The Lotic Intersite Nitrogen Experiments: an example of successful ecological research collaboration

Author: collaborators, LINX

Source: Freshwater Science, 33(3) : 700-710

Published By: Society for Freshwater Science

URL: https://doi.org/10.1086/676938

The Lotic Intersite Nitrogen Experiments: an example of successful ecological research collaboration

LINX collaborators[1,2,3]

[1]Kansas State University, Manhattan, Kansas 66506 USA
[2]The LINX participants who collaborated on this manuscript are listed in the supplementary online materials

Abstract: Collaboration is an essential skill for modern ecologists because it brings together diverse expertise, viewpoints, and study systems. The Lotic Intersite Nitrogen eXperiments (LINX I and II), a 17-y research endeavor involving scores of early- to late-career stream ecologists, is an example of the benefits, challenges, and approaches of successful collaborative research in ecology. The scientific success of LINX reflected tangible attributes including clear scientific goals (hypothesis-driven research), coordinated research methods, a team of cooperative scientists, excellent leadership, extensive communication, and a philosophy of respect for input from all collaborators. Intangible aspects of the collaboration included camaraderie and strong team chemistry. LINX further benefited from being part of a discipline in which collaboration is a tradition, clear data-sharing and authorship guidelines, an approach that melded field experiments and modeling, and a shared collaborative goal in the form of a universal commitment to see the project and resulting data products through to completion.
Key words: collaboration, LINX, ecology, science, stream ecology, nitrogen dynamics

This contribution is dedicated to the memory of Patrick J. Mulholland (Fig. 1) in recognition of the leadership, mentoring, and friendship he provided to the LINX group and the collaborative spirit he championed.

The grand challenges in ecology and environmental science increasingly require interdisciplinary teams to perform complex, coordinated research across diverse locations. Here we share our insights from creating and sustaining 2 collaborative projects over 17 y: the Lotic Intersite Nitrogen eXperiments (LINX I and II, funded by the US National Science Foundation [NSF]). Authors of this paper have been involved in many other collaborative projects. Here, we address why these 2 collaborations were particularly successful.

Numerous authors have described how collaborative groups are more successful than individuals (Hong and Page 2004, Hall et al. 2012, Uzzi et al. 2013), how scientific groups can work together successfully (e.g., Cheruvelil et al., in press), and various structures of collaborative groups (O'Sullivan and Azeem 2007, Goring et al. 2014). Most of the research and suggestions from studies to date indicate that characteristics of successful collaborative teams include: 1) a diversity of researchers (Hong and Page 2004), 2) sensitivity to needs and enfranchisement of project participants at all levels (Goring et al. 2014), 3) good listening skills among group members (Thompson 2009), 4) development of the group process over time (Scott and Davis 2007, Thompson 2009), and 5) a willingness for individuals to bear a fair share of the costs of the collaboration (Goring et al. 2014). Our collaborative experiences in the LINX project are consistent with prior collaborative scientific research. Our success is built from a similar foundation of characteristics, as detailed herein.

The LINX collaboration joins many other excellent examples of successful collaboration, in disciplines ranging from mathematics to geography. Mathematicians and climatologists worked together to model ice movement and changes in ocean levels (Katsman et al. 2011). Relationships between land-surface and subsurface variability were quantified in permafrost environments using Light Detection and Ranging (LiDAR) technology and a surface geo-

E-mail address: [3]wkdodds@ksu.edu

*The PERSPECTIVES *section of the journal is for the expression of new ideas, points of view, and comments on topics of interest to aquatic scientists. The editorial board invites new and original papers as well as comments on items already published in Freshwater Science. Format and style may be less formal than conventional research papers; massive data sets are not appropriate. Speculation is welcome if it is likely to stimulate worthwhile discussion. Alternative points of view should be instructive rather than merely contradictory or argumentative. All submissions will receive the usual reviews and editorial assessments.*

DOI: 10.1086/676938. Received 02 April 2013; Accepted 07 January 2014; Published online 06 May 2014.
Freshwater Science. 2014. 33(3):700–710.

Figure 1. Patrick J. Mulholland (1952–2012), leader of the Lotic Intersite Nitrogen eXperiments (LINX).

physical data set (Zhang et al. 1999, Hubbard et al. 2013) through collaboration across the disciplines of hydrology, ecology, geography, and modeling. Collaboration between ecophysiologists and hydrologists addressed the fate of water use by vegetation (Brooks et al. 2009). A large cross-continent experiment on terrestrial nutrient enrichment (NUTNET) has provided broad and general results (Borer et al. 2014). Like LINX, these studies were able to address large-scale scientific questions by applying disciplinary expertise to interdisciplinary problems through focused collaborative effort.

Our goal is to describe the specifics of the LINX collaborations, with the hope that others can build on our concrete examples to guide and design their own collaborations. We quantify our tangible collaborative products, discuss the intangible benefits of working as a group, and describe the group characteristics that led to our success. This article is not intended as a basic contribution on the social science of collaborative research, but rather a self-analysis of what was successful in our case, with references to social-science research for interested readers (see supplementary materials for more project details). We avoid reporting history that retrospectively assigns inevitable progress and success, but think that our assessment of the past in light of the present has intrinsic value (Mayr 1990). We anticipate our analysis will be useful for researchers, particularly early-career investigators as they design new collaborative projects. Collaboration is increasingly necessary, as is exemplified by recent expansion of groups, such as National Ecological Observatory Network (NEON), Stream Experimental and Observational Network (STREON) embedded within NEON, and individual projects and cross-site initia tives in the Long Term Ecological Research (LTER) network. Recent funding opportunities requiring collaboration include NSF initiatives, such as LTER, Macrosystems Biology, Critical Zone Observatories, and Coupled Natural and Human Systems. These initiatives demand formation of large collaborative groups to obtain funding successfully and to carry out projects.

WHAT WAS LINX AND WHY DO WE CONSIDER IT SUCCESSFUL?

