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COMMUNICATION

A model for training undergraduate students in collaborative science

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Abstract

Engagement of undergraduate students in research has been demonstrated to correlate with improved academic performance and retention. Research experience confers many benefits on participants, particularly foundational skills necessary for graduate school and careers in scientific disciplines. Undergraduate curricula often do not adequately develop collaborative skills that are becoming increasingly useful in many workplaces and research settings. Here, we describe a pilot program that engages undergraduates in research and incorporates learning objectives designed to develop and enhance collaborative techniques and skills in team science that are not typical outcomes of the undergraduate research experience. We conducted a collaborative science project that engaged faculty advisors and upper year undergraduates at four institutions and conducted a review to assess the program's efficacy. Students developed a broad suite of competencies related to collaborative science, above and beyond the experience of completing individual projects. This model also affords distinct advantages to faculty advisors, including the capacity of the network to collect and synthesize data from different regions. The model for training students to conduct collaborative science at an early stage of their career is scalable and adaptable to a wide range of fields. We provide recommendations for refining and implementing this model in other contexts.

Key words: communication, collaborative science, inter-personal skills, networks, numeracy, skill development, undergraduate research

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Introduction

Research experience is a valuable and widespread component of undergraduate science education contributing positively to academic performance (Zydney et al. 2002) and resulting in greater participation in research activities following the first degree, particularly through increased enrollment in graduate school (Lopatto 2004; Russell et al. 2007; Eagan et al. 2013). It is common for undergraduate science programs in North America to culminate in a research project such as an Honours thesis or capstone project. Such projects typically aim to develop foundational skills necessary for conducting research or working in a science-focused career, including intellectual, practical, communication, numeracy, and interpersonal skills (Table 1). These skills are valued by employers and graduate

Table 1. Skills typically developed as part of a typical Honours thesis or research course project (adapted from Finn and Crook 2003), and additional skill development for collaborative science possible through the LUGNuts model.

	Typical one-on-one supervisory model		Collaborative model	
Skill type	Learning objective	Activity	Learning objective	Activity
Intellectual	T1	Define research questions and devise and evaluate approaches to answering them	C1	Develop skills for online collaboration, scientific discussion, and brainstorming
	T2	Critically evaluate scientific literature and other sources of information	C2	Use tools for sharing literature and collaborative writing
	T3	Place work appropriately in the context of relevant scientific literature	C3	Build skills for understanding and communicating the credibility of information sources
Practical	T4	Plan, conduct, and present a research project	C4	Develop and refine protocols collaboratively
	T5	Develop specialized field and lab skills, depending on the specific project	C5	Implement protocols in a consistent way across researchers
			C6	Communicate with collaborators about challenges or modifications to the protocols
Communication	T6	Communicate the context and results of a project through a written thesis	C7	Incorporate feedback from a range of collaborators
	T7	Communicate the context and results of a project through an oral presentation	C8	Develop the ability to give useful and appropriate feedback to collaborators
			C9	Use a variety of online presentation and discussion tools suited to specific needs
Numeracy	T8	Prepare, process, and interpret your own data	C10	Develop common data management frameworks, metadata standards, and appropriate sharing and version control procedures
	T9	Perform basic statistical analyses using appropriate software	C11	Collaboratively develop statistical approaches, and share code and results
Personal and career development	T10	Develop personal skills necessary to conduct research, such as time management and organizational skills	C12	Move from personal use of social media and other online resources to professional use
	T11	Cultivate a relationship with a faculty mentor who can provide career advice and references	C13	Share experiences, goals, and challenges in developing key skills for the workplace
			C14	Build professional relationships online with researchers outside the home institution

supervisors (Hart Research Associates 2010), making these projects attractive to students who intend to pursue careers in science. As these projects are often among the earliest opportunities students have to engage in scientific research, the projects are bounded or scaffolded by advisors to ensure students develop foundational research skills (Willison and O'Regan 2008). Although skill levels vary, undergraduates often lack the background to develop novel, answerable questions and hypotheses, and the range of skills necessary to develop experimental or field-based protocols for data collection; these gaps are often filled by advisors (Willison and O'Regan 2007).

