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CURE for Undergraduate Education: How Course-based Undergraduate Research Experiences (CUREs) can scale innovative practices in STEM education and assessment

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Abstract

As part of a large effort to study educational innovation, we developed, implemented, and assessed the effectiveness of Course-based Undergraduate Research Experiences (CUREs) across five large universities in the USA. We developed five semester-long STEM courses to offer undergraduates the opportunity to conduct cutting-edge and team-based original research projects. To assess the effectiveness of the CUREs in meeting overarching teaching and learning objectives, we conducted paired pre- and post- surveys of >2,500 undergraduate participants (including students in non-CURE control courses). We found statistically significant increases in interdisciplinary thinking, confidence in scientific skills, sense of science identity, intention to pursue STEM careers, and teamwork satisfaction. These gains were greater in CURE courses than in non-CURE control courses - and greater still for underrepresented minority and first-generation college student. We highlight the value of CUREs for increasing student engagement, belonging, and retention in STEM fields.

Keywords: *educational innovation; active learning; STEM education, team-based learning, program assessment, comparative education.*

1. Introduction

Many studies in higher education have shown that early research experiences increase student persistence in STEM fields (e.g., Seymour et al. 2004, Russell et al. 2007, Lopatto 2007). This is especially true for students from historically underrepresented groups (Jones et al. 2010, Espinosa 2011, Hernandez et al. 2013). However, opportunities for students to gain research experiences are not widely accessible, even at the undergraduate level (Wei & Woodin 2011). Laboratory courses typically provide exposure to "cookbook" - rather than original - research approaches. Moreover, relatively few students obtain one-on-one mentored research experiences outside the classroom. Thus, it can be difficult to scale best practices in STEM education and provide meaningful research experiences to large numbers of undergraduate students.

One solution to this challenge is to embed mentored research experiences within standard university courses. Because the opportunity to conduct original research increases persistence of undergraduate students in STEM, both the President's Council of Advisors on Science and Technology and the American Association for the Advancement of Science recommend replacing standard undergraduate lab courses with discovery-based research courses. Course-based Undergraduate Research Experiences (CUREs) can reach large numbers of students and satisfy the need for early research exposure within the curriculum. Additional innovation within the CURE framework – like team-based research approaches – can further scale the impact of research experiences for undergraduates.

As part of a large, multi-university Biology Integration Institute (sponsored by the US National Science Foundation), we developed, implemented, and assessed five semester-long undergraduate CURE courses. We focused specifically on scaling the reach of our courses using a team-research approach, whereby students work in small groups on original research projects. We measured student outcomes in CURE courses versus standard lab-based courses in multiple demographic groups across five different US universities. Below we describe our universal design principles, assessment approach, teaching and learning outcomes, and recommendations for incorporating more discovery-based research approaches into STEM curricula.

2. Methods

2.1. Course design

We used an established CURE model (Auchincloss et al. 2014. Bangera & Brownell 2014) to create interdisciplinary courses to allow groups of undergraduate students to investigate original research questions of broad scientific importance. We designed our CURE courses to explicitly engage students in the five features of work that define a CURE:

(1) employs multiple scientific practices (e.g., proposing hypotheses, analyzing data, communicating findings)
(2) leads to scientific discovery (e.g., the outcome is unknown to student and instructor)
(3) has meaning beyond the course (e.g., to the broader scientific community)
(4) is collaborative (e.g., team-based)
(5) is iterative (e.g., builds on other work or uses multiple interdependent approaches)

Thematically, our US National Science Foundation funded Biology Integration Institute focuses on the theme of *Biodiversity Resilience*, specifically the decline and rebound of amphibians around the world. Therefore, our CURE courses generally focus on studying local amphibian populations near our focal universities.