To our knowledge, the investigators who conducted LINX experiments were the first to characterize stream nutrient uptake and retention at the reach-scale across a wide array of biomes and land uses with consistent experimental methods. The LINX experiments were conceived to address questions about the role of stream ecosystems in processing and transforming N in roughly 0.2-km-long stream segments. The experiments, conducted across multiple North American biomes by regional teams, consisted of direct addition of a stable isotope (^{15}N) to streams using the same protocols at all sites. Results were synthesized within and across all sites, with models to quantify N uptake, transformation, and removal by streams.

The 1st experiment (LINX I) revealed the potential for small streams to assimilate, retain, and transform inorganic N. LINX I featured 6-wk additions of $^{15}N\text{-}NH_4^+$ to trace N uptake and cycling through stream food webs (Peterson et al. 2001). This experiment was conducted in 12 headwater streams draining catchments with predominantly native vegetation. LINX I demonstrated that small streams at baseflow retain, on average, 64% of terrestrial dissolved inorganic N inputs/stream km during biologically active seasons and, therefore, play a disproportionately large role in N transformations within fluvial networks (Peterson et al. 2001; Fig. 2A). LINX I also revealed the dynamics of N flow through aquatic food webs and the variable degree

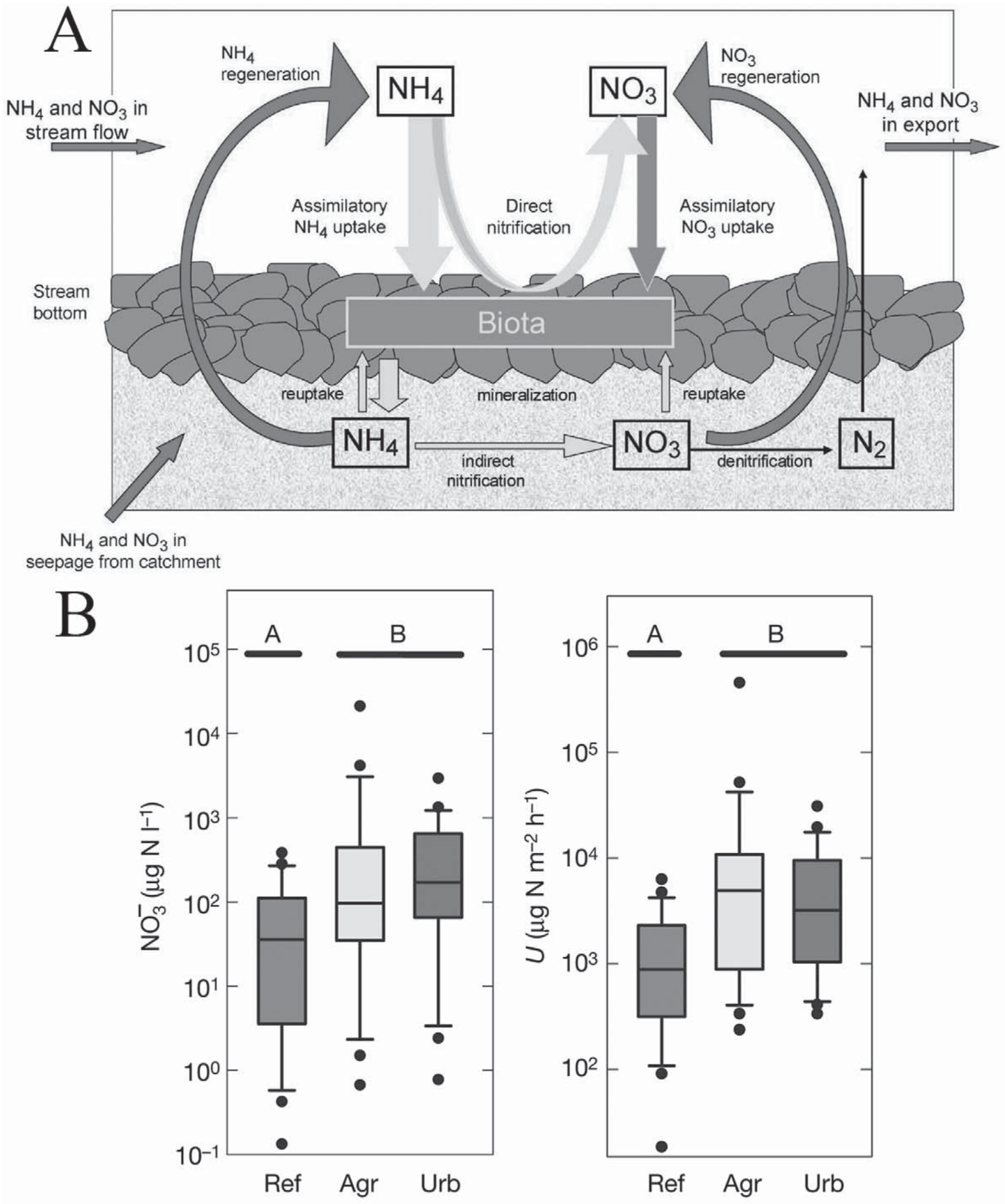

Figure 2. A.—The Lotic Intersite Nitrogen eXperiments (LINX) conceptual view of N dynamics in streams as mediated by benthic biota (courtesy of Science, from Peterson et al. 2001). B.—Major findings of the LINX II project (courtesy of Nature, from Mulholland et al. 2008), including streamwater NO_3^- concentrations (left) and total biotic NO_3^- uptake per unit area of streambed (U; right). Box plots display 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles, and individual data points outside the 10^{th} and 90^{th} percentiles. Land use had a significant effect on NO_3^- concentration (Kruskal–Wallis test, $p = 0.0055$) and U ($p = 0.0013$). Horizontal bars above plots labeled A or B denote significant differences determined by pairwise comparisons among landuse categories with Bonferroni correction ($\alpha = 0.05$). Ref = reference streams, Agr = agricultural, Urb = urban.

to which stream food webs depend on in-stream primary production.