Beyond their early stage of skill development and depth of understanding of the literature, there are several other challenges to engaging undergraduates in meaningful research. By nature, final thesis and capstone research projects are typically short, lasting between 4 and 12 months, which results in a tight timeframe for initiating and undertaking a complete project. In the case of undergraduates pursuing Honours thesis research, the students usually take a suite of classes at the same time as pursuing a thesis, placing constraints on time and the ability to complete field or lab work that requires a rigid schedule or travel to other sites. In the context of professional socialization—an important outcome of research apprenticeship (Thiry and Laursen 2011)—the network of researchers to which an undergraduate is exposed is often limited to a student's advisor, other undergraduate or graduate students supervised in the same lab, and, rarely, one or two members of an advisory committee, depending on the program structure at a given institution. This gives the student a limited window into how research can be conducted and a modest start to their professional network.

There has been a marked shift over the past five decades in the dominant model of scientific research from lone investigators working on discrete questions toward collaborative teams working on projects from a multitude of inter- and intra-disciplinary perspectives (Wuchty et al. 2007). This shift is particularly pronounced in the environmental sciences, where there is a recognized need to incorporate multiple perspectives to address the complex, multifaceted issues faced by society (Knowlton et al. 2014). Working in teams on collaborative science projects brings a set of challenges around communication, information sharing, and relationship building (Read et al. 2016). Overcoming these challenges requires that collaborative skills be developed in students, in the same way that technical skills such as field and laboratory methods, statistics, and writing are explicit parts of university science curricula. Training programs that aim to develop collaborative skills in graduate students and postdoctoral researchers exist in North America (e.g., the Global Lake Ecological Observatory Network (GLEON) fellowship (Read et al. 2016), the Natural Sciences and Engineering Research Council (NSERC) Collaborative Research and Training Experience (CREATE) program (NSERC 2017a), and the National Science Foundation (NSF) Integrative Graduate Education and Research Traineeship (IGERT) program (NSF 2015)). Programs providing opportunities for undergraduates to engage in research (e.g., the NSF Research Experience for Undergraduates (REU) program (NSF 2017) and the NSERC Undergraduate Student Research Award (USRA) program (NSERC 2017b)), however, are not typically designed with collaborative science as a targeted outcome. As a result, undergraduates rarely develop the skills for collaborative science and professional network building that are known to be valuable to them and their scientific careers (Read et al. 2016).

We developed the Linked Undergraduate Experiments on Nutrients network (LUGNuts) to address the issue that typical undergraduate research projects do not sufficiently equip students in collaborative science. This pilot program aimed to develop a network of Honours (or upper year) undergraduates and faculty advisors working on a common project related to nutrient cycling in the environment. The network enhances the Honours thesis project by providing opportunities for students to learn techniques for undertaking collaborative science and to develop a network of peers and mentors from a number of institutions. This paper reports on the experiences in this pilot year including (a) network design, (b) successes and challenges identified through a program review, and (c) recommendations for applying this model in other contexts to build collaborative science skills training into more undergraduate research programs.

Network design

The LUGNuts program is a research network designed to advance collaborative science at the undergraduate level. In the pilot year, the core components include faculty advisors from different institutions, a cohort of undergraduates enrolled in research courses, reliable web-based communications technology, and a common research question that can be answered by several students completing (<1 year) projects. The network (**Fig. 1**) featured interconnected research projects conducted by individual students and faculty advisors (paired in "nodes"). The network collectively developed common

