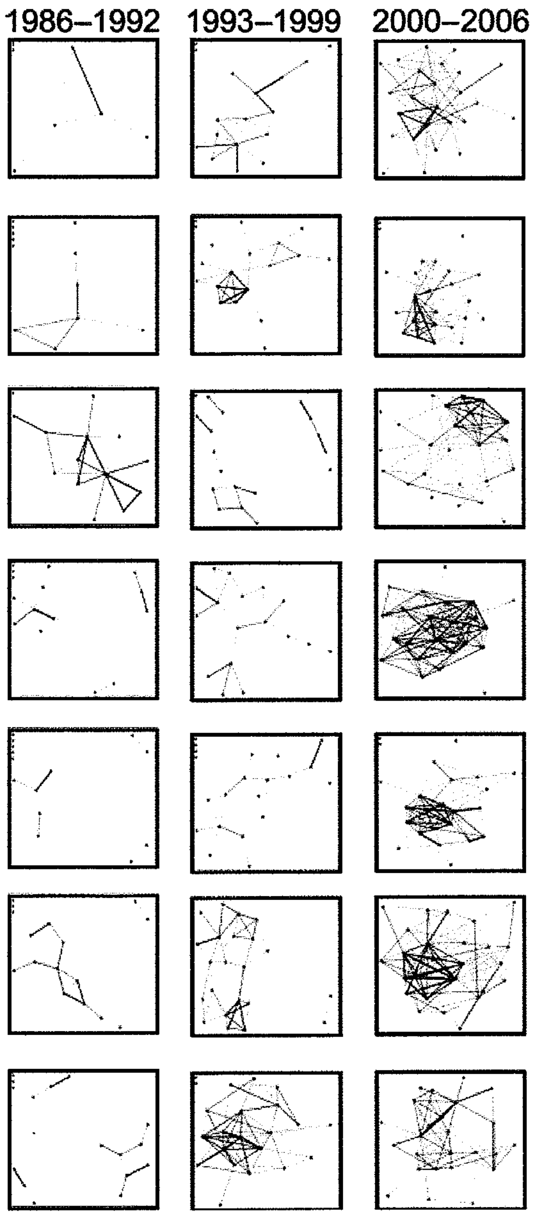

Figure 1. Evolution of the US Long Term Ecological Research Network from 1986–2006, as quantified through joint, intersite publications. Sites are represented as circles. Circles disconnected from others represent sites that reported no intersite publications during that year. Lines between sites correspond to publications coauthored by scientists at the connected sites. The width of lines is proportional to the number of coauthorships, up to a maximum of five.