The subsequent LINX II experiment focused on quantifying uptake and transformation of NO_3^- based on 24-h additions of $^{15}N\text{-}NO_3^-$ in 72 streams draining 3 landuse types (urban, agriculture, and native vegetation) in each of 8 regions (Mulholland et al. 2008). LINX II provided knowledge on the functional relationship between NO_3^- loading and uptake in streams draining catchments with varying land uses, including reach-scale measurements of denitrification in a wide variety of streams (Fig. 2B). Uptake and denitrification efficiency decrease with NO_3^- loading, which affects NO_3^- retention in downstream reaches of a stream network (Mulholland et al. 2008). LINX II also demonstrated that in-stream production and emission of the greenhouse gas N_2O (Beaulieu et al. 2011) are substantially greater than previously assumed in climate-change assessments by the Intergovernmental Panel on Climate Change. As human activities add more N to watersheds, LINX research has helped us understand the fate of some of this N across diverse stream types.

This paper began from group discussions on what made these collaborations successful. The 18 coauthors of this paper anonymously answered a questionnaire to quantify how many research projects in which they had been involved had ≥10 collaborators (with continued collaborations, such as LINX or LTER sites counting as a single collaboration). This self-reporting should be viewed with caution, but the results indicate that participants felt the collaboration was very successful. The number of collaborations in which respondents had participated ranged from 1–14 with a median of 5.5 collaborations. All but 2 respondents ranked LINX as the most successful collaboration of their career. The remaining 2 ranked LINX second. Success was defined based on productivity (see below), not camaraderie. Three senior researchers involved in ≥10 collaborative efforts all ranked LINX as the most productive.

We view LINX as a successful and productive collaboration for many reasons, including publications, future career opportunities, and training. The project has produced 74 peer-reviewed publications to date (Table 1; see supplemental information for complete bibliography), including a number of first-time continent-wide assessments of stream N biogeochemistry, nutrient limitation, and ecosystem metabolism. The most cited papers (Peterson et al. 2001, Mulholland et al. 2008) had received 565 and 281 citations, respectively, as of January 2014 (Web of Science; Thomson Reuters, New York) and are still accruing references. At least 10 of the LINX papers have each received >50 citations. Results have been cited in textbooks to exemplify the nutrient-spiraling concept and the critical role that streams play in N processing (e.g., Hauer and Lamberti 2006, Allan and Castillo 2007). The LINX field and laboratory protocols continue to be used worldwide to address complementary questions (e.g., Simon et al. 2007, von Schiller et al. 2009, Riis et al. 2012). LINX results have been incorporated into management plans for watershed-scale N mitigation. For example, the role of N transformation in small streams is recognized as important in mitigating hypoxia in the Gulf of Mexico (USEPA 2007). At regional scales, management plans have used LINX research to justify the protection of small streams to mitigate N pollution in drinking-water reservoirs (e.g., the Jordan Lake Rules; see Tetra Tech, Inc. 2003).

Table 1. Number of participants and research outputs from the Lotic Intersite Nitrogen eXperiments (LINX) I and LINX II collaborations to date.

Variable	LINX I	LINX II
Participants		
PhD scientists	31	23
Graduate students	38	41
Undergraduate students	22	41
Technicians	18	17
Nonprofessional volunteers	23	2
Total participants	132	124
Outputs		
Synthesis papers	8	8
Site-data papers	8	3
Other LINX-related papers	12	35
Theses and dissertations	7	11
Total peer-reviewed publications	28	46

Beyond the scientific contributions, successful outcomes of the LINX projects include new research collaborations, training, and education involving >130 individuals (Table 1). Partnerships initially developed in LINX spawned new research projects on topics, such as mechanisms of N retention and processing, nutrient spiraling in large rivers, and scaling stream processes up to the entire watershed. The group responsible for the design and development of the STReam Experimental Observatory Network (STREON), the aquatic component of the National Ecological Observatory Network (NEON), adopted LINX approaches to collaboration and the project was planned, in part, based on LINX results. Coordinated research networks on streams in Europe are also partially based on the LINX collaborative model (e.g., the STREAMES project of the European Union; http://www.pcb.ub.edu/streames/overview.htm).

LINX enhanced the training of graduate students and post-doctoral researchers (Table 1), and created a new group of highly collaborative scientists who are emerging leaders in the field. The LINX collaboration provided a springboard for the career trajectory of many graduate students and post-doctoral researchers, who have since started successful academic and research careers while continuing their collaborations with former LINX members. Participation in LINX during graduate school provided unique opportunities to work with prominent scientists across disciplines (stream ecology, ecosystem modeling, biogeochemistry, and hydrology) and to experience directly the leadership and team building required to collaborate successfully. Students and post-doctoral researchers also gained valuable training in science communication by contributing to multiple outreach products, ranging from high-impact, peer-reviewed papers to press releases and radio interviews.

In total, 79 graduate students (MS and PhD) participated in LINX. As metrics of accomplishment, students funded by LINX each received an advanced degree, collectively led authorship of >35 peer-reviewed papers, and have largely remained in science-related careers (~90% of former students). In addition, their experience with LINX created an informal network for career advice, friendly reviews, and grant collaborations. The value of the human resource achievements cannot be easily quantified.

HOW THE HISTORY OF STREAM ECOLOGY LAID THE GROUNDWORK FOR SUCCESSFUL COLLABORATION

Cross-site collaboration among stream ecologists began long before LINX, and this history fostered a culture for future collaboration. The International Biological Programme (IBP) established the idea that understanding ecology requires large-scale and cross-system ecological measurements. A propensity for collaboration among stream ecologists has its roots in 1974, when several stream ecologists from Coweeta Hydrologic Laboratory (North Carolina, USA) and H. J. Andrews Experimental Forest (Oregon, USA) met to discuss research coordination associated with the IBP. They began cross-site comparisons that ultimately resulted in the River Continuum Concept. In stream-ecology research, the River Continuum Project exemplified the disciplinary advancement and research productivity that can ensue from collaborative and synthetic cross-site comparisons (Vannote et al. 1980, Minshall et al. 1985).