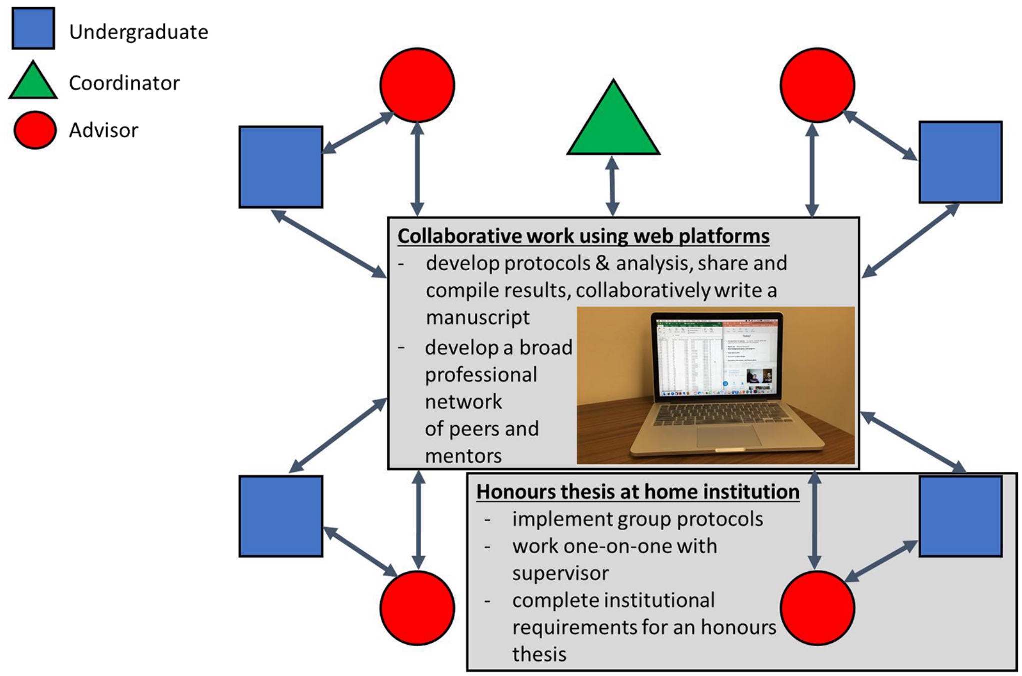

Fig. 1. A conceptual diagram of the LUGNuts network.

protocols and data analysis methods, and compared results and pooled data with the goal of collaboratively writing a manuscript across the nodes. Students in the network participated in the program in addition to satisfying the formal requirements of the thesis or research courses at their home institutions. In the pilot year (2016–2017), LUGNuts involved five faculty advisors, four undergraduate students, and one research assistant from four institutions in Canada or the United States. The advisors developed a set of learning objectives focused on collaborative techniques and skills designed to complement and enhance the traditional Honours thesis model (Table 1).

Faculty advisors were responsible for developing a project that could be undertaken by the undergraduates within the two-semester duration of the program. Although undergraduate researchers working outside such a network may have more independence in formulating and planning their project, a modest degree of protocol development by advisors in advance of students starting their research in the network is necessary. This planning helped ensure that students avoid potential delays in establishing a project at the outset and allowed students to progress through the network program at a similar pace. Early organization can also ensure that each institution (node) has the resources (e.g., instrumentation, equipment) to carry out the protocol; alternatively, with advance coordination, different analyses can be conducted for the network by individual institutions where the capacity exists.

During the summer, faculty advisors discussed ideas and developed an experimental protocol that could be carried out in each node's region. The experimental design was devised with a core protocol for the students to follow, but that lent itself to additional investigations of student-driven research questions beyond the central network question(s). In this case, a scientific objective of the network was to quantify the effect of freeze–thaw cycles on nutrient release from the wetland plant *Typha*. With faculty supervision, students built their own questions from this base; for instance, they expanded the investigation to different wetland vegetation types and whether the timing (seasonality) of sample collection affected the results.

