



SYMPOSIUM

Connected While Distant: Networking CUREs Across Classrooms to Create Community and Empower Students

Patrice K. Connors^{ID*,1}, Hayley C. Lanier[†], Liesl P. Erb[‡], Johanna Varner^{*}, Laurie Dizney[§], Elizabeth A. Flaherty[¶], Jennifer M. Duggan^{||}, Christopher J. Yahnke[#] and John D. Hanson^{**}

*Department of Biological Sciences, Colorado Mesa University, Grand Junction, CO 81501, USA; [†]Sam Noble Oklahoma Museum of Natural History and Department of Biology, University of Oklahoma, Norman, OK 73072, USA; [‡]Departments of Biology and Environmental Studies, Warren Wilson College, Asheville, NC 28815, USA; [§]Department of Biology, University of Portland, Portland, OR 97203, USA; [¶]Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN 47906, USA; ^{||}Department of Applied Environmental Science, California State University, Monterey Bay, 100 Campus Center, Seaside, CA 93955, USA; [#]Department of Wildlife Ecology, University of Wisconsin - Stevens Point, Stevens Point, WI 54481, USA; ^{**}Institute for Biodiversity Research and Education, Charleston, IN 47111, USA

The first two authors contributed equally to this work.

From the symposium “Biology Beyond the Classroom: Experiential Learning through Authentic Research, Design, and Community Engagement” presented at the annual meeting of the Society for Integrative and Comparative Biology, January 3–7 virtually via Pathable.

¹E-mail: pconnors@coloradomesa.edu

Synopsis Connections, collaborations, and community are key to the success of individual scientists as well as transformative scientific advances. Intentionally building these components into science, technology, engineering and mathematics (STEM) education can better prepare future generations of researchers. Course-based undergraduate research experiences (CUREs) are a new, fast-growing teaching practice in STEM that expand opportunities for undergraduate students to gain research skills. Because they engage all students in a course in an authentic research experience focused on a relevant scientific problem, CUREs provide an opportunity to foster community among students while promoting critical thinking skills and positively influencing their identities as scientists. Here, we review CUREs in the biological sciences that were developed as multi-institutional networks, and highlight the benefits gained by students and instructors through participation in a CURE network. Throughout, we introduce Squirrel-Net, a network of ecology-focused and field-based CUREs that intentionally create connections among students and instructors. Squirrel-Net CUREs can also be scaffolded into the curriculum to form connections between courses, and are easily transitioned to distance-based delivery. Future assessments of networked CUREs like Squirrel-Net will help elucidate how CURE networks create community and how a cultivated research community impacts students' performance, perceptions of science, and sense of belonging. We hypothesize networked CUREs have the potential to create a broader sense of belonging among students and instructors alike, which could result in better science and more confident scientists.

Science is a social enterprise. Despite stereotypes of isolated researchers toiling away alone at lab benches, 21st century science has become highly collaborative (Vermeulen et al. 2013; Barlow et al. 2018). This trend is driven by many influences, including the complexity and interdisciplinarity of modern research questions (Aubin et al. 2020) and the power of technology to facilitate long-distance collaboration (Siemens 2020). Col-

laboration and community development in science also enhances problem solving and results in higher impact publications (Rigby and Edler 2005; Franceschet and Costantini 2010). Additionally, collaborations including individuals representing diverse identities and backgrounds are more fruitful and efficient (Hong and Page 2004; Phillips 2014), and inclusion of individuals from historically marginalized communities improves

scientific discourse (Phillips 2014; Den Broeder et al. 2018). Although sometimes overlooked, there are also benefits of social connection for scientists' wellbeing and self-confidence (Termini and Pang 2020).

Not surprisingly, undergraduate students also benefit from collaborative educational experiences, especially early in their science careers. Science, technology, engineering and mathematics (STEM) students who participate in collaborative learning often express greater self-efficacy as scientists, earn higher grades in science courses, and are more likely to persist in STEM fields (Springer et al. 1999; Freeman et al. 2014). Undergraduate students also benefit from social connections with mentors and peers through increased self-confidence, particularly those from backgrounds historically underrepresented in the sciences (Chemers et al. 2011; McGee et al. 2012). Yet, in order to achieve diverse and thriving scientific communities, it is important for all students to feel a sense of belonging in STEM (Chemers et al. 2011; Syed et al. 2019).

One way of achieving this sense of belonging is through activities that connect students to peers, mentors, and authentic research experiences at the undergraduate level. Course-based undergraduate research experiences (CUREs) are experiential learning activities that can build community around research. By designing activities around relevant and novel discovery, engaging students in authentic research, and emphasizing collaboration and iteration, CUREs teach scientific concepts through *doing* science in the undergraduate classroom (Auchincloss et al. 2014). As a result, CUREs are becoming more common in higher education, and evidence is emerging that they may be a powerful tool for not only mastering content and critical thinking skills (Caruso et al. 2016; Staub et al. 2016), but also fostering a strong sense of community and belonging (Malotky et al. 2020). In fields from geosciences (Kortz and van der Hoeven Kraft 2016; Allen et al. 2020) to musical education (Dvorak and Hernandez-Ruiz 2019), CUREs positively influence students' impressions of their profession, their confidence as practitioners, and their ability to initiate, navigate, and maintain collaborations (Esparza et al. 2020).

CUREs are structured in a variety of ways, and a growing number of CUREs are being developed as multi-institutional networks (Table 1). These cross-institutional or "networked" CUREs seek to reduce barriers to implementation by providing a shared curriculum, technical resources, and/or faculty training all focused around a common theme (Lopatto et al. 2014; Hanauer et al. 2017). Here, we review the ways that CURE networks can intentionally build elements of connections, community, and inclusion in the classroom to understand their impact on undergraduate stu-

dent outcomes and guide the implementation of these high-impact teaching practices. Specifically, we (1) provide an overview of existing networked CUREs in biology and describe how they foster iteration and discovery, (2) summarize benefits of participation in networked CUREs for students and instructors, and (3) outline research questions on community and collaboration in networked CUREs. Throughout, we present a new CURE network (Squirrel-Net) that is field-based, investigates ecological questions, and intentionally designed to promote a sense of belonging and community.