Following the 1980 initiation of the LTER program, collaboration among stream researchers continued through a series of LTER-sponsored workshops and meetings, including data syntheses (e.g., Webster and Meyer 1997) and research coordination. The LTER network promoted cross-site and collaborative research, and consideration of the regional to continental context. Tri-annual LTER "all scientists' meetings" encouraged the formation of the LINX group (including the idea for the stream-modeling workshop described in the next section). The convivial evening gatherings at scientific meetings engaged new researchers, cultivating the excitement of collaboration among a new generation of stream ecologists.

The core theoretical underpinning of LINX research is the nutrient-spiraling concept, which links stream biological processes with hydrologic transport (Webster and Patten 1979, Newbold et al. 1981). Spiraling was first tested in whole streams using a radioisotopic P-tracer addition (e.g., Mulholland et al. 1985). The "Solute Dynamics in Stream Ecosystems" workshop, organized by Nick Aumen in 1989 and attended by many of the future LINX collaborators, introduced stream ecologists to hydrologists who had developed tools to model stream nutrient transport (Stream Solute Workshop 1990). Ken Bencala's presentation explored the relationship between the hydrologists' solute-transport models (Bencala 1984) and the stream ecologists' nutrient-spiraling models (Webster and Patten 1979, Newbold et al. 1981). This "aha moment" in the historical origins of the LINX collaboration illustrates how scientific progress often results from the juxtaposition of tools and concepts from diverse fields (Fisher 1997). Subsequently, the LINX projects investigated spiraling of NH_4^+, NO_3^-, organic N, and gaseous forms of N. In all phases of this work, we tried to link our measurements with hydrologic foundations (e.g., N uptake length [S_w] linked with hydraulic retention, subsurface area, and hydraulic uptake length; Webster et al. 2003).

PLANNING AND FINDING FUNDING FOR LINX

Following the All Scientist Meeting, Judy Meyer obtained NSF funding for a stream-modeling workshop that was the seed from which LINX I grew. At this hands-on, feet-wet workshop at Coweeta Experimental Forest in 1995 (Fig. 3A), participants collected samples, viewed demonstrations of methods to release biologically active and conservative tracers into streams, learned about data analysis for isotope-tracer experiments, and created site-specific predictive models of N dynamics based on isotopic tracers. Workshop participants and others developed the LINX I proposal to the NSF Ecosystem Studies program for just >US$1,000,000, in which they proposed to use these methods in coordinated experiments across the USA.

The success of LINX I led directly to the development of LINX II. LINX II moved beyond the use of a single reference stream in each biome to explore landuse influences on the fate of NO_3^- in streams. The LINX II research group evolved from LINX I, with junior LINX II principal investigators (PIs) recruited from LINX I students and postdocs, while simultaneously adding new students and postdocs to LINX II.

Denitrification was of particular interest in LINX II because it can mitigate downstream eutrophication. Thus, LINX II was based on 3 new ideas: 1) expanding the range of potential factors controlling in-stream N cycling, 2) increasing the diversity of stream types to include more variation in land use, and 3) quantifying denitrification at the stream-reach scale using whole-stream $^{15}N\text{-}NO_3^-$ tracer additions at 72 sites (Mulholland et al. 2004).

STRATEGIES FOR SUCCESSFUL COLLABORATION: WHY WAS LINX SUCCESSFUL?

A solid scientific foundation

A key factor in the success of both LINX projects was relevant, hypothesis-driven, and novel science. The research agendas appealed to a wide range of stream ecologists and to funding panels because they had both basic and applied significance. The novelty of the research ap-

Figure 3. A.—Preliminary group of collaborators at Coweeta Hydrologic Laboratory in 1995 that led to formation of the LINX I group. B.—Lotic Intersite Nitrogen eXperiments (LINX) II collaborators at a synthesis workshop at the Sevilleta long-term ecological research site (LTER) near the end of the experiment in November 2006.

proach, which included whole-stream ^{15}N-tracer experiments bolstered by other ecosystem measurements, a cross-site comparative design, and integration of modeling and empirical approaches, also added to its appeal.

Models played a central role in both planning and synthesis stages of LINX. The initial LINX workshop (1995) focused not only on field and analytical techniques but also on the parameterization of an initial model to simulate ^{15}N fluxes downstream and through stream food webs. That modeling was subsequently reevaluated and refined as results became available (Hall et al. 1998, Wollheim et al. 1999, Hamilton et al. 2004). Models also were important in examining the implications of LINX results beyond the experimental sites to include broader spatial domains (Peterson et al. 2001, Mulholland et al. 2008). Models showed that N cycling in small streams could regulate N export from catchments (Peterson et al. 2001). These stream network models indicated that increased N loading to small streams diminishes NO_3^- removal efficiency, leading to the propagation of N saturation from headwaters to downstream reaches through a stream network (Mulholland et al. 2008). LINX researchers also identified the limits of understanding that could be achieved using field ^{15}N-tracer experiments conducted only in small streams (Helton et al. 2011) and helped clarify the role of streams and rivers in contributing to global N_2O emissions (Beaulieu et al. 2011).

As with all projects, LINX I and II had areas that could have been improved. The LINX studies would have been better served by a priori planning for integrated data management, including allocation of funding for a data manager and the use of new tools for data sharing and version control. Only now is the LINX group working to make data available online. The LINX II project was funded a few years before this approach became a popular (or required) goal.