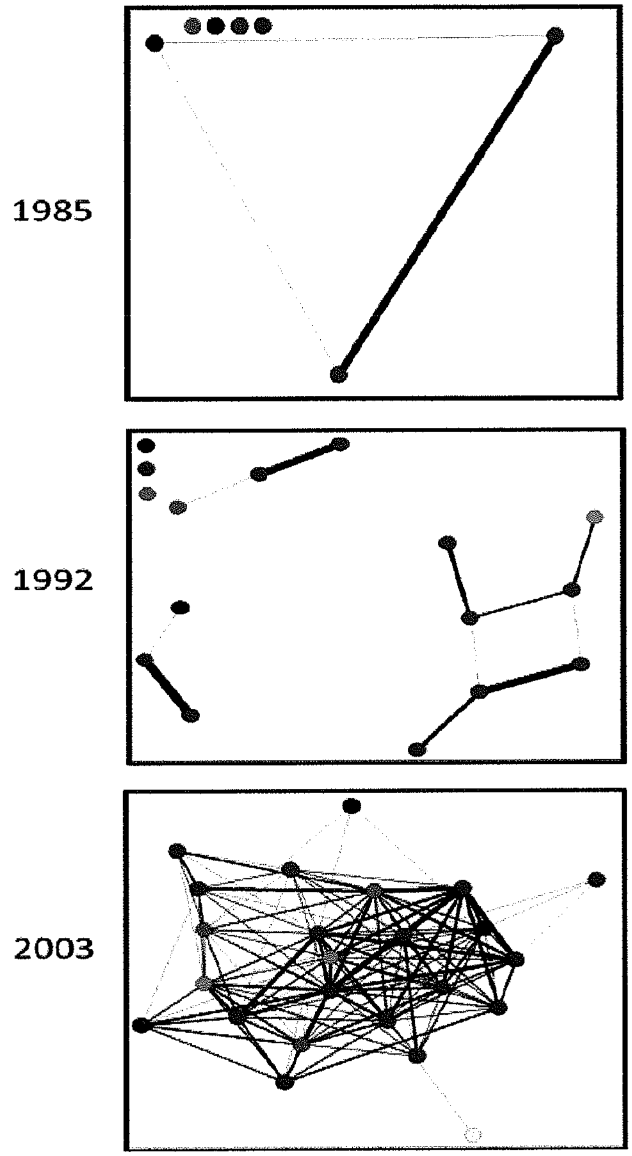

Figure 2. Graphs of three years (1985, 1992, and 2003) of significance within the evolution of collaboration in the US Long Term Ecological Research Network. Sites are represented as circles. Circles disconnected from others represent sites that reported no intersite publications during that year. Circle colors reflect classification of biome or ecosystem type (table 1). Lines between sites correspond to publications coauthored by scientists at the connected sites. The width of lines is proportional to the number of coauthorships, up to a maximum of five.

intersite coauthorships. Certain elements of the LTER mission promote intersite coauthorship: cross-site measurements and comparisons (Hobbie 2003, Redman and Foster 2008), information technology transfer (Porter et al. 2005, Brunt and Michener 2009), documentation of methodologies (Robertson et al. 1999, Greenland et al. 2003, Fahey and Knapp 2007), and synthesis of ecological concepts (Peters 2008).

Quantifying collaboration

Quantitative analyses support and extend the interpretations of the visualizations. We tracked the number of LTER sites (including the network office; see table 1) reporting their publications each year. The number of LTER sites also rose over this time (from six during the first year) and stabilized around the year 2000 (figure 2). The number of sites, including the

LTER Network Office, rose only from 25 to 27 after the year 2000, although the number of sites reporting their publications varied between 24 and 26 (in 2005). Components per site is a measure of the cohesion, or lack thereof, of the network, with a maximum value of 1 when every site is unconnected from others and no cohesion is evident. As values decrease below 1, cohesion increases. Before the first joint papers in 1985, each site appeared as a separate component in the analysis (figure 3). As the number of LTER sites increased in subsequent years, both the total number of separate components (not shown) and the mean number of components per site reporting declined. Interannual variability in the number of components and components per site was high from 1987 through 1993. The network cohesion strengthened, with less variation after 1993 as components per site often reached its minimum in years when the network formed a single component.

Mean degree centrality is another network measure of cohesion. Each site has a degree centrality determined as the number of other sites with which it has published coauthored publications. The annual means for all sites rose from zero in the early years of the network to consistently near or above six by 2000. Thus, as of 2000, each site had an average of six or more jointly authored publications with other sites. The highest mean degree of centrality occurred in 2003 (> 11). The LTER Network had developed a high level of cohesion by the turn of the century, but this development took 20 years.

