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Eco-Education

Improving access to undergraduate research using digitized natural history collections course-based research experiences

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Abstract

Course-based undergraduate research experiences (CUREs) can be a powerful tool in broadening participation in undergraduate research. In this paper, we review the benefits of and barriers to undergraduate research experiences and explore how CUREs can mitigate some of those issues. As a part of the NSF-supported Biological Collections in Ecology and Evolution Network (BCEENET) activities, a series of network meetings produced a set of recommendations to increase the accessibility of CUREs for all students at all institution types. We use BCEENET CUREs that focus on digitized natural history collections data to illustrate how leveraging adaptable open educational resources that use freely available data and analysis tools can increase accessibility of undergraduate research. We also discuss how inclusive networks of

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educators and research collaborators can support broadening CURE implementation.

KEYWORDS
accessibility, CURE, digital data, digitized natural history collections, ecology, equity, evolution, inclusion, open access resource, open educational resource

BACKGROUND

Undergraduate research experiences (UREs) are widely recognized as a critical component of undergraduate STEM education (e.g., American Association for the Advancement of Science, 2011) that improve student learning outcomes (Ing et al., 2021). These experiences support student gains in research and professional skills, which are positively associated with increased student self-efficacy (Adedokun et al., 2013; Bauer & Bennett, 2003; Flaherty et al., 2017; Hunter et al., 2007; Kardash, 2000; Lopatto, 2004; Thiry & Laursen, 2009). Undergraduate researchers show growth in self-identification as scientists and their sense of belonging in scientific communities (Cooper et al., 2020; Hunter et al., 2007; Mraz-Craig et al., 2021).

Students who engage in UREs have higher overall graduation rates (Haeger et al., 2024) and are more likely to persist and graduate in their STEM majors (Jones et al., 2010; Nagda et al., 1998; Rodenbusch et al., 2016). UREs help students to clarify their career aspirations and decide whether they are interested in attending graduate school (Hunter et al., 2007; Russell et al., 2007; Seymour et al., 2004; Smith et al., 2021; Zydney et al., 2002). Student researchers show increased interest in pursuing graduate studies in STEM-related disciplines (Eagan et al., 2013; Harrison et al., 2011; Sorensen et al., 2018), enter graduate programs at higher rates (Bauer & Bennett, 2003; Hathaway et al., 2002; Zydney et al., 2002), and show increased interest in pursuing a career in STEM fields (Harrison et al., 2011; Mraz-Craig et al., 2021; Sorensen et al., 2018).

While the benefits of UREs have been clearly demonstrated, access to research experiences and the associated benefits is uneven across diverse student populations and institutional types. Historically, UREs in STEM were primarily based on an apprenticeship model, which greatly limited accessibility of these experiences (Wei & Woodin, 2011). Faculty engaging students under this model typically only have time and resources for a small number of undergraduates, resulting in a lack of opportunities for most students (Bangera & Brownell, 2014; Linn et al., 2015; Wei & Woodin, 2011).

Student access to UREs is littered with challenges, beginning with knowing they should engage in research, understanding the benefits of participating in research, learning of research opportunities, reaching out to faculty and other gatekeepers, applying to programs, and competing with other students for opportunities (reviewed in Cooper et al., 2021). The magnitude of these challenges will vary based on a student's social capital—the resources gained through relationships, network associations, group membership, and identity (Bourdieu, 1986; Gin et al., 2022). Interactions with professors are influenced by race and institution type, with students of color having the greatest difficulties connecting to faculty at primarily white institutions (Hurtado et al., 2011; Shehab et al., 2007). This exacerbates limited access to research opportunities as students of color report difficulty finding willing research mentors at primarily White institutions (McCoy et al., 2017). Additionally, students with disabilities can find it challenging and potentially problematic to self-advocate for accommodations that support participation in STEM education, and these challenges may be increased by the intersectionality of disability, race, and gender (Gin et al., 2022; Pfeifer et al., 2021). Access to scarce UREs relies on a hidden curriculum (i.e., word-of-mouth or faculty invitation) that can act as a barrier for students based on race, ethnicity, and social background (Bangera & Brownell, 2014; Pierszalowski et al., 2021). This may also specifically place first-generation college students at a severe disadvantage (Bangera & Brownell, 2014).