Also of concern in cross-site studies is comparability of laboratory methods, including precision and detection limits. For LINX I, all stable-isotope samples were analyzed by the Marine Biological Laboratory at Woods Hole, Massachusetts. For LINX II, interlaboratory comparisons of some particularly challenging analyses (e.g., ^{15}N tracer in dissolved N_2 and N_2O gases) revealed that samples sent to some contract laboratories were not analyzed with the needed accuracy and precision. These challenges led to new and improved analytical methods and the decision to use a single laboratory at Michigan State University for N_2 analyses (Hamilton and Ostrom 2007), but LINX II data would have been more robust had analytical issues been identified earlier in the project. This experience underscores the importance of submitting known blind samples to any contract laboratories early in the experiment.

Several aspects might have been improved by garnering additional expertise. Data management was lacking, and the procedure of trading spreadsheets was not optimal. An information manager would have helped make that process more efficient. Gas tracer measurements were done with propane, but we now recognize that sulfur hexafluoride is more stable and sensitive. Consultation with physical limnologists experienced with inert gaseous tracers could have improved our precision and accuracy of aeration measurements.

Many aspects could have been improved with more financial resources. For example, both experiments occurred at all sites during low-flow periods of greatest seasonal activity. More resources would have allowed us to run the experiments at different times of the year. Additional resources also would have allowed us to expand the number of comparative sites in LINX I.

Good leaders, collaborators, planning, and communication

Leadership is paramount to collaborative science. Both LINX projects were fortunate to have a seminal group of leaders who worked well together. The LINX I and II projects benefited from the strong leadership of 4 senior investigators, Jack Webster, Judy Meyer, Bruce Peterson, and Pat Mulholland. These accomplished researchers set the tone for a collaborative scientific group. However, the late Pat Mulholland (Fig. 1) played a key role in leadership by assuming many administrative duties and coordinating scientific discussion, particularly in the LINX II project. He exemplified a combination of scientific expertise, high standards, encouragement, patience, humor, and a willingness to invest time in project management that facilitated scientific communication. In the development of collaborative projects, effective communication is crucial (Thompson 2009). During our many extended meetings, from project design through final synthesis, Mulholland spotted and defused tension early on and brought out the best in the group, while motivating everyone and ensuring they were respected and treated justly. He did not lead aggressively, instead preferring to nudge participants to meet deadlines. Mulholland had only one hard line: a commitment to produce the very best science. He would accept nothing less.

The LINX participants were altruistic and willing to work hard to contribute to the project, but successful collaboration requires more than good intentions. The group included the strong personalities and viewpoints (and egos) characteristic of scientists. Many academic and research institutions encourage and reward competitive rather than collaborative behaviors. These and other factors made collaboration challenging, but the team established a productive group via leadership, developed a social norm of cooperation, and fostered open communication.

The project operated with a dispersed rather than a hierarchical structure (Goring et al. 2014), a successful model that has worked for other experimental ecological research groups (e.g., Borer et al. 2014) with each member of each research group providing input to experimental design and analysis. A dispersed project structure has some similarities to a "community of practice" (sensu O'Sullivan and Azeem 2007), wherein the group is self-organized and geographically dispersed, but individuals communicate regularly. The group could also be classified as a "participatory collaboration" (Shrum et al. 2007) in which members of the group belong to a single specialty and governance is egalitarian. A more detailed description of project structure can be found in the supplementary materials. This type of project structure worked well in LINX. All major decisions were made by group consensus, but that consensus could take some time to reach.

Willingness to meet for extended periods to work out details and wade through numerous e-mail discussions was essential. Extended meetings helped members learn particular methods, and address problems with approaches. A key point of contention was how many measurements should be added vs the time and money it took to make additional measurements. In a discussion of the idea that one 24-h measurement/stream at baseflow would be fairly specific to season and 1 flow condition, it became clear that we simply did not have the resources to cover multiple seasons and flow conditions and maintain spatial coverage. An additional example of this issue was the bihourly diurnal measurements in LINX II. Once we learned that minor information was added for an extended 24-h of sampling, the group agreed to curtail that work for the 2nd y. Many discussions were spirited, but scientific disagreement was not taken personally and was viewed as part of the process. A commitment to communication was needed because substantial e-mailing, document sharing, and meeting time were required at every step of both projects.

LINX researchers convened annually at North American Benthological Society (NABS) meetings to discuss future plans, present results, develop analytical approaches, and initiate synthesis efforts. Annual meetings were known for their camaraderie, and the atmosphere was welcoming for new scientists. These meetings were always open to any interested participants. The success of LINX also was enhanced by linkages to LTER sites; most LINX studies were on or near LTER sites where detailed, long-term site data and resources were leveraged.

The success of LINX I was enhanced by a "traveling postdoc", Jennifer Tank, who rotated among sites, coordinating with local PIs and graduate students to ensure execution of uniform experimental techniques and collection of consistent, high-quality data. Her technical proficiency, organization, interpersonal skills, positive outlook, and ability to work with many different personality types were critical.

LINX II involved 72 sites, and this traveling postdoc model was not feasible. Instead, building on experience gained from LINX I, more time and resources were invested in writing a detailed manual of methods via a series of group workshops. The final product explained clear, consensus-driven protocols that would work across many stream types and were linked to the key hypotheses. Any modifications in protocols made during the experiment were cleared with the whole group and this topic dominated mid-project group meetings. Investigators at individual sites also were encouraged to develop supplementary measurements or metrics to understand local patterns, which they then shared with the group for potential adoption project wide.

Intangible factors enhanced project success. The first workshop set a tone of equality and respect among early-career and established researchers. The opinions and ideas of early-career researchers were welcomed, and their involvement in central aspects of the collaboration was essential. In LINX II, early-career scientists were lead authors of several synthesis papers (e.g., Johnson et al. 2009, Bernot et al. 2010, Beaulieu et al. 2011, Helton et al. 2011). Frequent conversations via an e-mail LISTSERV maintained lines of communication between meetings.