Meetings (~1 h) of the full network were held using web-based conferencing software approximately twice monthly beginning in the fall semester. Because the students were required to implement the protocol consistently across institutions, in the early part of the year these meetings featured discussion of initial experiences with the protocol. Students were subsequently able to refine the protocol with guidance from the advisors to ensure that a common set of techniques were employed across the network and to adapt to local resources and equipment. To encourage interaction among the student cohort and promote the ideals and skills of team science, faculty advisors used collaborative exercises that built on the concepts that were introduced during these meetings (Table 2). For example, one session introduced the students to the principles of data management. Students were tasked with designing a data structure that would meet their individual needs for the data they were collecting. The students subsequently reviewed each of the data structures and collaborated to transform these into a single structure suitable for use across the network. This single data structure was considered and finalized at the following network meeting. In another exercise, students solicited feedback on a section of their thesis via (student) peer review from the network prior to revising it and submitting it to their advisor.

Throughout the year, the meetings served, in part, as a forum in which students could provide progress updates to the group. During this time, students frequently asked questions of their student peers or advisors, or offered others warnings regarding challenges they had encountered in the field or

Table 2. Examples of teaching themes and activities used in LUGNuts, and their targeted learning objectives (as listed in Table 1).

Theme	Learning objectives	Online and remote collaborative activities
Intellectual		
Literature searches	T2, T3, C2, C3	Guided "scavenger hunt" activity introducing the basics of using Web of Science
Experimental design and hypothesis testing	T8, T9, C10, C11	Brainstorming and constructing hypotheses
Practical		
Protocol implementation	T4, C4, C5	Attempt, discuss, and revise the scaffolded experimental protocol
Data management	C10, C11	Build common data file template, use for data sharing/synthesis
Lab skills, QA/QC	C4, C5, C6, C10	Online discussion of QA/QC and document successes and challenges
Communication		
Thesis writing styles/tools	T3, T6, C2, C3, C7, C8	Collaborative introduction writing and revision according to advisor feedback
		Peer-review methods exchange
Oral/visual presentations	T4, T7, C9	Provide a synopsis of study sites
Numeracy		
R intro, data visualization basics	T8, T9, C10, C11	Jigsaw—students present on statistical analyses and their use
Making sense of results, sharing results	T7, C11	Presenting results via web conference
		Code sharing
Personal and career development		
Collaborative science	T1, C1, C4, C9, C12	Discussion of goals for the project, and implementation of shared online tools
Mid-project check-in	C12, C13, C14	Discussion of progress on the project and changes to be made or new skills to work on
Network results and wrap-up	T11, C13, C14	Career options and strategies

Note: QA, quality assurance; QC, quality control.

laboratory. One hour was generally sufficient to afford each student the opportunity to provide an update and ask questions of the other students or mentors, and for advisors to lead a discussion theme or activity around a collaborative learning outcome (Table 2).

In the pilot year, a research assistant tested an early version of the experimental protocol leading up to the network launch. Because of this experience, the individual initially participated in the network meetings to serve as a resource to the students and address questions about methods. As the year progressed, the research assistant's role and participation evolved into that of a coordinator, with responsibilities including scheduling meetings, circulating meeting summaries, sending out reminders and action items, and managing the web-based directory used for sharing the network resources and data.

Program review

After concluding the pilot year, staff at the University of Saskatchewan Gwenna Moss Centre for Teaching and Learning conducted a review of the program through individual semi-structured interviews with all participating faculty advisors, staff, and students. The questions in these interviews (Box 1) were qualitative and used as a way for network participants to share their perspectives on

Box 1. Interview questions used in the program review.

Faculty advisors

1. How do you think this experience has benefited your student in comparison to past students with a single mentor and stand-alone project?
2. How can the LUGNuts model be adapted to build larger networks of researchers?
3. What do you value most about the LUGNuts network?
4. What aspects of the LUGNuts program did you find challenging?
5. What improvements do you envision for the LUGNuts program?
6. How could the program promote exchange/collaboration among students?
7. Did your expectations for the network match the reality of the pilot year?