Testing network principles

At least two fundamental network principles are potentially important in understanding the evolution of the network: homophily and preferential attachment. Homophily is the tendency toward interactions among similar site types, as in "birds of a feather flock together" (McPherson et al. 2001). Thus we might expect "grassland" and "desert" sites to have preferences for collaboration with other grassland and desert sites, and "forest" sites with "forest" sites, but we wouldn't necessarily expect

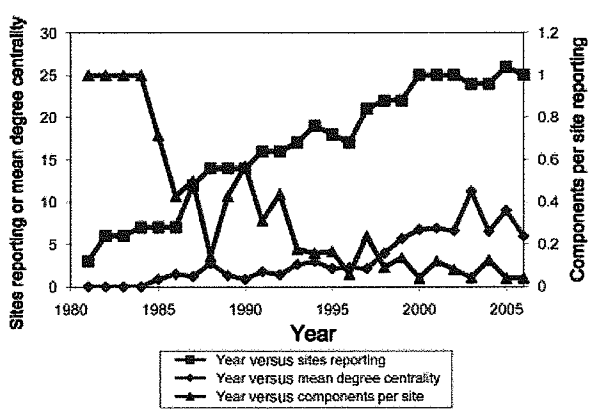

Figure 3. Time series of network attributes for the evolution of collaboration of the US Long Term Ecological Research Network: number of sites reporting (blue), mean degree centrality of sites (green), and number of network components per site (red).

collaborations across site type. The color of each circle within figure 2 refers to a category based on the dominant ecosystem type studied by that site (table 1), but the actual identities are not important for this exercise. Edges connecting like colors reflect homophily, but the majority of edges connect unlike colors (i.e., ecosystem type). Figure 4 shows changes in the E-I index over time, a specific test for homophily. Unexpectedly, homophily was not a dominant factor associated with annual collaborations, except once, in an analysis of the 26 years of the study period. The predominant tendency is toward heterophily even when controlling for site type size and site type density or connectance (i.e., E-I rescale). The only significant degree of homophily was observed in 2003. Although efforts to cluster sites of similar biome or ecosystem type during site selection within the LTER Network undoubtedly fostered collaboration, such clustering did not in fact dominate collaboration.

The second principle is preferential attachment. Preferential attachment refers to the tendency of sites that were frequently collaborative in early years to maintain or increase in importance over time (i.e., increase in degree). This is a characteristic of many "small world" networks (Buchanan 2002). Such networks have cohesion with relatively short path lengths among nodes, which could foster rapid exchanges of information within a research network. Some of the sites with the greatest longevity tended to dominate collaboration over time as measured by high site-specific degree centrality (table 1). This tendency may arise from either a preference of authors from newer sites to collaborate with authors from older sites, or movement of authors from old to new sites while maintaining collaborations. The latter would be expected as cohorts of previous graduate students or young professionals continue within the LTER Network. Six sites were among

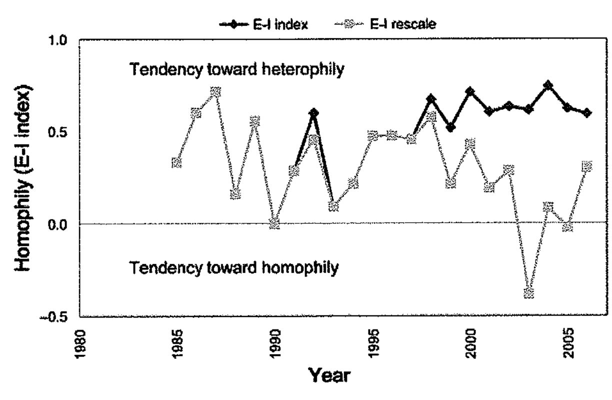

Figure 4. Evolution of homophily (E-I index) over time. Site categorization for this analysis is given in table 1. The E-I index reflects the comparison of the number of external to internal coauthorships relative to the total number of possible intersite coauthorships (which can range from 1 to –1, with –1 reflecting complete homophily; light gray line). When controlling for site type size (i.e., number of sites in a biome type) and site type density or connectance, the rescaled E-I index still shows a tendency toward heterophily, with the exception of one year (dark gray line).