Lively discussions among all participants, impromptu data presentations, and informal opportunities for learning characterized the numerous planning and synthesis meetings. For example, Bob Hall introduced structural equation modeling to the group, providing us with a new tool that allowed exploration of cause and effect using experimental data from our complex systems (e.g., Hall et al. 2009, Bernot et al. 2010). In addition, the 1st y of LINX II data showed that existing methods for detecting tracer ^{15}N in N_2 at low concentrations were inadequate. New methods were developed and reported at LINX meetings prior to their publication (Hamilton and Ostrom 2007). These 2 examples of early adoption of new methods illustrate the need for ongoing communication, that early-career researchers often have important ideas to contribute, and that adaptive research approaches are necessary in large collaborative projects.

Clear definition of roles and responsibilities

Disagreements about authorship and data sharing can plague collaborations and are best prevented through openness, transparency, and advanced planning. Policies for data sharing and authorship in LINX were thoroughly vetted among participants early in the collaboration (Table 2), and presentation, publication, and authorship ideas were discussed before the work began. This early investment in potential problem solving is a key to maintaining long-term positive communication within a collaborative group (Thompson 2009). A number of our subsequent projects and others have adopted the LINX data sharing and authorship agreement as a template for their own projects. The LINX policy defined expectations for lead authors and supporting authors, the obligations of lead authors to provide ample time and opportunity for supporting authors to contribute in meaningful ways, and the obligations of supporting authors to provide substantive input and feedback. These policies were discussed and reevaluated regularly and used as guide for the sharing of unpublished data with other investigators.

CONCLUSION

The LINX team structure was built upon a strong foundation of existing interpersonal relationships and led to a social norm of cooperation among participants. This more-horizontal (as opposed to hierarchical) structure relied on regular communication and transparency, while addressing issues of recognition and authorship in a forthright consensus-driven manner, which was characterized by respect for all participants without regard to rank. The LINX team was fortunate to have drawn in collaborators who made up such a collegial team, and even more fortunate to have had one of the central leaders, Pat Mulholland, who always promoted and worked hard to facilitate scientific progress within the group. Ideas, hypotheses, and techniques were developed through a process of collaborative brainstorming and intense vetting, made possible because the LINX team enjoyed a certainty that these ideas, and the data collected, would be shared. These intangible aspects of the LINX collaboration were critical to fostering

Table 2. Summary of Lotic Intersite Nitrogen eXperiments (LINX) publication policies based on LINX II June 2006 version (complete text available in the Supplementary Materials). PI = principal investigator.

Aspect	Policy
Site papers	Each site has control over its own data and its publication. No limitations on when publications can be submitted.
	If data from other sites are used, then offer coauthorship opportunity to ≥1 person from that site.
	If a synthesis analysis is used in a site paper in any significant way, then the synthesis leader should be a coauthor.
Synthesis papers	Synthesis papers will not be submitted for publication prior to 1 January 2007 (~1 y after all experiments are complete) unless there is a specific need and all project PIs and coPIs are in agreement.
	All sites will attempt to have raw data submitted to the data management system for all releases within 6 mo of their last ^{15}N release (i.e., by 1 August 2006).
	There will be ≥1 coauthorship offered to each site (in some cases ≥2 may be appropriate) on all synthesis papers that use data from that site. It is expected that all coauthors will comment on each manuscript or contribute in some fashion in addition to allowing their site's data to be used.
	Topics and authorship of all synthesis papers will be discussed with all project PIs and coPIs prior to substantial amounts of writing (preferably at a project meeting) and consensus agreement should be reached.
	At a minimum, approximate paper title, tentative coauthor list, and a few sentences on scope and data used will be sent to all project PIs and coPIs for discussion and agreement prior to writing the paper.
All papers	A copy of all papers (site and synthesis) should be sent for comment to all project PIs and coPIs prior to submission to a journal. Comment period is limited to a maximum of 3 wk for site papers and 2 mo for synthesis papers.
Talk abstracts	Abstracts for talks and posters also should follow the guidelines above, except that purely site papers need not be sent to the entire project group for comment prior to submission and the review period for synthesis abstracts by all project PIs and coPIs is only 1 wk.
Accepting authorship offers	Did I make an intellectual contribution to the topics covered in the paper?
	Did I participate in preparing the paper by writing or providing substantive input (extensive comments, figures, etc.)?
	Can I explain and or defend the methods and results in the paper?

trust and strong interpersonal relationships, which in turn allowed ideas to flourish and a true synergy of effort and expertise to emerge. The organizational structure, communication model, and leadership style of the LINX collaboration were not novel among potential group approaches to collaboration, but we think that this combination was critical to the success of LINX, and would be ideal for many other groups. The lesson learned is that scientific collaboration can be one of the most intellectually and personally fulfilling avenues to success in ecological research.

ACKNOWLEDGEMENTS

We thank all LINX participants, including undergraduates and technicians, for their hard work and dedication. We thank the US National Science Foundation for funding the LINX grants and the LTER grants that provided logistical support, the numerous federal, state, and private landowners who provided site access, and the LINX universities and institutes that provided additional support and facilities.

LITERATURE CITED

Allan, J. D., and M. M. Castillo. 2007. Stream ecology: structure and function of running waters. Springer, Dordrecht, The Netherlands.

Beaulieu, J. J., J. L. Tank, S. K. Hamilton, W. M. Wollheim, R. O. Hall, P. J. Mulholland, B. J. Peterson, L. R. Ashkenas, L. W. Cooper, C. N. Dahm, W. K. Dodds, N. B. Grimm, S. L. Johnson, W. H. McDowell, G. C. Poole, H. M. Valett, C. P. Arango, M. J. Bernot, A. J. Burgin, C. L. Crenshaw, A. M. Helton, L. T. Johnson, J. M. O'Brien, J. D. Potter, R. W. Sheibley, D. J. Sobota, and S. M. Thomas. 2011. Nitrous oxide emission from denitrification in stream and river networks. Proceedings of the National Academy of Sciences of the United States of America 108:214–219.

Bencala, K. E. 1984. Interactions of solutes and streambed sediment: 2. A dynamic analysis of coupled hydrologic and chemical processes that determine solute transport. Water Resources Research 20:1804–1814.