Networked CUREs in biology

CUREs in the biological sciences have increased in number and accessibility over the past decade, as evidenced from online repositories such as CUREnet (serc.carleton.edu/curenet/index.html). In general, CUREs can be categorized based on their structure, duration, financial support, and the mentorship that is provided (Dolan 2016). For example, many CUREs were developed by individual instructors building on their specific research strengths and implemented solely in their classrooms (e.g., Drew and Triplett 2008). Other CUREs were created within departments or institutions to bring together a course or set of courses around a common theme while also providing research experiences to a larger student body (e.g., SIRIUS project, McDonald et al. 2019). In contrast, networked CUREs were developed to connect numerous institutions and create national or international programs (e.g., BASIL, Craig 2017). CURE networks can be broadly grouped based on commonalities across research goals or technologies and methodologies (Dolan 2016), with some networks focused on a single, shared research goal and others focused around a common framework or technology. Networked CUREs allow students and instructors to share results, overcome roadblocks, and identify best practices in teaching and research. Due to their inclusive design and often centralized support, networked CUREs can also provide opportunities for community building from start to finish. By recruiting from a wide variety of institutions and emphasizing collaborative development of knowledge, networked CUREs can connect students both culturally and spatially.

Most well-known networked CUREs in biology are focused on microbiology, cellular biology, or genetics (Table 1). For example, one long-running networked CURE is the Howards Hughes Medical Institute's Science Education Alliance—Phage Hunters Advancing Genomic and Evolutionary Science (SEA-PHAGES), which has involved thousands of undergraduate students from almost 200 institutions in the common goal

Table 1 Networked course-based undergraduate research experiences (CUREs). Provided for each CURE is a summary of the student activity, the estimated time frame needed to complete the CURE, and a link to the CURE website for additional information, including how to join or participate in the network

CURE	Student activity	Time frame	Link
Biochemistry Authentic Scientific Inquiry Lab (BASIL)	Predict protein function in silico from known structure and test protein function in vitro with multiple techniques.	1 semester	https://basilbiochem.github.io/basil/
Biological Collections in Ecology and Evolution Network (BCEENET)	Investigate morphological traits and geographic distributions of plants and insects using digital natural history collections.	1 semester (4 weeks possible)	https://bceenetwork.org/
Cell Biology Education Consortium (CBEC)	Student-driven projects centered around multiple cell–tissue culture techniques.	1 semester	https://www.cellbioed.com/
Design to Data (D2D)	Use a design-build-test workflow to discover novel enzymes for applications in therapy, agriculture or industry.	1 semester	https://d2d.ucdavis.edu/
Ecological Research as Education Network (EREN)	Network of collaborative ecological projects connecting primarily undergraduate institutions (multiple CUREs).	Variable	https://erenweb.org/
Genomics Education Partnership (GEP)	Clean and analyze genomic data from raw sequence to high quality finished sequences to understand structure and evolution of genes.	Flexible: a few class periods to multiple semesters	https://thegep.org/
Prevalence of Antibiotic Resistance in the Environment (PARE)	Isolate bacteria from local soil samples and test tetracycline resistance to identify potential antibiotic hotspots.	Flexible: a few class periods to 1 semester	https://sites.tufts.edu/ctse/pare/
SEA-PHAGES	Isolate, purify, amplify, and characterize new viruses from local soil samples.	2 semesters	https://seaphages.org/
SEA-GENES	Sequel to SEA-PHAGE. For phage genes or products, generate expression libraries, test ability to modulate host phenotype and identify host targets.	1–2 semesters	https://www.hhmi.org/science-education/programs/science-education-alliance
Small World Initiative	Isolate, test against medically-relevant pathogens, and characterize bacteria from local soil samples.	1 semester	http://www.smallworldinitiative.org/about
Squirrel-Net	Examine squirrel behavioral ecology through four field-based modules.	Flexible: 1 class to 1 semester	https://www.squirrel-net.org/
Tiny Earth	Culture, screen for antibiotic resistance, and characterize bacteria from local soil samples.	1 semester	https://tinyearth.wisc.edu/about-us/

of discovering and describing of novel viruses. Similarly, the Tiny Earth and Small World Initiative CUREs provide students authentic research experiences in discovering novel soil-dwelling bacteria, with the aim of discovering new antibiotic treatments. Project design in these two large networks (e.g., 10,000 students from 15 countries for Tiny Earth) is flexible, allowing research activities to be tailored to specific students and course goals (e.g., Bueso-Bordils et al. 2020). These CURE networks have positively influenced students' knowledge of and interest in science (Caruso et al. 2016, Hanauer et al. 2017), as well as significantly advanced antibiotic and virology discoveries (Basalla et al. 2020, Hatfull 2020). As a result, these networks have become standards against which new CUREs are compared (Laungani et al. 2018) and a source of inspiration for the development of new CUREs.

In contrast, there are very few networked CUREs in organismal biology or ecology (Table 1), despite the widely recognized importance of biological field studies (Fleischner et al. 2017). This gap highlights an op-

portunity to create equitable research experiences for future zoologists, botanists, wildlife biologists, and conservationists. Networked CUREs in ecology and organismal biology could also play an important role in developing the large-scale, longitudinal datasets that are critical to understanding ecological responses to climate change, habitat alteration, or biodiversity loss. A total of two recently developed CURE networks address this need: Squirrel-Net (Box 1) and the Biological Collections in Ecology and Evolution Network (BCEENET). Both focus on common frameworks as opposed to a single research goal. BCEENET focuses on using digitized museum specimens to answer questions about species adaptations, invasive species, and range shifts due to climate change (Table 1). Unlike many lab-based CUREs, research activities in BCEENET and Squirrel-Net can be conducted remotely. Squirrel-Net has developed additional resources for adapting to remote or hybrid learning, including modifications for collecting data at home without specialized equipment (Dizney et al. 2021).