- At the **University of Pittsburgh** and **Vanderbilt University**, the "*Frog Slime CURE"* offers students an opportunity to investigate amphibian defenses against pathogens. Students use samples of amphibian skin mucus to generate research questions and test hypotheses about the role of constituents, like antimicrobial peptides and the microbiome, as antifungal defenses. Students use techniques in disease ecology, microbiology, cell biology, chemistry, and bioinformatics to identify defensive compounds, test hypotheses about antifungal defenses, and build predictions about fungal pathogens and their hosts. In a separate Organic Chemistry *"Antimicrobials Discovery CURE"* at Pittsburgh, students perform chemical extractions and separations from slime bacteria to isolate and identify antifungal compounds.
- At the **University of Mississippi**, the "*Conservation Physiology CURE"* offers students an opportunity to investigate the impacts of interacting stressors on amphibian resilience using physiological tools. Students design and propose research projects focused on examining the effects of abiotic and biotic variables on ectotherm physiology, including thermal traits and immune function, in both lab and field settings, to test hypotheses about how climate and disease interact to affect resilience. Students then collect, analyze, and interpret their data as a group, culminating in a poster presentation to the biology department.
- At the **University of California, Berkeley**, the "*Genomics of Amphibian Declines CURE*" offers students an opportunity to evaluate pathogen presence in local amphibian populations and waterways. Students are guided through all stages of the scientific research process from reading the primary literature and forming hypotheses to designing field experiments, to collecting and analyzing DNA samples, to statistical analysis and scientific communication. Students integrate ecological and molecular biology to test hypotheses about factors effecting pathogen presence in local amphibians and present their results at a culminating showcase.

- At the **University of Massachusetts** the "*Microbiome CURE*" offers students an opportunity to investigate the contribution of the skin microbiome to amphibian resilience. Using non-invasive skin swab samples, students apply cutting-edge tools in molecular biology and microbiology to test hypotheses about the microbiome's role in amphibian resilience.

Thus, the content of each course is unique, but the principles underlying their design is shared, particularly with regard to course assessment.

2.2. Course assessment

We designed two types of assessments for our CURE courses. First, we assessed student progress and performance following best practices to ensure alignment of learning objectives, course activities, and assessments (Shortlidge & Brownell 2016). Assessments in this first category included scaffolded student papers, presentations, and reflection exercises and were unique to each institution. Second, we assessed higher level learning objectives of our courses using programmatic assessment tools. Assessments in this second category included pre- and post- course surveys and were shared across all institutions.

Our matched pre- and post-assessments provided students an opportunity to self-assess - on a five-point scale from "strongly disagree" to "strongly agree" - on the following topics:

- Interdisciplinary thinking*:* 7 questions, e.g., "*I can use what I have learned in one field in another setting", "I see connections between ideas in biology and ideas in the humanities and social sciences"*, and "*I enjoy thinking about how different fields approach the same problem in different ways*" (Lattuca et al. 2012).

- Science efficacy: 6 questions, e.g., "*I am confident I can use technical tools, instruments, and techniques*", "*I am confident I can generate a research questions to answer", "I am confident I can use scientific literature to guide my research*" (Hanauer et al. 2017).

- Science identity*;* 5 questions; e.g., "*I think of myself as a scientist", "I see myself as a science communicator*", and "*I feel like I belong in the field of science*" (Hanauer et al. 2017).

- Career intention: 5 questions; e.g., "*I intend to pursue a science-related career", "I intend to enroll in a science related graduate program*", and "*In the future, I would like to be a research scientist*" (Camacho et al. 2021).

- Teamwork satisfaction*:* 3 questions; e.g., "*I have found that working as part of a team to be a valuable experience", "In most of the teams I have been on, the team has* *worked well together",* and *"I have found teamwork to be a productive use of course time*", and "*I have found that working with a team has enhanced my sense of who I am*" (Gallegos et al.2011).

Surveys were administered through Qualtrics (goshenconsulting.qualtrics.com) with control and normalizing features such as mid-survey attention checks. In addition to surveying CURE participants, we also surveyed students in thematically related biology courses lacking an original research project (i.e., non-CUREs). We used these non-discovery courses as controls. Results were analyzed using standard paired statistical approaches.

3. Results

We analyzed matched pre- and post-survey data from 2,689 students enrolled in our courses between 2020-2024 across five universities. 2,052 of these students participated in one of our CURE courses, while 611 students participated in one of our "control" courses (STEM courses with traditional labs but no original team-based research projects). We also looked separately at the subset of students who self-identified as underrepresented minorities (137 students) or first-generation college students (196 students). We present here the results of our pooled analyses across all universities (Figure 1, Figure 2).