the highest three sites for degree centrality during 6 or more of the 26 years of record (table 1). Two of them originated in 1980 (HJ Andrews Experimental Forest [AND] and Coweeta [CWT]), Short Grass Steppe (SGS) began in 1981, and the other three began in the late 1980s (Arctic [ARC], Hubbard Brook Experimental Forest [HBR], and Luquillo Experimental Forest [LUQ]). Thus, older sites tended to have higher degree than younger sites, but age did not guarantee high centrality. Seven other sites originating in the 1980s were less frequently (< 4 years) among the highest centralities. As shown in figure 5, the extent of collaboration by sites before 2000 significantly correlated with extent from 2000–2006 (r = 0.577, n = 25, p = 0.003). Most sites fell near the 1:1 line; but ARC had proportionally more collaborations after 1999, and HBR had considerably fewer. We cannot discern a reason why certain sites foster collaboration from our current efforts. Such a determination may require examination of lower hierarchical levels of organization involving author characteristics.

Examination of the fine-scale structure of each of the annual networks suggests that a few factors contributed significantly to the development of collaboration. For example, initial collaborations often developed between sites in close geographic proximity (e.g., Sevilleta [SEV]–Jornada [JRN] in New Mexico, ARC–Bonanza Creek [BNZ] in Alaska) before expanding to other sites. A group of US Forest Service experimental forests

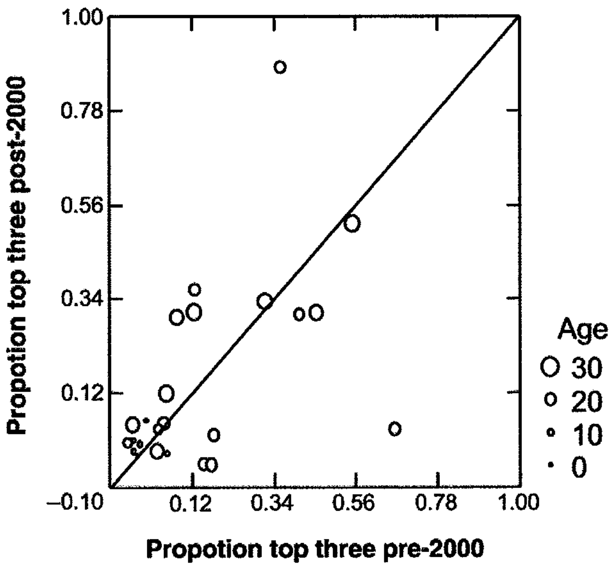

Figure 5. Comparison of the sites included in the top three degree centralities before and after 2000. Graph shows a scatter plot comparing the proportion of time each site was in the top three of ranked degree before 2000 (x-axis) and after 2000 (y-axis). If a site lies on the line, it represents no change from pre- to post-2000. Sites above the line reflect preferential attachment, or "the rich get richer," whereas sites below the line reflect sites that have lost degree over time. Site age is represented by circle size as a continuous variable. Circle sizes associated with different ages are shown under age.

(AND, BNZ, CWT, BNZ, LUQ) showed strong collaboration beginning in 1988, and this group of sites has maintained strong collaboration, with some annual variation, to the present. The association of individual investigators with more than one site can also encourage collaborative publications. For example, Plum Island Ecosystems (PIE) in Massachusetts has had a consistent link to ARC in Alaska since PIE joined the network in 1998. This consistent relationship stems from the fact that both LTER sites are managed from the same institution. Surprisingly, site type similarity did not play a statistically significant role in the evolution of the formation of coauthorships. We conjecture that this lack of a homophily effect on the basis of site type in fact may have allowed for a more rapid evolution of cooperation, ultimately leading to the high degree of cohesion in the 2000s. Homophily might actually promote multiple components or subgroups within the network, with each component or subgroup consisting of like sites.