Box 1 Squirrel-Net: A CURE network investigating behavioral ecology

In 2017, a group of nine mammalogists from a range of academic institutions assembled at the American Society of Mammalogists conference to discuss ways to engage more undergraduate students in authentic research. Our goal was to develop a field-based, mammal focused CURE that was networked across institutions (Fig. 1). The result was Squirrel-Net and our four, peer-reviewed, field-based CURE modules (www.squirrel-net.org/). Since then, our network has grown to include instructors from 42 institutions across North America.

By developing shared approaches for investigating how squirrels interact with their surroundings, Squirrel-Net modules provide a framework for students to ask questions about how urbanization and the surrounding environment shape animal behavior across broad geographic scales. Squirrel-Net modules are highly flexible, allowing them to be adapted from a single class period to a semester-long CURE, with approaches ranging from instructor-provided to student-driven inquiry (Dizney et al. 2020). All students use standardized protocols and submit their data to shared databases, the process of which highlights the importance of consistency in data collection and links a student's data to a broader scientific community.

The simplest CURE module, *Squirreling Around for Science* (Connors et al. 2020), invites students to observe squirrels on or near their campuses and to construct an activity budget. Students collect standardized focal-animal observations, categorizing behaviors every 20 s with an ethogram, as well as information on the location, habitat, nearby organisms, and weather. These data can be used to investigate trade-offs among different squirrel behaviors in relation to their environment, species or ecoregion.

A second CURE module, *Sorry to Eat and Run* (Yahnke et al. 2020), teaches students to measure giving-up density (GUD), or the amount of food remaining when an animal abandons a foraging patch (Brown 1988). Students leave trays with a known quantity of seeds in various locations. After 8–12 h, the remaining seeds are measured, along with data on environmental conditions, distance from safety and presence of predators. GUD data can be used to investigate the perceptions of risk versus reward and the relative costs or benefits of foraging under different conditions.

In a third CURE module, *How Many Squirrels are in the Shrubs* (Varner et al. 2020), students estimate wild mammal population sizes using three different

estimation techniques: strip censuses, scat counts, and camera traps. In so doing, they must also evaluate how the underlying assumptions of each technique might bias the results. Students can then query the national dataset to investigate which method might be most appropriate for a given habitat type or species, based on how well the assumptions of each estimator are met, and evaluate regional differences in population density.

In the most advanced module, *Squirrels in Space* (Duggan et al. 2020), students use radio telemetry equipment (i.e., transmitters, antennae, and receivers) coupled with environmental data to examine squirrel movement across the landscape, estimate home range size, and evaluate habitat associations. Similar to other modules, students contribute to a national database and can use this larger dataset to test their hypotheses.

Ecology-based CUREs like Squirrel-Net are important in shaping students' perspectives of science as a discipline, as undergraduate students are sometimes unaware that professional science takes place outside of a lab (Fleischner et al. 2017). Along with the shared experience of observing common and charismatic mammals like squirrels, Squirrel-Net modules provide opportunities that connect students to their local environments (Myers et al. 2009), which can influence their attitudes and beliefs regarding environmental stewardship (Myers et al. 2013; Fleischner et al. 2017).

Iteration and innovation in networked CUREs

Networked CUREs provide unique opportunities for iteration of the scientific process, another key component that sets CUREs apart from other teaching strategies (Auchincloss et al. 2014). Some networked CUREs (Table 1) can require a full academic semester to complete; this time frame accommodates iterative processes, including data interpretation and creation of new hypotheses, and sharing results with others in the network to foster constructive discussions. However, there is growing interest in returning to similar research themes across multiple courses within the undergraduate curriculum (Staub et al. 2016; Hanauer et al. 2017). Squirrel-Net is unique among networked CUREs in that the modules are designed to be scaffolded across a curriculum, thereby facilitating connections between concepts and courses (Dizney et al. 2020). When integrated into multiple courses at various stages of undergraduate education, students can form meaningful connections among ideas and develop a deeper