There is a lack of published evidence on how the additional time commitments required for many apprentice-style UREs may be unmanageable for students from diverse backgrounds and with other responsibilities. In 2020, 40% of full-time students and 74% of part-time students were employed (National Center for Education Statistics, 2022). For students whose economic status requires them to work part- or full-time, potential loss of wages can be an important consideration in deciding whether or not to pursue a research experience. Many research opportunities for undergraduates are unpaid, a practice that has been criticized by the research community as it may exclude students from economically disadvantaged backgrounds (Bautista, 2022; Emery et al., 2019; Fournier & Bond, 2015). For student caregivers who have a lower quantity and quality of time available (time poverty), there are negative impacts on college persistence and

credit accumulation (Wladis et al., 2018) that would likely be exacerbated by the time required for independent research. One study found that nearly 6% of undergraduate and graduate students at a public university in North Carolina identified as caregivers for a minor or someone who is elderly or chronically ill (Armstrong-Carter et al., 2022). These economic and time barriers mean that for equitable access to the demonstrated benefits of UREs, educators must bring research experiences into the everyday classroom curriculum for all students (Handelsman et al., 2022).

Course-based undergraduate research experiences can help to remove barriers by bringing research into the classroom

There have been numerous calls to expand the implementation of course-based undergraduate research experiences (CUREs) to reach more students and improve equity in STEM education nationwide (Elgin et al., 2021; Estrada et al., 2016; Rodenbusch et al., 2016). CUREs increase access to authentic research experiences because they are embedded into courses and therefore are available to all students (Auchincloss et al., 2014; Bangera & Brownell, 2014; Corwin et al., 2015; Linn et al., 2015; Smith et al., 2021). CUREs also reduce barriers, such as lack of awareness of opportunities and their benefits, and challenges in contacting faculty about potential projects (Bangera & Brownell, 2014; Hurtado et al., 2011; Pierszalowski et al., 2021). Additionally, as students already allot time for coursework each week, CUREs can reduce personal and financial barriers, allowing all students to participate in research as a required and integral part of regularly scheduled course activities, therefore gaining the associated benefits (Genet, 2021).

Despite the many advantages of CUREs for democratizing research experiences for all students, implementation of a CURE can be challenging at some institutions. Faculty may lack the required departmental or administrative approval to modify courses to include research experiences, especially if the research requires large financial investments (Ero-Tolliver, 2019; Messager et al., 2022; Spell et al., 2014). Additionally, faculty can be prevented from learning new teaching methods and developing new teaching materials due to lack of time caused by high teaching loads or lack of financial support for professional development (Shortlidge et al., 2016; Spell et al., 2014). Educators worry that their lack of expertise or experience in a particular field may prevent them from beginning a CURE (Shortlidge et al., 2016), and graduate student instructors with less teaching experience yield variable outcomes without CURE-specific training (Shortlidge et al., 2023). Also, faculty at community colleges often report that they feel isolated from scientific communities, and this lack of connection impedes their ability to offer undergraduate research (Hewlett, 2018). Compounding this, many 2-year institutions may not have the physical laboratory facilities or funding for supplies to support costly UREs. Together, these barriers reduce accessibility to CUREs for many students, especially at under-resourced institutions, and contribute to uneven CURE implementation across institution types (Govindan et al., 2020).

DIGITAL OPEN ACCESS RESOURCES CAN REDUCE BARRIERS TO CURE IMPLEMENTATION

Digital open access resources (e.g., open source/free software and open access data) can help to mitigate the impacts of financial barriers to CURE implementation. These resources can reduce costs and physical obstacles for both institutions and students, thereby increasing implementation potential for CUREs. For example, these resources can be used to create CUREs that can be implemented in institutional types where laboratory access may be limited, or across a variety of course formats, including different course sizes, levels, durations, and modalities. The proliferation of open access resources has created new undergraduate research opportunities that can be offered even when there is a lack of institutional resources, whether temporary (e.g., COVID-19 pandemic) or long-term (Cook et al., 2014; Record et al., 2022). In ecology and evolutionary biology, the ability to offer undergraduate research opportunities can be further limited by field season constraints (e.g., lack of annual plants in dry or cold seasons) and travel limitations for fieldwork. Yet, digital open data resources (e.g., iDigBio, Global Biodiversity Information Facility [GBIF], National Ecological Observatory Network [NEON], eBird, and GenBank) allow all students to access large datasets suitable to address cutting-edge research questions in ecology and evolution through all seasons and across geographic regions when travel costs would be prohibitive.