Bernot, M. J., D. J. Sobota, R. O. Hall, P. J. Mulholland, W. K. Dodds, J. R. Webster, J. L. Tank, L. R. Ashkenas, L. W. Cooper, C. N. Dahm, S. V. Gregory, N. B. Grimm, S. K. Hamilton, S. L. Johnson, W. H. McDowell, J. L. Meyer, B. J. Peterson, G. C. Poole, H. M. Valett, C. Arango, J. J. Beaulieu, A. J. Burgin, C. L. Crenshaw, A. M. Helton, L. T. Johnson, J. L. Merriam, B. R. Niederlehner, J. M. O'Brien, J. D. Potter, R. W. Sheibley, S. M. Thomas, and K. Wilson. 2010. Land use homogenizes stream ecosystem function: inter-regional comparison of land-use effects on whole-stream metabolism. Freshwater Biology 55:1874–1890.

Borer, E. T., W. S. Harpole, P. B. Adler, E. M. Lind, J. L. Orrock, E. W. Seabloom, and M. D. Smith. 2014. Finding generality in ecology: a model for globally distributed experiments. Methods in Ecology and Evolution 5:65–73.

Brooks, J. R., H. R. Barnard, R. Coulombe, and J. J. McDonnell. 2009. Ecohydrologic separation of water between trees and streams in a Mediterranean climate. Nature Geoscience 3: 100–103.

Cheruvelil, K. S., P. A. Soranno, K. C. Weathers, P. C. Hanson, and S. Goring. Creating and maintaining high-performing collaborative research teams: the importance of diversity and socio-cognitive skills. Frontiers in Ecology and the Environment (in press).

Fisher, S. G. 1997. Creativity, idea generation, and the functional morphology of streams. Journal of the North American Benthological Society 16:305–318.

Goring, S., K. C. Weathers, W. K. Dodds, P. A. Soranno, L. C. Sweet, K. S. Cheruvelil, J. S. Kominski, J. Rüeggm, A. M. Thorn, and R. M. Utz. 2014. Improving the culture of interdisciplinary collaboration in ecology by expanding measures of success. Frontiers in Ecology and the Environment 12:39–47.

Hall, K. L., D. Stokols, B. A. Stipelman, A. L. Vogel, A. Feng, B. Masimore, G. Morgan, R. P. Moser, S. E. Marcus, and D. Berrigan. 2012. Assessing the value of team science: a study comparing center- and investigator-initiated grants. American Journal of Preventive Medicine 42:157–163.

Hall, R. O., B. J. Peterson, and J. L. Meyer. 1998. Testing a nitrogen cycling model of a forest stream by using a nitrogen-15 tracer addition. Ecosystems 1:283–298.

Hall, R. O., J. L. Tank, D. J. Sobota, P. J. Mulholland, J. M. O'Brien, W. K. Dodds, J. R. Webster, H. M. Valett, G. C. Poole, B. J. Peterson, J. L. Meyer, W. H. McDowell, S. L. Johnson, S. K. Hamilton, N. B. Grimm, S. B. Gregory, C. N. Dahm, L. W. Cooper, L. R. Ashkenas, S. M. Thomas, R. W. Sheibley, J. D. Potter, B. R. Neiderlehner, L. T. Johnson, A. M. Helton, C. L. Crenshaw, A. J. Burgin, M. J. Bernot, J. J. Beaulieu, and C. P. Arango. 2009. Nitrate removal in stream ecosystems measured by ^{15}N addition experiments: total uptake. Limnology and Oceanography 54:653–665.

Hamilton, S. K., and N. E. Ostrom 2007. Measurement of the stable isotope ratio of dissolved N_2 in ^{15}N tracer experiments. Limnology and Oceanography: Methods 5:233–240.

Hamilton, S. K., J. L. Tank, D. F. Raikow, E. Siler, N. J. Dorn, 1and N. Leonard. 2004. The role of instream vs allochthonous N in stream food webs: modeling the results of a nitrogen isotope addition experiment. Journal of the North American Benthological Society 23:429–448.

Hauer, F. R., and G. A. Lamberti (editors). 2006. Methods in stream ecology. Academic Press, New York.

Helton, A. M., G. C. Poole, J. L. Meyer, W. M. Wollheim, B. J. Peterson, P. J. Mulholland, E. S. Bernhardt, J. A. Stanford, C. Arango, L. R. Ashkenas, L. W. Cooper, W. K. Dodds, S. V. Gregory, R. O. Hall, S. K. Hamilton, S. L. Johnson, W. H. McDowell, J. D. Potter, J. L. Tank, S. M. Thomas, H. M. Valett, J. R. Webster, and L. H. Zeglin. 2011. Thinking outside the channel: modeling nitrogen cycling in networked river ecosystems. Frontiers in Ecology and the Environment 9:229–238.

Hong, L., and S. E. Page. 2004. Groups of diverse problem solvers can outperform groups of high-ability problem solvers. Proceedings of the National Academy of Sciences of the United States of America 101:16385–16389.

Hubbard, S. S., C. Gangodagamage, B. Dafflon, H. Wainwright, J. E. Peterson, A. Gusmeroli, C. Ulrich, Y. Wu, C. Wilson, J. Rowland, C. Tweedie, and S. D. Wullschleger. 2013. Quantifying and relating land-surface and subsurface variability in permafrost environments using LiDAR and surface geophysical datasets. Hydrogeology Journal 21:129–149.

Johnson, L. T., J. L. Tank, and W. K. Dodds. 2009. The influence of land use on stream biofilm nutrient limitation across eight North American ecoregions. Canadian Journal of Fisheries and Aquatic Sciences 66:1081–1094.

Katsman, C. A., A. Sterl, J. J. Beersma, H. W. van den Brink, J. A. Church, W. Hazeleger, and R. Weisse. 2011. Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta—the Netherlands as an example. Climatic Change 109:617–645.