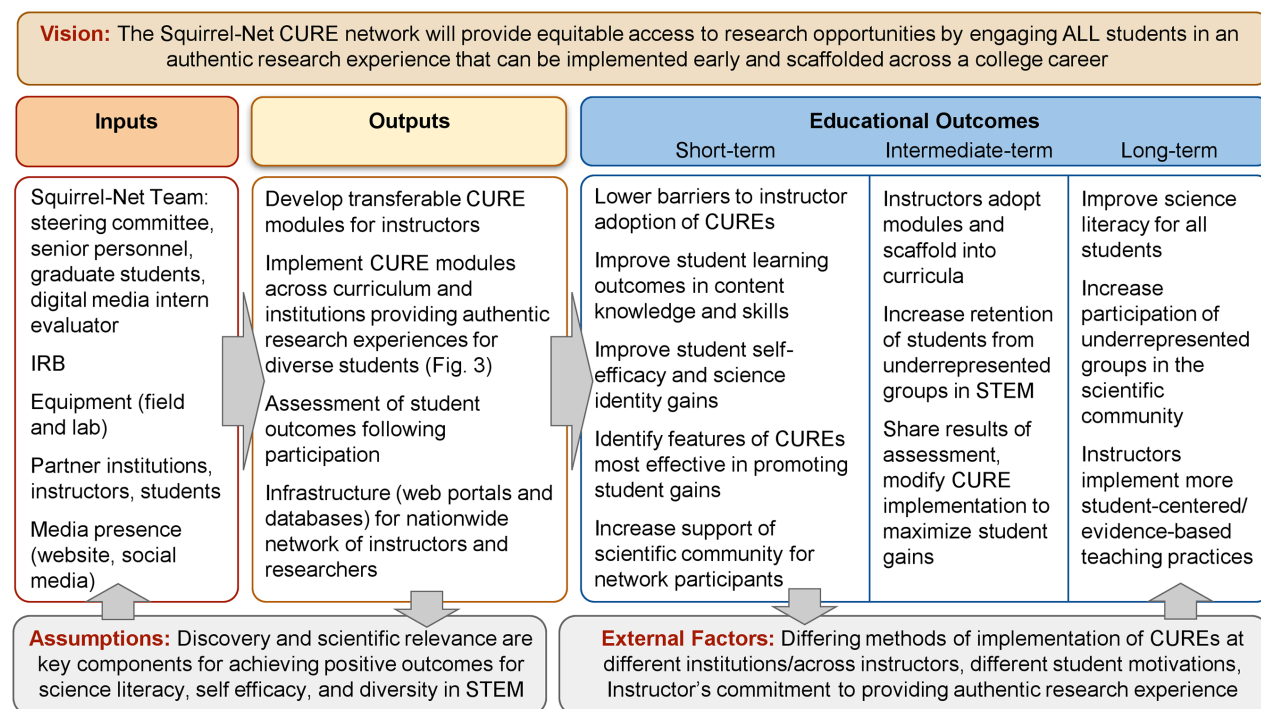


Fig. 1 Logic model for Squirrel-Net educational outcomes. The underlying logic model links program inputs to desired educational outcomes through the project outputs, which lead to short (< 1–2 years) to long-term (> 5 years) educational outcomes. Discovery and scientific relevance are key components for achieving these positive outcomes. External factors such as differences in implementation of CUREs, student motivations, and instructor's commitment to providing authentic research experience are expected to impact the program outcomes.

understanding of their applications (Allen et al. 2020). For example, Squirrel-Net CUREs are currently implemented in both introductory and upper-division courses at Colorado Mesa University and California State University, Monterey Bay (see Dizney et al. 2020). These iterative experiences provide time to master technical skills and accumulate multiple scientific or scholarly competencies so that students are better prepared for either graduate programs or careers (Lee et al. 2019). Such experiences allow students to reflect on their learning and gain confidence in new skills and abilities (Lee et al. 2019; Allen et al. 2020), as well as increase resilience to and understanding of the nonlinear process of science. Additional time immersed in research may also provide opportunities to overcome setbacks during the scientific process. Indeed, as students experience the challenges of the scientific process, they learn to connect new knowledge and skills, perceive their research as more authentic (Goodwin et al. 2021), and build the perseverance and scientific identity that are closely associated with retention in STEM (Kowalski et al. 2016).

Similar to individualized CUREs, networked CUREs foster the novel discovery of broadly relevant knowledge (Auchincloss et al. 2014). As many networked CUREs have developed shared, publicly available databases (e.g., Prevalence of Antibiotic Resistance

in the Environment, Genné-Bacon and Bascom-Slack 2018; Squirrel-Net, Dizney et al. 2020; and Tiny Earth, Hurley et al. 2021; Table 1), students participating in those CUREs can develop and test broader hypotheses than would be possible in a single course or at a single institution. For example, students in Squirrel-Net CUREs have investigated how climate or urbanization affect vigilance behavior and how different squirrel species behave in their native versus introduced ranges. These questions are broadly relevant, authentic in that the answers are unknown, and necessitate data from multiple geographic areas and/or habitats.

Benefits of CURE communities for instructors and students

For students, participating in a CURE network can offer many benefits (Table 2). Students can experience greater feelings of belonging to a scientific community (Jordan et al. 2014), and their impressions of science and their confidence as scientists can be positively influenced (Hanauer et al. 2017). Social interaction, mentorship in the research process, and identifying questions relevant to the broader scientific community also help to cultivate a sense of project ownership (Hanauer et al. 2012; Cooper et al. 2019) and increase student

Table 2 Benefits to participating in networked CUREs. Student researchers and instructors gain a range of benefits by participating in research activities within a CURE network

Benefits to students	Benefits to instructors
An authentic research experience (not a “cookie-cutter” lab activity) with broad scientific relevance.	Course-based Undergraduate Research Experiences (CUREs) involve more students in authentic research, advancing STEM pedagogy.
A hands-on, inclusive, scientific research experience that promotes project ownership.	New teaching lab(s) to add to your curriculum that is fully developed and vetted at numerous institutions.
Gain skills and learn methods specific to areas of science (e.g., biochemistry, genomics, museums, and ecology) that are transferable to other courses and potential careers.	Free access to content-specific teaching materials (biochemistry, genomics, natural history, and mammalogy), some with flexible course implementation (short modules to semester-long projects).
Connection to and collaborating with a national community of other students working on the same research project or with the same tools.	Connection to a national community of instructors, including authors of the modules, who can provide additional support.
Access to a national or international database of student-generated data, enabling the testing of creative and novel student-driven hypotheses.	Access to a national or international database of student-collected data, allowing students to test broader hypotheses compared to data collected in one place or at one time.
Experience with data analysis and interpretation, and the iterative process of science (e.g., unexpected results followed by new hypotheses).	Evidence of service outreach and teaching development for merit and retention decisions.
Opportunities to share research with the network and larger scientific community through presentations and publications.	Opportunities to share scientific and education research with the network and larger scientific community through presentations and publications.
Participation in a national science community.	Participation in a national science community.

motivation during the research process (Esparza et al. 2020). The collaboration inherent to the CURE model may also help to affirm student dignity and inclusion through increased social kindness (Estrada et al. 2018). For field courses in particular, facilitating community camaraderie and developing accessible CURE activities is critical to promoting diversity and inclusion in ecology and evolutionary biology (Zavaleta et al. 2020).