Overall, students in both traditional lab courses and CURE courses self-reported significantly increased skills, confidence, and belonging in all categories measured (i.e., interdisciplinary thinking, science efficacy, science identity, career intention, teamwork satisfaction) over the course of one semester (Figure 1). However, students in CURE courses exhibited greater gains and higher ending scores than students in non-CURE courses (Figure 1, Figure 2). Specifically, students in the CURE courses exhibited greater gains in *all* categories measured compared to students in traditional laboratory courses. Similarly, in all categories except "teamwork satisfaction", students in CURE courses had higher ending scores than students in traditional lab courses (it is worth noting, that "teamwork satisfaction" was the category with the lowest scores overall, reflecting undergraduate student ambivalence toward working in teams).

Beyond, demonstrating an overall positive impact of CURE courses, our data also suggest that under-represented minorities (URM) and first-generation college students (First-Gen) benefitted disproportionately. URM or First-Gen students showed the highest gains (delta pre-post scores) in all categories except career intention. Gains in these student demographics are particularly notable given lower statistical power from smaller sample sizes. Because demographic questions were optional to answer, the proportion of URM and First-Gen students in the total sample pool is also likely larger than documented here. It is also important to note that the slight numerical decrease is career intention for URM students is not statistically different from zero.

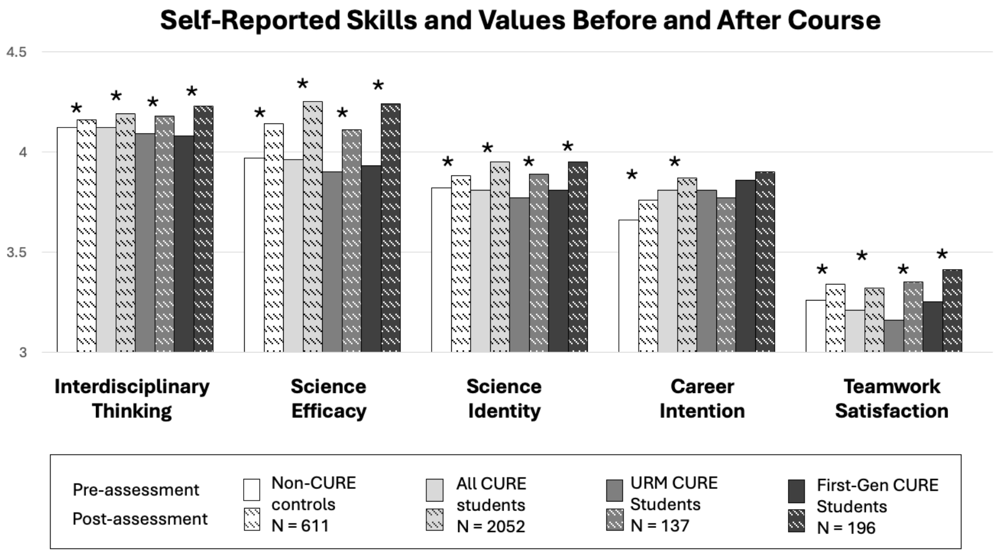

Figure 1. Average scores from paired self-assessment from 2,689 students across five US universities. Students responded to the same questions at the beginning (pre) and end (post) of the semester on a five-point scale (1 = "strongly disagree". 2 = "disagree", 3 = "neither agree nor disagree", 4 = "agree" and 5 = "strongly agree"). All averages were above 3, so the y-axis is scaled accordingly. Students in both CURE and non-CURE courses showed a significant increase in all categories, but CURE students exhibited higher ending scores in all arenas except "teamwork satisfaction". Students self-reporting as under-represented minorities (URM) or first-generation (First-Gen) were evaluated independently. Asterisks indicate statistically significant differences between pre and post averages within categories.