Digitized natural history collections (dNHC) data aggregators (e.g., iDigBio and GBIF) have rapidly grown into important resources for increasing access to UREs (Cook et al., 2014). Natural history museums and herbaria have digitized and made publicly accessible taxonomic data, collection locality information (sometimes including GPS coordinates), habitat characteristics, and digital images of millions of specimens (Lendemer et al., 2020; NASEM, 2020; Nelson & Ellis, 2019). With over 139 million specimen records (iDigBio, 2024) and

over 2.6 billion occurrence records (GBIF, 2024) spanning multiple centuries, these digital aggregators provide access to dNHC data to students and educators around the globe regardless of their proximity to the physical collections (Krumm et al., 2018; Monfils et al., 2017). Using dNHCs reduces barriers because research activities are possible anywhere there is internet access, can be conducted year-round with no travel or special equipment requirements, and do not involve activities that are difficult to navigate with physical disabilities such as off-trail sampling and field experiences (Gin et al., 2022; Trillo et al., 2022).

The expansive nature of natural history collections data makes it possible for researchers to address a wide variety of questions (Nelson & Ellis, 2019; Winker, 2004). Collections data have long been used for research in biodiversity, taxonomy, and systematics, and combined with increasingly available climate and land cover data, these resources can also answer important ecological questions (Lacey et al., 2017). Educators and researchers have created resources and modules to engage undergraduates with dNHC resources through groups like Biological Collections in Ecology and Evolution Network (BCEENET; Doan et al., 2022; Trillo et al., 2022), Biodiversity Literacy in Undergraduate Education (BLUE; Ellwood et al., 2019), and Advancing Integration of Museums into Undergraduate Programs (AIM-UP; Cook et al., 2014; Lacey et al., 2017). By utilizing dNHC data, students are able to download and analyze large datasets, gaining experience in the use, organization, and analysis of big data (Lacey et al., 2017; Mabry et al., 2022), a key area of expertise in current biological research and an important step toward creating a data-literate STEM workforce (Ellwood et al., 2020; Gibson & Mourad, 2018; O'Reilly et al., 2017).

Combining dNHC data resources with open access data analysis programs can provide all students with opportunities to practice valuable data analysis skills. It is generally accepted that access to costly software limits their use at many institutions (Williams et al., 2019; Ye et al., 2014). Fortunately, free software is available for many research activities, including statistical analyses (i.e., R studio), image analyses (i.e., ImageJ/Fiji), and geospatial analyses (i.e., QGIS, Google Earth, GEOLocate).

Open educational resources (OER) are shared digitized learning resources created intentionally to be freely used, modified, and distributed (OECD, 2007). OERs can address barriers to research by providing instructional materials for both students and educators (e.g., Data Carpentries; Teal et al., 2015 and QUBEShub; Donovan et al., 2018). Additionally, by developing and choosing OERs that maximize accessibility for disabled learners, educators can more effectively support learning experiences for all students (Zhang et al., 2020). Together, dNHC data, free software, and accessible OER resources have the potential to level the playing field for research opportunities and train students in critical data science skills including data literacy, management, and analysis.

RECOMMENDATIONS FOR INCREASING ACCESS THROUGH DIGITAL OER CURES

Increasing accessibility to UREs is a core goal of the BCEENET, a research coordination network in undergraduate biology education. This network supports collaboration between undergraduate educators, natural history collections professionals, education and collections researchers, and data experts to expand access to UREs through dNHC CUREs. Since its origin in 2019, BCEENET has grown from 11 founding members to a collaborative network of over 100 active members representing dozens of institutions across North America. The BCEENET community has aggregated around a series of recommendations for expanding access to undergraduate research in ecology and evolution through OER CUREs. Three areas have been identified as critical to the successful widespread implementation of OER CUREs: (1) establishment of inclusive networks of OER CURE implementers and collaborators; (2) creation of adaptable, accessible, and inclusive OER CUREs in ecology and evolution; and (3) support of implementation of OER CUREs (Box 1).

The creation of OER CURE networks that bring together CURE implementers with experts in pedagogy and research expertise can provide a strong supportive community as well as opening the door to collaboration in both CURE research topics and pedagogical studies. Additionally, faculty implementing a CURE benefit from a central support structure that provides curriculum resources, workshops, and expertise (Lopatto et al., 2014). Efforts to make these networks inclusive, including establishing community norms and expectations, are critical in being welcoming to diverse participants and expanding access across institution types.