Interestingly, networked CUREs may also play an important role in both normalizing failure and empowering students. Students conducting CUREs often experience failure in some capacity, such as methodological setbacks or inconclusive results, providing opportunities to iteratively overcome these challenges. Experiencing and overcoming such obstacles are key to students’ self-identity as scientists and their perception of having conducted “real” research (Goodwin et al. 2021), and networked CUREs provide additional opportunities for interacting around those challenges. In doing so, students become part of a scientific community studying soil-dwelling microbes, squirrels, or museum specimens (Wiley and Stover 2014). Furthermore, students who participate in networked CUREs interact with students from other institutions in ways that mirror how industry and academic scientists collaborate in the 21st century. For instance, students that participated in a remote CURE reported feeling that learning to collaborate in remote teams was relevant to their future careers as scientists (Fey et al. 2020). Thus, networked CUREs can help break the stereotypes that students are limited to collecting data to be later analyzed or communicated by the “expert scientists” or that science is only “authentic”

or “meaningful” when presented by credentialed academics in peer-reviewed publications.

Connections among student researchers and faculty are also frequently forged through CURE network-hosted annual symposia or regional meetings. SEA-PHAGES and Tiny Earth host network-wide symposia each year, creating physical and virtual communities for students, instructors and researchers to share findings and foster connections. Both SEA-PHAGES and the Genomics Education Partnership (GEP, Table 1) also host regional meetings, which include undergraduate presentations and opportunities for networking at nearby institutions. During the COVID-19 pandemic, many meetings have continued virtually, with positive results for students. For example, students who presented the results of their course-based research during virtual poster sessions in a virtual reality platform reported enjoying the interactions with their peers nearly as much as in-person interactions (Holt et al. 2020). For some students, using virtual avatars actually reduced student stress compared to standing by their poster and answering face-to-face questions (Holt et al. 2020). An added benefit of such a virtual experience is the ability to expand access to the event, potentially connecting students from across the country, and even globally, who might not otherwise have the opportunity to attend.

Networked CUREs can also maintain important scientific and research communities for faculty and instructors (Table 2). Connections to scientific research communities may be particularly important at smaller, teaching-focused schools, where faculty have higher

teaching loads and/or may be less likely to have colleagues with similar research interests. For many networked CUREs, faculty also have the opportunity to collaborate on scientific and educational papers (Lopatto et al. 2014). Moreover, a sense of community and connection are important for supporting faculty in implementing evidence-based teaching practices in STEM (Handelsman et al. 2007), both through encouraging reflective teaching practices and in developing a shared vision (Borrego and Henderson 2014). For example, faculty learning communities are a successful approach to supporting the adoption of novel teaching methods (Cox 2004). The development of faculty communities or peer mentoring around networked CUREs provides peer support and can lower the activation energy of implementing CUREs (Shaffer et al. 2010; Jordan et al. 2014; Lopatto et al. 2014). Tiny World and Squirrel-Net also have active social media accounts (e.g., Twitter, Facebook, and Instagram) to support online connections and foster community. These approaches for building and maintaining instructor communities can improve the sustainability of learner-centered teaching practices (e.g., Ebert-May et al. 2015; Derting et al. 2016).

New directions: evaluating the impacts of CURE network activities

While networked CUREs are inherently based around scientific communities, the impacts of cross-institutional connections within CURE networks have rarely been directly assessed and represent a critical gap in the literature. For example, one model of CURE outcomes is grounded in situated-learning theory, which suggests that engagement in a “community of practice” (a group of people addressing a common question with shared approaches) is key to persisting in science (Auchincloss et al. 2014). Under this model, elements such as student access to professional networks and subsequent increased access to mentoring are important intermediate steps in the development of STEM persistence and identity. Access to professional networks and opportunities for mentoring may be strengthened through CURE networks where cross-institutional interactions are emphasized. Squirrel-Net was intentionally designed (Fig. 1) to investigate these benefits of building and fostering a community. By connecting multiple, varied institutions, including community colleges, primarily undergraduate institutions, and R1 universities, we plan to assess gains in scientific skills, sense of belonging to a community, and self-identity as a scientist for students who participate in Squirrel-Net CUREs. Because several of our assessment questions specifically address students’ sense of belonging to a

research community of multiple institutions, the results of this study will allow us to improve the community and connectedness of each module.

In addition, few studies have investigated the potential benefit of scaffolding multiple thematic CUREs within an undergraduate curriculum (Hanauer et al. 2017). CURE networks such as SEA-PHAGES and Squirrel-Net may be well-situated to address these questions. While many CUREs are focused either on students in either lower- (e.g., Beckham et al. 2015) or upper-division courses (e.g., Beatty et al. 2021), having students return to similar themes with new tools across courses (e.g., SEA-GENES, Staub et al. 2016) may provide greater opportunities for iteration, innovation, and discovery (Thiry et al. 2012). Since the four modular CUREs created by Squirrel-Net include research activities designed to be run across multiple courses, future assessments of Squirrel-Net CUREs will help elucidate these key knowledge gaps regarding the importance of course level, prior research experience, and iteration within a curriculum on student outcomes.

Evaluating the importance of CURE networks for supporting faculty and undergraduate students has perhaps never been so salient as during the COVID-19 pandemic, when most higher education courses were forced online in the Spring of 2020. The sudden pivot to remote instruction greatly affected students and instructors, with many students reporting a loss of connection and engagement (Theodosiou and Corbin 2020). These effects were felt disproportionately by students who are low income (Aucejo et al. 2020) and/or black, indigenous and people of color (BIPOC, Blake et al. 2021). Likewise, many instructors in the biological sciences found authentic field research experiences particularly difficult to adapt to the online environment. A survey of college instructors forced to adapt their field courses to distance-learning identified the social aspects of field work, including loss of community and student-instructor connections, as important barriers to inclusive and effective teaching (Barton 2020). Together, these findings suggest we should evaluate the potential for CURE networks, especially those that are ecology-focused, to sustain engagement and foster community in remote learning environments as well as their importance to diversity, equity, and inclusion in the classroom.