Mayr, E. 1990. When is historiography whiggish? Journal of the History of Ideas 51:301–309.

Minshall, G. W., K. W. Cummins, R. C. Petersen, C. E. Cushing, D. A. Bruns, J. R. Sedell, and R. L. Vannote. 1985. Developments in stream ecosystem theory. Canadian Journal of Fisheries and Aquatic Sciences 42:1045–1055.

Mulholland, P. J., A. M. Helton, G. C. Poole, R. O. Hall, S. K. Hamilton, B. J. Peterson, J. L. Tank, L. R. Ashkenas, L. W. Cooper, C. N. Dahm, W. K. Dodds, S. Findlay, S. V. Gregory, N. B. Grimm, S. L. Johnson, W. H. McDowell, J. L. Meyer, H. M. Valett, J. R. Webster, C. Arango, J. J. Beaulieu, M. J. Bernot, A. J. Burgin, C. L. Crenshaw, L. Johnson, J. Merriam, B. R. Niederlehner, J. M. O'Brien, J. D. Potter, R. W. Sheibley, D. J. Sobota, and S. M. Thomas. 2008. Stream denitrification across biomes and its response to anthropogenic nitrate loading. 2008. Nature 452:202–205.

Mulholland, P. J., J. D. Newbold, J. W. Elwood, L. A. Ferren, and J. R. Webster. 1985. Phosphorus spiraling in a woodland stream: seasonal variations. Ecology 66:1012–1023.

Mulholland, P. J., H. M. Valett, J. R. Webster, S. A. Thomas, L. W. Cooper, S. K. Hamilton, and B. J. Peterson. 2004. Stream denitrification and total nitrate uptake rates measured using a field ^{15}N tracer addition approach. Limnology and Oceanography 49:809–820.

Newbold, J. D., J. W. Elwood, R. V. O'Neil, and W. Van Winkle. 1981. Measuring nutrient spiraling in streams. Canadian Journal of Fisheries and Aquatic Sciences 38:860–863.

O'Sullivan, K. J., and S. W. Azeem. 2007. An analysis of collaborative group structure technological facilitation from knowledge and management perspectives. Electronic Journal of Knowledge Management 5:223–230.

Peterson, B. J., W. M. Wollheim, P. J. Mulholland, J. R. Webster, J. L. Meyer, J. L. Tank, E. Martí, W. B. Bowden, H. M. Valett, A. E. Hershey, W. H. McDowell, W. K. Dodds, S. K. Hamilton, S. V. Gregory, and D. D. Morrall. 2001. Control of nitrogen export from watersheds by headwater streams. Science 292: 86–90.

Riis, T., W. K. Dodds, P. B. Kristensen, and J. Baisner. 2012. Nitrogen cycling and dynamics in a macrophyte-rich stream as determined by a $^{15}N\text{-}NH_4^+$ release. Freshwater Biology 57: 1579–1591.

Scott, W. R., and G. F. Davis. 2007. Organizations and organizing: rational, natural, and open systems perspectives. Pearson, Prentice and Hall, Upper Saddle River, New Jersey.

Shrum, W., J. Genuth, and I. Chompalov. 2007. Structures of scientific collaboration. MIT Press, Cambridge, Massachusetts.

Simon, K. S., D. K. Niyogi, R. D. Frew, and C. R. Townsend. 2007. Nitrogen dynamics in grassland streams along a gradient of agricultural development. Limnology and Oceanography 52:1246–1257.

Stream Solute Workshop. 1990. Concepts and methods for assessing solute dynamics in stream ecosystems. Journal of the North American Benthological Society 9:95–119.

Tetra Tech, Inc. 2003. B. Everett Jordan Lake TMDL Watershed Model Development. Contract Number EW030318, Project Number 1-2. North Carolina Department of Environment and Natural Resources, Raleigh, North Carolina. (Available from: http://portal.ncdenr.org/web/jordanlake/7)

Thompson, J. L. 2009. Building collective communication competence in interdisciplinary research teams. Journal of Applied Communication Research 37:278–297.

USEPA (US Environmental Protection Agency). 2007. Hypoxia in the northern Gulf of Mexico: an update by the EPA Science Advisory Board. EPA-SAB-08-004. US Environmental Protection Agency, Washington, DC.

Uzzi, B., S. Mukherjee, M. Stringer, and B. Jones. 2013. Atypical combinations and scientific impact. Science 342:468–472.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130–137.

von Schiller, D., E. Martí, and J. L. Riera. 2009. Nitrate retention and removal in Mediterranean streams bordered by contrasting land uses: a ^{15}N tracer study. Biogeosciences 6: 181–196.

Webster, J. R., and J. L. Meyer. 1997. Stream organic matter budgets: an introduction. Journal of the North American Benthological Society 16:3–4.

Webster, J. R., P. J. Mulholland, J. L. Tank, H. M. Valett, W. K. Dodds, B. J. Peterson, W. B. Bowden, C. N. Dahm, S. Findlay, S. V. Gregory, N. B. Grimm, S. K. Hamilton, S. L. Johnson, E. Martí, W. H. McDowell, J. L. Meyer, D. D. Morrall, S. A. Thomas, and W. M. Wollheim. 2003. Factors affecting ammonium uptake in streams—an inter-biome perspective. Freshwater Biology 48:1329–1352.

Webster, J. R., and B. C. Patten. 1979. Effects of watershed perturbation on stream potassium and calcium dynamics. Ecological Monographs 49:51–72.

Wollheim, W. M., B. J. Peterson, L. A. Deegan, M. Bahr, J. E. Hobbie, D. Jones, W. B. Bowden, A. E. Hershey, G. W. Kling, and M. C. Miller. 1999. A coupled field and modeling approach for the analysis of nitrogen cycling in streams. Journal of the North American Benthological Society 18:199–221.

Zhang, T., R. G. Barry, K. Knowles, J. A. Heginbottom, and J. Brown. 1999. Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere. Polar Geography 23:132–154.