Students

Thinking about your experience in LUGNuts:

1. What were some of the benefits to you?
2. What was a high point in this experience?
3. What was a frustration or disappointment?
4. What skills do you think you've gained?
5. What aspects of the LUGNuts program do you value most?
6. How could the LUGNuts experience be improved?
7. Why did you choose this experience?
8. How did your experience match your expectation?

the LUGNuts model. Perceptions on engagement in research using the Research Skill Development Framework (Willison and O'Regan 2008) were also gathered during these interviews. The responses from these interviews were anonymized and the emerging themes (strengths and challenges) from this feedback are discussed below.

Advantages of the network

The LUGNuts network design affords clear advantages over standard undergraduate research opportunities. It supplements the student skill development of a typical research course experience with a large number of competencies and breadth of experience in collaborative science (**Tables 1** and **2**).

Student perspectives

In the program review, several highlights emerged for the students as a result of their involvement in LUGNuts. Some of these, such as the opportunity to conduct field work for the first time, were not unique to this network model. Nonetheless, it was clear from the feedback that the students valued the collaborative nature of the program. Students indicated that by being part of a larger project they were invited to think about the wider significance of the study beyond the local systems they studied and to consider the complexities inherent to conducting research spanning multiple regions, collaborators, and institutions. Additionally, the students identified value in having had the opportunity to connect to multiple faculty mentors, each with different skills, areas of expertise, and perspectives on research. For example, one student commented that the program "strengthened [their] interactions with people in academics", and another that it was a benefit to see "different perspectives among faculty".

The students felt that they benefited from the biweekly meetings because these sessions promoted the exchange of ideas between students and advisors, and provided a forum for progress updates and for presentation and discussion of their project results. In addition to being informative and providing students insights as they put their results in the context of the systems their fellow students worked in, the meetings were considered a useful tool for building student confidence (e.g., when students realized their peers encountered similar challenges). These meetings contributed to the students identifying networking as an important skill they developed through LUGNuts. The students affirmed that they learned how to communicate with collaborators, including those they had not met in person. In the interviews, one student commented that they had learned "how to talk to someone [they] didn't know, to ask for help", an experience that is not common in other undergraduate programs. Another program benefit identified in the review was that students gained experience expressing their ideas to the group, and had the opportunity to consider divergent views, as well as different ways in which members of the network articulated these views. This is an important outcome, as undergraduate students may be prone to exhibit either/or thinking wherein there is one "correct" answer (Hager et al. 2003). Data management skills developed through the LUGNuts network approach were also identified by students as being highly valuable. In the interviews, multiple students identified "Excel skills" or "increased stats skills" as being among the most important skills they had gained. Incorporating data management training as a critical part of undergraduate curricula is gaining acceptance, but this training remains relatively rare (Reisner et al. 2014). Perhaps because training on these skills can be absent from undergraduate science education, some of the LUGNuts students indicated that they applied their emerging information management skills almost immediately in other classes. Beyond the collaborative science skills the network program promoted, students felt that they gained practical laboratory, field, and analytical skills that would be useful as they progressed in their careers.

Faculty perspectives

In the program review, faculty advisors identified advantages to students. In instances where faculty advisors were temporarily absent from campus, LUGNuts students benefited from more continuous support from the network, and demonstrated more progress than students not participating in the network. With access to multiple mentors, students benefited from a greater breadth of experience and more contact time with professors with specialized skills and strengths than is typical of one-to-one mentored projects. Because LUGNuts students worked with different researchers, they had opportunities to experience different research and mentorship styles and to witness how the faculty worked as a team to deliver the program, particularly through shared faculty responsibilities during web-based meetings. Further, faculty indicated in their survey responses that participation in these meetings gave the students skills to discuss research, echoing team science. This experience is expected to help participants comfortably and effectively communicate science in defences, conferences, comprehensive exams, or similar fora in which they may participate in the future.