Conclusions

Community connections and collaborations are not only paramount to science as a field, but also a key component of effective undergraduate education. Linking CUREs through a multi-institutional network can help foster such connections and may create a broader sense

of belonging among all participants. However, less is known about the impacts of community on students and instructors within networked CUREs. While intentionally developing activities within CURE networks with the goal of fostering connectivity and collaboration will likely result in better science and more confident scientists, this has yet to be rigorously evaluated. There is also a clear need for more organismal, ecological, and field-based activities among CURE networks. One CURE network that emphasizes connecting students to form a scientific community is Squirrel-Net (Box 1). The Squirrel-Net modules connect concepts and courses by iteratively revisiting the same system in different contexts as students progress through the curriculum. Taken together, such connections may be important for overcoming teaching challenges, particularly those imposed by the COVID-19 pandemic. Finally, the structure of the Squirrel-Net team itself models a successful collaborative research network for our students, demonstrating first-hand the benefits of team science and the ability of a group to tackle larger tasks than could be accomplished alone.

Acknowledgments

We thank all of the students and instructors who have participated in our modules and become an integral part of Squirrel-Net, Dr. Lorelei Patrick for her thoughtful feedback and support of Squirrel-Net, and five anonymous reviewers for their constructive comments. We would also like to thank the “Biology: Beyond the Classroom” Symposium for their engaging discussion.

Funding

This work was supported by the National Science Foundation under collaborative grants [2013483, 2013281, 2013308, and 2013320 to H.C.L., J.M.D., J.V., and E.F., respectively].

Supplementary data

Supplementary data available at [ICB](#) online.

Data availability

No new data were generated or analyzed in support of this research.

References

- Allen JL, Kuehn SC, Creamer EG. 2020. A boost for the CURE: improving learning outcomes with curriculum-based undergraduate research. *GSA Today* 30:28–9.
- Aubin I, Cardou F, Boisvert-Marsh L, Garnier E, Strukelj M, Munson AD. 2020. Managing data locally to answer questions globally: the role of collaborative science in ecology. *J Veg Sci* 31:509–17.
- Aucejo EM, French J, Ugalde Araya MP, Zafar B. 2020. The impact of COVID-19 on student experiences and expectations: evidence from a survey. *J Public Econ* 191:104271.
- Auchincloss LC, Laursen SL, Branchaw JL, Eagan K, Graham M, Hanauer DI, Lawrie G, McLinn CM, Pelaez N, Rowland S, et al. 2014. Assessment of course-based undergraduate research experiences: a meeting report. *CBE Life Sci Educ* 13:29–40.
- Barlow J, Stephens PA, Bode M, Cadotte MW, Lucas K, Newton E, Nuñez MA, Pettoelli N. 2018. On the extinction of the single-authored paper: the causes and consequences of increasingly collaborative applied ecological research. *J Appl Ecol* 55:1–4.
- Barton DC. 2020. Impacts of the COVID-19 pandemic on field instruction and remote teaching alternatives: results from a survey of instructors. *Ecol Evol* 10:12499–507.
- Basalla J, Harris R, Burgess E, Zeedyk N, Wildschutte H. 2020. Expanding Tiny Earth to genomics: a bioinformatics approach for an undergraduate class to characterize antagonistic strains. *FEMS Microbiol Lett* 367(1):fnab018.
- Beatty AE, Ballen CJ, Driessen EP, Schwartz TS, Graze RM. 2021. Addressing the unique qualities of upper-level biology CUREs through the integration of skill-building. *Integr Comp Biol* icab006. <https://doi.org/10.1093/icb/icab006>.
- Beckham JT, Simmons SL, Stovall GM, Farre J. 2015. The freshman research initiative as a model for addressing shortages and disparities in STEM engagement. In: *Directions for mathematics research experience for undergraduates*. Hackensack (NJ): World Scientific. p. 181–22.
- Blake H, Brown N, Follette C, Morgan J, Yu H. 2021. Black, indigenous, people of color, and international students: experiences and resolutions beyond COVID-19. *Am J Public Health* 111:384–6.
- Borrego M, Henderson C. 2014. Increasing the use of evidence-based teaching in STEM higher education: a comparison of eight change strategies. *J Eng Educ* 103:220–52.
- Brown JS. 1988. Patch use as an indicator of habitat preference, predation risk, and competition. *Behav Ecol Sociobiol* 22:37–47.
- Bueso-Bordils JJ, Suay-García B, Galiana-Roselló C, Marco-Crespo E, Pérez-Gracia M-T. 2020. Evaluation of the impact of the tiny earth project on the knowledge about antibiotics of pre-university students in the province of Valencia on three different school years (2017–2020). *Front Microbiol* 11:576315.
- Caruso JP, Israel N, Rowland K, Lovelace MJ, Saunders MJ. 2016. Citizen science: the small world initiative improved lecture grades and California critical thinking skills test scores of non-science major students at Florida Atlantic university. *J Microbiol Biol Educ* 17:156–62.
- Chemers MM, Zurbriggen EL, Syed M, Goza BK, Bearman S. 2011. The role of efficacy and identity in science career commitment among underrepresented minority students. *J Soc Issues* 67:469–91.
- Connors PK, Varner J, Erb LP, Dizney L, Lanier HC, Hanson JD, Yahnke CJ, Duggan JM, Flaherty EA. 2020. Squirreling around for science: observing sciurid rodents to investigate animal behavior. *CourseSource* 7. doi: 10.24918/cs.2020.7.
- Cooper KM, Blattman JN, Hendrix T, Brownell SE. 2019. The impact of broadly relevant novel discoveries on student project