Promoting cohesion

Other factors may have contributed to the development of interactions among LTER sites. A number of steps were taken by the LTER Network and the NSF to actively promote cohesion. During the 1990s, support specifically for cross-site research and synthesis became available briefly through the NSF. From 1990 on, triennial all-scientist meetings and annual meetings of the information managers from each site, funded by the NSF and organized by the LTER Network Office, encouraged cross-site interactions. And beginning in 2003, the LTER Network Office provided support for small research working groups specifically to address intersite research. These activities have often promoted two themes that build cohesion: information management and similarity of ecosystem processes. Information management and the communication of that information are essential components of a research network. This study, for example, could not have been completed without considerable effort in these areas. Although information management has been incorporated into the LTER design from the beginning (Callahan 1984), the emergence of a strong information management group beginning in 1990 has contributed to cohesion by creating a community of practice where trust has developed around technology transfer, development of standards and policies, and the design of a common data system. Combined, these efforts effectively lower the barriers for access to data in the network. The evolution of this group is illustrated by a time series beginning in 1994 of important information management publications describing network actvities (Stafford et al. 1994, Michener et al. 1997, Baker et al. 2000, San Gil et al. 2009) with authors from 3, 4, 6, and 27 sites, respectively.

Similarity of ecosystem processes has also been a fundamental tenet of the LTER Network, with establishment of core areas of study for all sites (e.g., primary production, trophic dynamics, organic matter accumulation, nutrient dynamics, and disturbance). These, rather than ecosystem classification, have often been the subject of sessions at triennial meetings, as well as workshops and joint proposals. The increased emphasis on integrating results from greater numbers of sites required the LTER Network to begin to address ecological principles fundamental to multiple sites, continental ecological gradients, and widespread environmental issues.

Learning to collaborate

The initial call for proposals for LTER sites issued in 1979 pointed out that "attention must be given to the tasks of assuring information comparability and inter-project coordination" (NSF 1979). Despite that early focus on intersite comparison, significant interactions among sites took more than 10 years to develop, and only in the last decade were all sites in the network involved. Part of that time was dedicated to efforts to learn how to collaborate and to incorporate integrative approaches into our preferred methods of doing science. In retrospect, certain steps would have promoted more rapid development of a functional network. We discuss some of these steps below to provide insight into how new synthetic networks could be constructed more effectively.

Changing the mindset. Most new participants in the collaborative network have been trained to conduct research as individuals or members of a laboratory directed by a single person. Moreover, individual accomplishment is the most important contributor to advancement in most academic settings. Thus, there is an initial tendency to think as an individual or as a member of a clan (site) rather than as a participant in a network, and this mindset takes time to evolve. Some members of the first LTER cohort resisted the concept of network coordination of research quite strongly at first, despite the fact that the importance of collaboration was at least implied in the first call for LTER proposals. Developing networks must have clear, well-understood expectations for collaboration that are apparent to groups seeking to join the network. Progress toward collaboration needs to be encouraged and reviewed from the beginning to ensure that all participants understand their responsibilities.

Characterizing new sites. Most sites, even well-established sites, require significant modifications or additions to research programs as the result of joining a network. In the case of LTER sites, this often involved the establishment of new measurements to address core areas or the extension of existing studies into new research sites. New LTER sites need to focus on getting their research programs established within three years to be ready for their first external review. Thus, intersite collaboration is often a secondary objective, at least initially. The need for an extended start-up period should be taken into account in the development of new networks.

Building capacity. New networks require time to build the capacity for collaboration. Part of this capacity building involves the development of trust; after all, new collaborators were competitors a short time ago. Capacity building also involves the coordination of ideas, approaches, and technology, and requires meetings, workshops, and training. Researchers need to make compromises among existing techniques and discuss and agree upon techniques for new measurements or analyses. The bigger the network, the more effort must be expended in these early discussions. For example, agreements reached between the initial six LTER sites had to be renegotiated when five new sites joined the network in the second year.