Faculty advisors also identified likely benefits for students as they progress into future careers. This network approach to research more closely resembles professional scientific environments where employees interact and collaborate with a diverse group of people, compared with traditional one-on-one projects. Moreover, by increasing students' professional networks, participating in the network increases their capacity to secure a job, both by improving access to a pool of available references and greater connectivity to the natural science job network (Denecke et al. 2017). Specific to the field of environmental sciences, students in LUGNuts tackled a research question across multiple regions, wherein the students were exposed first-hand to environments outside of their institution's region. Having this broader understanding of natural systems should enhance participants' employability.

Engaging undergraduate students in research confers professional rewards to faculty advisors (Osborn and Karukstis 2009). As researchers conducting field-based environmental science research, a strength of the LUGNuts network was assembling smaller chunks of data into a sizeable body of evidence incorporating across-systems analysis. This capacity to collect and synthesize data from different regions (or at different times) can be powerful (e.g., Schindler 1998). This model, featuring advisors with different expertise, but complementary research programs, was useful for developing a project of common interest and helped to deliver a program that benefitted the students. These factors should lead to a higher number of Honours students contributing to authorship of (collaborative) peer-reviewed publications. This has tremendous value, as there is an opportunity for students to publish more quickly than a typical graduate student. The faculty advisors felt that the LUGNuts network met or exceeded their expectations for student skill development, with students in the network often reaching higher-than-anticipated levels in the Researcher Skill Development Framework (Willison and O'Regan 2008).

Faculty advisors participating in an undergraduate research network like LUGNuts have taken different career paths and have had varying levels of experience in collaborative science. Therefore, much like the students, this network presents an opportunity for advisors to become more adept at contributing to and leading collaborative science. Faculty advisors involved in this network valued the chance to collaborate with new people, learn from their peers, and to share leadership across the network. A distinct advantage is that network meetings can be (co-)led by individual advisors, according to their expertise and availability. This offers flexibility to individual faculty advisors who invariably experience periods of limited availability. One faculty participant responded in the interview that it was nice to have "a group who can pick up when I'm busy". The network format ensures that students have resources and supervision to draw on during these times. Likewise, the network promotes team writing of peer-reviewed manuscripts, which in the early stages of the network has been a productive model and helped to avoid periods of individual stagnancy.

Recommendations for network enhancement and adaptation

Although the network had many successful aspects based on student, staff, and faculty advisor feedback, the program review also identified opportunities for improvement. One area of weakness, identified by both students and faculty, was that the initiation of meetings was delayed because of the urgency of sample collection. As such, there was a missed opportunity to promote interaction among the student cohort initially. Student interview responses reflected this; when asked about frustrations associated with the program, one student commented that the meetings "felt a bit ad hoc" and another commented that it would have been better to "start the meetings earlier" in the semester. Students worked collaboratively later in the semester, but there would be value added in fostering early cohort-building, for example, via an early meeting of students with the coordinator, in the absence of faculty advisors, to develop a sense of community among the cohort. Creating a forum for one-to-one mentorship of students by faculty from outside their home institution would likewise help to increase some students' comfort in reaching out to their other mentors and strengthen the development of these networks. In addition, there is flexibility to devise experimental protocols in a way that could further promote additional collaboration. This could be achieved by sharing responsibilities for generating the data among the students (e.g., individual students conduct specific analyses for the whole network). Finally, although the feedback on the collaborative exercises the students undertook was positive, the success of student collaboration was not evaluated. Developing tools for evaluating the network could, in future, or in other networks elsewhere, be useful for reflective redesign of the program.

As could be imagined in a new project involving multiple students, advisors, and institutions, unforeseen challenges arose. These factors included course loads, time-zone changes, and differing credit for research courses and semester timing between institutions. Managing the trajectories of individual students in the context of larger group goals requires adequate forethought. Feedback from the program review indicated that the project suffered from being overly onerous toward the second academic semester, and the students' data became available too late in the program for students to fully benefit from the opportunity to synthesize the network data. It is important to carefully consider the scope of work to ensure that the data generated through the student research activities is available by the start of the second semester. Scope and milestones are also important considerations in light of the contrasting demands of individual student schedules, and the network program should strive for an evenly distributed workload with collaborative student exercises being adaptable to such constraints.