- ownership in a traditional lab course turned CURE. *CBE Life Sci Educ* 18:ar57.
- Cox MD. 2004. Introduction to faculty learning communities. *New Dir Teach Learn* 2004:5–23.
- Craig PA. 2017. A survey on faculty perspectives on the transition to a biochemistry course-based undergraduate research experience laboratory. *Biochem Mol Biol Educ* 45:426–36.
- Den Broeder L, Devilee J, Van Oers H, Schuit AJ, Wagemakers A. 2018. Citizen science for public health. *Health Promot Int* 33:505–14.
- Derting TL, Ebert-May D, Henkel TP, Maher JM, Arnold B, Passmore HA. 2016. Assessing faculty professional development in STEM higher education: sustainability of outcomes. *Sci Adv* 2:e1501422.
- Dizney L, Connors PK, Varner J, Duggan JM, Lanier HC, Erb LP, Flaherty EA, Yahnke CJ, Hanson JD. 2020. An introduction to the Squirrel-Net teaching modules. *CourseSource* 7. doi: 10.24918/cs.2020.26.
- Dizney L, Varner J, Duggan JM, Lanier HC, Connors PK, Erb LP, Flaherty EA, Yahnke CJ, Hanson JD. 2021. Squirreling from afar: adapting Squirrel-Net modules for remote teaching and learning. *CourseSource* 8. doi: 10.24918/cs.2021.2.
- Dolan EL. 2016. Course-based undergraduate research experiences: current knowledge and future directions. *Natl Res Counc Comm Pap* 1:1–34.
- Drew JC, Triplett EW. 2008. Whole genome sequencing in the undergraduate classroom: outcomes and lessons from a pilot course. *J Microbiol Biol Educ* 9:3–11.
- Duggan JM, Varner J, Lanier HC, Flaherty EA, Dizney L, Yahnke CJ, Connors PK, Erb LP, Hanson JD. 2020. Squirrels in space: using radio telemetry to explore the space use and movement of sciurid rodents. *CourseSource* 7. doi: 10.24918/cs.2020.25.
- Dvorak AL, Hernandez-Ruiz E. 2019. Outcomes of a course-based undergraduate research experience (CURE) for music therapy and music education students. *J Music Ther* 56:30–60.
- Ebert-May D, Derting TL, Henkel TP, Middlemis Maher J, Mommensen JL, Arnold B, Passmore HA. 2015. Breaking the cycle: future faculty begin teaching with learner-centered strategies after professional development. *CBE Life Sci Educ* 14:ar22.
- Esparza D, Wagler AE, Olimpo JT. 2020. Characterization of instructor and student behaviors in CURE and non-CURE learning environments: impacts on student motivation, science identity development, and perceptions of the laboratory experience. *CBE Life Sci Educ* 19:ar10.
- Estrada M, Eroy-Reveles A, Matsui J. 2018. The influence of affirming kindness and community on broadening participation in STEM career pathways. *Soc Issues Policy Rev* 12:258–97.
- Fey SB, Theus ME, Ramirez AR. 2020. Course-based undergraduate research experiences in a remote setting: two case studies documenting implementation and student perceptions. *Ecol Evol* 10:12528–41.
- Fleischner TL, Espinoza RE, Gerrish GA, Greene HW, Kimmerer RW, Lacey EA, Pace S, Parrish JK, Swain HM, Trombulak SC, et al. 2017. Teaching biology in the field: importance, challenges, and solutions. *Bioscience* 67:558–67.
- Franceschet M, Costantini A. 2010. The effect of scholar collaboration on impact and quality of academic papers. *J Informetr* 4:540–53.
- Freeman S, Eddy SL, McDonough M, Smith MK, Okoroafor N, Jordt H, Wenderoth MP. 2014. Active learning increases student performance in science, engineering, and mathematics. *Proc Natl Acad Sci* 111:8410–5.
- Genné-Bacon EA, Bascom-Slack CA. 2018. The PARE project: a short course-based research project for national surveillance of antibiotic-resistant microbes in environmental samples. *J Microbiol Biol Educ* 19:19.3.97.
- Goodwin EC, Anokhin V, Gray MJ, Zajic DE, Podrabsky JE, Shortlidge EE. 2021. Is this science? Students' experiences of failure make a research-based course feel authentic. *CBE Life Sci Educ* 20:ar10.
- Hanauer DI, Frederick J, Fotinakes B, Strobel SA. 2012. Linguistic analysis of project ownership for undergraduate research experiences. *CBE Life Sci Educ* 11:378–85.
- Hanauer DI, Graham MJ, Sea-Phages, Betancur L, Bobrownicki A, Cresawn SG, Garlena RA, Jacobs-Sera D, Kaufmann N, Pope WH, et al. 2017. An inclusive Research Education Community (iREC): Impact of the SEA-PHAGES program on research outcomes and student learning. *Proc Natl Acad Sci* 114:13531–6.
- Handelsman J, Miller S, Pfund C. 2007. *Scientific teaching*. 1st ed New York (NY): W.H. Freeman and Company.
- Hatfull GF. 2020. Actinobacteriophages: genomics, dynamics, and applications. *Annu Rev Virol* 7:37–61.
- Holt EA, Heim AB, Tessens E, Walker R. 2020. Thanks for inviting me to the party: virtual poster sessions as a way to connect in a time of disconnection. *Ecol Evol* 10:12423–30.
- Hong L, Page SE. 2004. Groups of diverse problem solvers can outperform groups of high-ability problem solvers. *Proc Natl Acad Sci* 101:16385–9.
- Hurley A, Chevrette MG, Acharya DD, Lozano GL, Garavito M, Heinritz J, Balderrama L, Beebe M, DenHartog ML, Corinaldi K, et al. 2021. Tiny Earth: a big idea for STEM education and antibiotic discovery. *mBio* 12:e03432–20.
- Jordan TC, Burnett SH, Carson S, Caruso SM, Clase K, DeJong RJ, Dennehy JJ, Denver DR, Dunbar D, Elgin SCR, et al. 2014. A broadly implementable research course in phage discovery and genomics for first-year undergraduate students. *mBio* 5:e01051–13.
- Kortz KM, van der Hoeven Kraft KJ. 2016. Geoscience education research project: student benefits and effective design of a course-based undergraduate research experience. *J Geosci Educ* 64:24–36.
- Kowalski JR, Hoops GC, Johnson RJ. 2016. Implementation of a collaborative series of classroom-based undergraduate research experiences spanning chemical biology, biochemistry, and neurobiology. *CBE Life Sci Educ* 15:ar55.
- Laungani R, Tanner C, Brooks TD, Clement B, Clouse M, Doyle E, Dworak S, Elder B, Marley K, Schofield FB. 2018. Finding some good in an invasive species: introduction and assessment of a novel CURE to improve experimental design in undergraduate biology classrooms. *J Microbiol Biol Ed* 19:1–8.
- Lee TW, Carpenter BS, Birol O, Katz DJ, Schmeichel KL. 2019. The pipeline CURE: an iterative approach to introduce all students to research throughout a biology curriculum. *CourseSource* 6. doi: 10.24918/cs.2019.29.
- Lopatto D, Hauser C, Jones CJ, Paetkau D, Chandrasekaran V, Dunbar D, MacKinnon C, Stamm J, Alvarez C, Barnard D, et al. 2014. A central support system can facilitate implementation and sustainability of a classroom-based undergraduate research experience (CURE) in genomics. *CBE Life Sci Educ* 13:711–23.