4. Discussion

Fostering a sense of belonging and STEM identity for undergraduates at large universities can be challenging. However, our results suggested that CUREs, particularly those that employ teamwork, can have significant impacts on key STEM learning outcomes. Moreover, CUREs can be particularly effective in increasing the sense of belonging for under-represented minorities and first-generation students, especially when these students enter the semester with a lower sense of belonging than their peers. The positive impact of discovery programs on historically marginalized student populations is consistent with other recent research (Gillen-O'Neel, 2019; Murphy and Zirkel, 2015) and the important finding that sense of belonging is associated with numerous positive outcomes for historically marginalized students, including metrics of GPA, retention, and health outcomes (Murphy et al., 2020; Walton and Cohen, 2011).

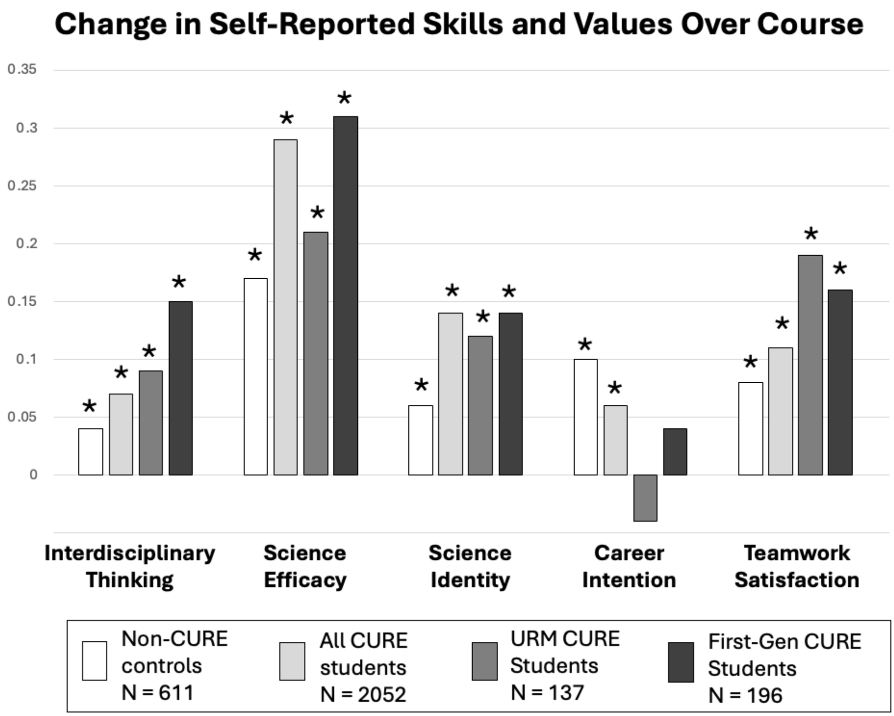

Figure 2. Average change in scores between pre- and post- self-assessment across 2,689 students across five US universities. Students in both CURE and non-CURE courses showed a significant increase in all categories, but CURE students showed a greater change in all arenas except "career intention". URM and/or First-Gen students reported the greatest gains in all categories except "career intention". Asterisks indicate statistically significant differences between pre and post averages within categories.

One limitation of this study is that students were only surveyed over the course of the semester when they participated in a CURE. We do not know whether student sense of STEM belonging or confidence persists over longer timescales. Future studies should employ surveys that are administered multiple times with anonymous identifiers to track student experience before, during, and after CURE interventions. A more longitudinal study of the same students could reveal the changing needs of students over time and how mentored research interventions can be tailored to different times in the educational lifecycle.

Ultimately, CUREs offer a high-value, relatively low-cost opportunity to increase STEM educational outcomes at universities of any size. CURE courses embedded within the curriculum allow many students to have an original research experience – rather than only those that obtain a mentored extra-curricular research opportunity. Moreover, structuring CURE courses with a team-based science approach allows best practices in STEM education to be scaled to more students. In team-based CUREs, students naturally experience more peer-based mentorship, reducing the demands on instructors. In conclusion, we suggest that our CURE model – and our assessment strategy - could be easily adapted at other institutions, ultimately contributing to a revitalized discovery ethos in higher education.

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