Funding intersite work. LTER research is funded through awards to sites, and it is therefore appropriate for sites to focus on their own research programs first. The lack of a clearly demarcated, consistent source of funding for networked research has hampered the development of intersite studies, since using resources for intersite studies diminishes the capacity to maintain existing long-term experiments and observations. As the LTER Network has matured, greater numbers of intersite studies have been facilitated by the development of long-term collaborations, by convergence of research approaches to common problems, and by leveraging LTER infrastructure to obtain other funding. However, the early establishment of a funding stream for intersite research would have stimulated collaboration without detriment to site research efforts. This is an important lesson for developing networks faced with the same tension between site and networked research.

Planning the network. The original conceptualization of the LTER program did not define common research goals or questions, and therefore did not provide criteria for the construction of a network. The first 11 LTER sites were selected through competitions that did not specify preferred ecosystem types, locations, or research themes; thus, the core group of sites included a broad range of ecosystems and conceptual approaches. Subsequent requests for proposals specified preferred types of ecosystems, but these preferences focused on broadening the number of ecosystems represented rather than building a network of sites that shared strong conceptual linkages. More recent competitions have added multiple sites in the same general kind of ecosystem (e.g., urban, coastal, marine) with similar conceptual underpinnings. In general, however, no rules were ever established for the assembly of a network of sites to meet specific research objectives. The network's current research objectives were established through identification of interests common to sites in the network as part of the process of self-evaluation. An earlier focus on network research might have accelerated the process of establishing collaborations, but it may have also detracted from individual successes by LTER sites.

Focusing research. The initial LTER competitions established five common research areas to be addressed by each site, and emphasized information comparability and interproject coordination. However, these core research areas were defined very broadly (see box 2), and soon lost relevance as a tool for providing a focus for cross-site research. Thus, although each site established strong local research initiatives in each of the core areas, the development of parallel network efforts took longer. The tendency to focus on site science was reinforced

Box 2. The five core research areas of Long Term Ecological Research sites.

1. Pattern and control of primary production
2. Dynamics of populations of organisms selected to represent trophic structure
3. Pattern and control of organic matter accumulation in surface layers and sediments
4. Patterns of inorganic inputs and movements of nutrients through soils, groundwater, and surface waters
5. Patterns and frequency of disturbances.

by the fact that individual LTER sites are selected, reviewed, and continued largely on the basis of the strength of their local science activities. Another approach that might have resulted in a more rapid development of collaborative efforts is the institution of specific common research questions rather than general research areas. The existence of such common questions could have resulted in parallel research efforts at sites and thus expedited collaborative science, while still maintaining individual creativity at sites. Such common questions might also have fostered quicker development of data standards and joint information-management approaches. As it is, the LTER Network has had to work hard to homogenize a broad range of data-management approaches that have been developed at individual sites.

Communicating. Collaboration among LTER sites and scientists has been enhanced by persistent efforts to provide opportunities for cross-site communication, principally through triennial all-scientist meetings. The first of these meetings took place in 1990 and 1993, and, after a hiatus, they started again in 2000. Personal experience tells us that these meetings strongly stimulate interaction and collaboration. Despite the success of these meetings, many people within the LTER Network feel that communication among sites and scientists needs further effort, that newsletters and Web pages aren't enough, and that video teleconferencing doesn't replace face-to-face interaction. As the LTER Network has grown, communication has become more important and more of a challenge.

The LTER Network recently completed a three-year self-analysis to formulate a research plan for the next 10 years that emphasizes synthesis of information across sites and throughout the network. By identifying common research themes that link LTER sites and scientists, this plan should provide additional stimulus for intersite research in the LTER Network and should also influence the structure of the social network that has developed among LTER sites. We anticipate the development of new relationships among sites as a result of common research ideas. One such initiative is "Integrative Science for Society and Environment," a program designed to integrate social science and other disciplines into site and LTER Network activities (Collins et al. 2007). Continuing studies of social networking within the LTER Network will allow us to track and understand these anticipated changes, and to examine in more detail the processes that create and maintain structure within this network.

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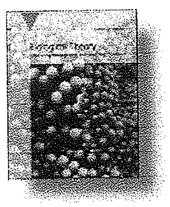

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