- Malotky MKH, Mayes KM, Price KM, Smith G, Mann SN, Guin-
yard MW, Veale S, Ksor V, Siu L, Mlo H, et al. 2020. Fostering
inclusion through an interinstitutional, community-engaged,
course-based undergraduate research experience. *J Microbiol
Biol Educ* 21:21.1.31.
- McDonald KK, Martin AR, Watters CP, Landerholm TE. 2019.
A faculty development model for transforming a department's
laboratory curriculum with course-based undergraduate re-
search experiences. *J Coll Sci Teach* 48(3):14–23.
- McGee R, Saran S, Krulwich TA. 2012. Diversity in the biomed-
ical research workforce: developing talent. *Mt Sinai J Med J
Transl Pers Med* 79:397–411.
- Myers O, Saunders C, Bexell S. 2009. Fostering empathy with
wildlife: Factors affecting free-choice learning for conservation
concern and behavior. In: Falk J, Heimlich J, Foutz S, editors.
Free-choice learning and the environment. Lanham (MD): Al-
tamira Press.
- Myers T, Maibach E, Roser-Renouf C, Akerlof K, Leiserowitz A.
2013. The relationship between personal experience and belief
in the reality of global warming. *Nat Clim Change* 3:343–7.
- Phillips KW. 2014. How diversity makes us smarter. *Sci Am*
311:42–7.
- Rigby J, Edler J. 2005. Peering inside research networks: some
observations on the effect of the intensity of collaboration on
the variability of research quality. *Res Policy* 34:784–94.
- Shaffer CD, Alvarez C, Bailey C, Barnard D, Bhalla S, Chan-
drasekaran C, Chandrasekaran V, Chung H-M, Dorer DR, Du
C, et al. 2010. The genomics education partnership: success-
ful integration of research into laboratory classes at a diverse
group of undergraduate institutions. *CBE Life Sci Educ* 9:55–
69.
- Siemens L. 2020. A hole in the wall: The potential of persistent
video-enabled communication channels to facilitate collabora-
tion in dispersed teams *Pop Public Open Particip* 2. doi:
10.48404/pop.2020.06.
- Springer L, Stanne ME, Donovan SS. 1999. Effects of small-
group learning on undergraduates in science, mathematics,
engineering, and technology: A meta-analysis. *Rev Educ Res*
69:21–51.
- Staub NL, Poxleitner M, Braley A, Smith-Flores H, Pribbenow
CM, Jaworski L, Lopatto D, Anders KR. 2016. Scaling up:
adapting a phage-hunting course to increase participation of
first-year students in research. *CBE Life Sci Educ* 15:ar13.
- Syed M, Zurbriggen EL, Chemers MM, Goza BK, Bearman
S, Crosby FJ, Shaw JM, Hunter L, Morgan EM. 2019. The
role of self-efficacy and identity in mediating the effects of
STEM support experiences. *Anal Soc Issues Public Policy* 19:
7–49.
- Termini CM, Pang A. 2020. Beyond the bench: how inclusion and
exclusion make us the scientists we are. *Mol Biol Cell* 31:2164–
7.
- Theodosiou NA, Corbin JD. 2020. Redesign your in-person
course for online: creating connections and promoting engage-
ment for better learning. *Ecol Evol* 10:12561–72.
- Thiry H, Weston TJ, Laursen SL, Hunter A-B. 2012. The benefits
of multi-year research experiences: differences in novice and
experienced students' reported gains from undergraduate re-
search. *CBE Life Sci Educ* 11:260–72.
- Varner J, Lanier HC, Duggan JM, Dizney L, Flaherty EA,
Connors PK, Erb LP, Yahnke CJ, Hanson JD. 2020. How
many squirrels are in the shrubs? A lesson plan for compar-
ing methods for population estimation. *CourseSource* 7. doi:
10.24918/cs.2020.6.
- Vermeulen N, Parker JN, Penders B. 2013. Understanding life to-
gether: a brief history of collaboration in biology. *Endeavour*
37:162–71.
- Wiley EA, Stover NA. 2014. Immediate dissemination of stu-
dent discoveries to a model organism database enhances
classroom-based research experiences. *CBE Life Sci Educ* 13:
131–8.
- Yahnke CJ, Dizney L, Varner J, Duggan JM, Lanier HC, Erb
LP, Flaherty EA, Connors PK, Hanson JD. 2020. Sorry to eat
and run: a lesson plan for testing trade-offs in squirrel behav-
ior using giving up densities (GUDs). *CourseSource* 7. doi:
10.24918/cs.2020.30.
- Zavaleta ES, Beltran RS, Borker AL. 2020. How field courses
propel inclusion and collective excellence. *Trends Ecol Evol*
35:953–6.