In the program review, faculty advisors were asked for recommendations on how to scale this model to larger networks. One suggestion pertained to personnel involved in the network. In this pilot, a flat leadership structure allowed advisors to be flexible and contribute as time allowed. Nonetheless, because planning and decisions were based on consensus among faculty advisors, this created some organizational challenges and the distributed nature of the network amplified a heavy email load. This was addressed, in part, through a part-time coordinator who facilitated the network organization. Formalizing the network coordinator position, by hiring a graduate student or research assistant would provide mentorship to the undergraduates and organizational support. This leadership opportunity is valuable for students and early career researchers because it promotes the development of researchers into leaders who can strengthen society by upholding the values of science (Steelman and McDonnell 2017). A larger network would likely require additional support from a coordinator and a more defined leadership structure to formalize contributions from faculty mentors. The network was initially funded from individual research grants; creative solutions are necessary to fund a formal coordinator position to support undergraduate student research across multiple institutions.

Faculty advisors also identified that a larger number of participants would change the nature of the group meetings. Larger groups limit the ability of individuals to participate in discussions and collaborative activities, present challenges for scheduling, and pose technological challenges for web-based conferencing software. With care, some growth in network size could be accommodated within the

1 h meeting window currently used in LUGNuts. Additional growth could be achieved by restructuring meetings and activities to involve subsets of the group, but these changes may involve a compromise between the quality of network-building and the greater number of students and nodes. Although the types of scientific questions that could be answered by a larger network are potentially novel and exciting, an increase in size would need to be balanced by considerations of the quality of training.

Given the rise in collaborative research across disciplines, this model of collaborative training for undergraduate research students could be adapted and applied to other fields of study. A key challenge is identifying a research question that would benefit from a team approach and can be successfully addressed by (Honours) projects that last for fewer than 12 months. In the environmental sciences, there is often a question about how measured results vary across sites with a range of climatic, geological, and ecological conditions, hence our implementation of a common protocol in different regions. In other fields, it may be logical to use this network model to overcome limitations on sample size or number of replicates—inherent in short-term undergraduate programs—or to have students work on different parts of a larger question to overcome limitations of equipment or expertise at a single institution. Regardless of the experiment specifics, training students to conduct collaborative science at an early stage of their career is beneficial across a wide range of fields.

Conclusions

Although current undergraduate engagement in research confers distinct advantages to participating students, we have identified opportunities to enhance these experiences. The LUGNuts program is a network approach to undergraduate research projects that develops many of the skills typical of a traditional Honours thesis, and supplements these with collaborative skill development that is key to success both in graduate level research and for early-career professionals. In the pilot year, both the participating students and faculty advisors identified advantages of the interaction promoted across the network. For environmental scientists, the network proved useful for addressing research questions across environmental gradients that would not be possible within typical undergraduate research projects. This network design can also afford advantages where access to specialized instrumentation is limited at individual institutions, or to overcome sample size limitations. In future years, we plan to enhance LUGNuts by integrating the recommendations herein, namely by having a graduate student gain leadership experience as network coordinator, and by expanding the network with more nodes at additional institutions. This model for collaborative science for undergraduates is demonstrated to enhance the undergraduate research experience, and can be readily adapted for use across additional fields of study.

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Author contributions

NJC, CJW, HMB, RLN, and JJV conceived and designed the study. SM performed the experiments/collected the data. NJC, CJW, HMB, RLN, and JJV analyzed and interpreted the data. NJC, CJW, HMB, RLN, and JJV contributed resources. NJC, CJW, HMB, SM, RLN, and JJV drafted or revised the manuscript.

Competing interests

The authors have declared that no competing interests exist.

Data availability statement

All relevant data are within the paper.

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