Improving the accessibility of OER CUREs is an important aspect of increasing research opportunities in ecology and evolution for all students. Regardless of institution type, we believe adaptable OER CUREs using open access data and programs can provide accessible research experiences. Flexibility in implementation can increase access for students who have extended absences or an inability to participate fully in in-person activities and can provide access to undergraduate research opportunities for students attending in hybrid or online formats. Additionally, ensuring that OER materials follow Universal Design for Learning (UDL) guidelines can

BOX 1 Recommendations for successful widespread implementation of digital open education resource (OER) course-based undergraduate research experiences (CUREs)

Establish inclusive networks of OER CURE implementers and collaborators

- Develop faculty mentoring support networks for those implementing OER CUREs.
- Create opportunities for collaboration between educators, research experts, and professionals.
- Collaborate with individuals with expertise on CURE development, including diversity training and inclusive pedagogy.
- Collaborate with research and data communities relevant to the open access programs and data the CUREs use (i.e., iDigBio).
- Collaborate with CURE-related networks to grow expertise in the community (i.e., BCEENET, CUREnet, Squirrel-Net, CCURI).
- Provide formal and informal online opportunities for community members to get together to foster a sense of belonging.
- Establish community norms for behavior and inclusivity, including a code of conduct and a diversity, equity, and inclusion statement.

Create adaptable, accessible, and inclusive OER CUREs in ecology and evolution

- Use research tools (databases, software) that are free and accessible by anyone, thereby reducing costs and minimizing technological barriers for students and instructors.
- Create flexible CUREs that can support in-person, hybrid, and online learning formats to expand research opportunities into more courses and allow continuity in the face of challenges (long-term student illness, pandemic).
- Design CUREs for use in first year through advanced courses. This may be achieved with varying levels of structure or add-ons for increasing independence or complexity.
- Design CUREs with a flexibility in focal species and topics to allow instructors and students to engage with community-driven and/or place-based issues and topics.
- Publish CUREs as OERs. Faculty can adapt the materials to fit their research interests and student learning objectives.
- Create CURE materials that adhere to principles of universal design for learning (Capp, 2017).

Support implementation of OER CUREs

- Reach underserved students through targeted outreach to faculty at community colleges and minority-serving institutions.
- Encourage faculty participation through funded training and implementation fellowships.
- Create free, accessible training opportunities for novice to experienced implementers in both live and recorded formats to maximize access by educators.
- Provide ongoing access to timely support for instructors on course design and technology issues throughout implementation.
- Assess impacts of OER CUREs (i.e., student learning, identity) to create evidence of efficacy that will encourage and support broad implementation of OER CUREs.

enhance learning experiences and remove barriers for all students.

Implementing a CURE for the first time can be a daunting task, particularly if the research is not directly in one's area of training or expertise or instructors encounter institutional barriers. Targeting outreach and support to instructors at institutions that are under-resourced or serving large numbers of historically excluded students, through focused recruitment efforts and funded training and implementation opportunities, can expand access to UREs for all. Creating training materials that introduce instructors to necessary datasets and open access analysis programs is essential because without accessible training, instructors and researchers can be hesitant or unable to incorporate new tools (Ye et al., 2014). Training should be provided both live and asynchronously to maximize

availability. Timely support for implementers is also crucial and may take many forms: holding drop-in office hours for technical and pedagogical questions, creating spaces for quick communication with experienced implementers (i.e., on a message board or a platform such as Slack), and offering opportunities for live, virtual help in the classroom via Zoom. Securing funding for experienced implementers to provide this support is important and also fosters further engagement among the network. Finally, evidence of CURE impacts through assessment can encourage broader and continued implementation.

BCEENET is implementing these recommendations using dNHC CUREs

BCEENET is a community of practice (Wenger, 1998) supporting dNHC CUREs through training, materials development and distribution, and ongoing implementer support. Community events, both formal and informal, have provided spaces for BCEENET members to establish a sense of belonging and create new projects and opportunities for participating in grant and program development. Links across OER CURE networks and connections to groups with related interests provide opportunities to share expertise and expand the reach of each network and group. BCEENET connects with CUREnet for training expertise, collaborates with SquirrelNet on CURE workshops, works with the Hidden Figures Network to increase distribution of OER CURE materials, and continues to welcome new collaborations.

BCEENET members with diverse areas of expertise (e.g., botany, entomology, data science, collections) collaborated to create four highly adaptable CUREs (Box 2). Suggestions from members included using specimen locality data to map shifts in species distributions, identifying species that are well represented in collections, and examining species that are likely to have images associated with the specimen record. Each of the BCEENET CUREs uses freely available dNHC data and can be completed with only internet access and computers, using open-source analysis tools such as QGIS and ImageJ. Because they make use of freely available online resources, these CUREs do not require continual funding to implement, allowing their sustained use. The CUREs also use only OERs, including hundreds of documents created by BCEENET members. This intersection of open access dNHC data and resources with the accessible CURE undergraduate research format brings together key elements that can greatly contribute to equity in undergraduate research.

These CUREs are extremely flexible and have been implemented in person, online, and in hybrid formats, both synchronously and asynchronously, with course lengths ranging from 4 to 16 weeks. BCEENET CUREs have been adapted to fit into a variety of course topics and levels, from non-majors introductory biology/environmental science courses to advanced ecology seminars, with enrollments from 8 to 250 (Table 1). Their adaptable nature allows instructors to use the same CURE year after year, easily creating new iterations or posing new questions by shifting species or locations, and many faculty have repeated their implementation of a BCEENET CURE. In the 5 years since

BOX 2 Summary of the initial four Biological Collections in Ecology and Evolution Network course-based undergraduate research experiences (BCEENET CUREs)

A CURE for invasions: Mobilizing digitized natural history collections to track invasive species. Students test hypotheses on potential mechanisms that influence the dispersal of invasive species through mapping and spatial analyses.

Species distribution changes: Exploring species distribution changes and their drivers using digitized natural history data. Students independently formulate and test research questions about how human impacts can accelerate shifts in species distributions.

Morphology CURE: Exploring the effects of invasion on plant morphology. Students use digital herbarium specimens to collect morphological data on invasive plant species and compare those data between native and invasive ranges.

Sexual dimorphism CURE: Exploring melanized wing patterns of Pieridae butterflies. Students measure melanization patterns using specimen images to test hypotheses about the impacts of sexual selection on variation in forewing melanization.

TABLE 1 Summary of Biological Collections in Ecology and Evolution Network (BCEENET) course-based undergraduate research experiences implementation from fall 2020 to spring 2024 by institution type, course type, and course audience.

Category	Type	No.
Course content	Introductory biology	19
	Ecology	10
	Plant biology	10
	Evolution	2
	Entomology	1
	Other/special topics	9
Course level	Introductory	23
	Intermediate/advanced	25
Institution type	PUI	26
	2-year	9
	R1	7
	R2	1
	Comprehensive	1
MSI	Total	13
	AANAPISI	7
	HBCU	3
	TCU	3
	HSI	2
	NASNTI	1

Note: Courses that were taught multiple times were only included once in the analysis. MSI subtypes do not sum to the total number of MSIs because some institutions hold multiple MSI designations. Data on course types were self-reported by instructors.

Abbreviations: AANAPISI, Asian American, Native American, and Pacific Islander–serving institutions; HBCU, historically black colleges and universities; HSI, Hispanic-serving institutions; MSI, minority-serving institutions; NASNTI, Native American–serving non-tribal institutions; PUI, primarily undergraduate institution; R1, doctoral universities, very high research activity; R2, doctoral universities, high research activity; TCU, tribal colleges and universities.

the formation of BCEENET, over 3800 undergraduates have participated in BCEENET CUREs at 43 institutions, including many community colleges and minority-serving institutions. All of the CURE materials and additional curricular publications will be made publicly available on the BCEENET page on QUBES (https://qubeshub.org/community/groups/bceenet).

In addition to recruiting at national meetings, BCEENET holds targeted regional workshops at community colleges and associated conferences, reaching faculty implementers from diverse institution types. BCEENET funds a pair of CURE facilitators each semester to provide technical and curricular support for implementers. We hold live, virtual summer training workshops; provide recordings of training sessions; and publish teaching modules to instruct both students and faculty how to use essential open access tools used in our CUREs. We also support assessment of the impacts of BCEENET CUREs on student learning and science identity in an effort to accumulate evidence to encourage institutional support and increase implementation.

SUMMARY

In this paper, we bring attention to the positive impacts of CUREs in increasing access to UREs, while recognizing the work that still needs to be done to increase equity and access in this field. We have created a set of recommendations that outline actions that could contribute to this effort. We also introduce the BCEENET community, highlighting implementation and support, materials development, and assessment. Our intent is to open discussions about ways to improve accessibility of CUREs and encourage the education community to engage with the suggested actions in a meaningful way to expand access to and broaden participation in undergraduate research for all students.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

No data were collected for this study.

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