Tiny Earth CURE Demonstrates Equitable Benefits for U.S. College Science Students

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ABSTRACT

Course-based undergraduate research experiences (CURE) enhance student retention in science, technology, engineering, and math (STEM), particularly among students who belong to historically excluded communities. Yet the mechanisms by which CUREs contribute to student integration and persistence are poorly understood. Utilizing the tripartite integration model of social influence (TIMSI), this longitudinal study examines whether and how Tiny Earth—an antibiotic-discovery CURE designed for flexible implementation in a variety of course contexts—impacts students' scientific self-efficacy, scientific identity, endorsement of scientific community values, and intentions to persist in science. The study also explores how gains in TIMSI factors (i.e., scientific self-efficacy, identity, and values) vary as a function of student demographics and course characteristics. A comparison of pre- and postcourse measurements showed that scientific self-efficacy and identity increased among students in Tiny Earth. Some student demographics and course characteristics moderated these gains. Gains in all three TIMSI factors correlated with gains in persistence intentions, whereas student demographics and course characteristics did not. This study shows that the Tiny Earth curriculum equitably improved students' scientific self-efficacy and identity. It also showed that orientation toward scientific values and STEM persistence intentions held steady across most demographic groups.

INTRODUCTION

Recruiting and retaining students with diverse lived experiences are imperative to achieve a more vibrant and talented science, technology, engineering, and math (STEM) workforce. Diversity within groups has been shown to increase intellectual rigor, creativity, and quality of decisions, illustrating some of the benefits of diversifying the STEM workforce (Nemeth and Kwan, 1987; McLeod *et al.*, 1996; Nemeth *et al.*, 2001; Guimerà *et al.*, 2005; Sommers, 2006; Paulus *et al.*, 2016). Yet inequities continue to plague college science education, denying opportunities to students who identify as members of underrepresented racial or ethnic groups, women, LGBTQIA2S$^+$, or first-generation in college. Collectively, we refer to these and other underrepresented groups as historically excluded communities (HEC).

Considerable research has shown that not all students integrate into their scientific community at the same rate. Furthermore, longitudinal research studies have

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shown that students' intentions to persist in STEM degree and career pathways decline over time in college (Schultz *et al.*, 2011; Hernandez *et al.*, 2020). For example, similar proportions (18–20%) of white, Black, and Latine students enter college intending to major in a STEM field, yet 58% of white students complete a STEM degree compared with 42% of Latine and 34% of Black students (Riegle-Crumb *et al.*, 2019). These data are particularly troubling in comparison with humanities, social sciences, and business fields, in which Black and Latine students are no more likely to switch majors than their white counterparts (Riegle-Crumb *et al.*, 2019).

In addition to the differential pattern of excluding college students from STEM based on race and ethnicity, talented students from most HECs leave STEM at higher rates than students from historically included communities (HIC) (Thiry *et al.*, 2019). Most HEC students who leave have the interest, confidence, and aptitude to be successful in STEM, but early college classes can dampen their interest and actively prevent them from persisting (Estrada *et al.*, 2019; Thiry *et al.*, 2019). Their departures after gateway STEM courses represent a major talent drain from the system. To achieve an equitable educational enterprise, we must address the structural, individual, intentional, and unintentional biases discouraging HEC students from pursuing STEM.

Although students' reasons for leaving STEM have been studied extensively (Estrada *et al.*, 2011; Estrada *et al.*, 2018a; Rosenzweig *et al.*, 2021), a stubborn gap persists in understanding the mechanisms by which certain interventions reduce attrition among HEC students. The guiding theory for this research is the tripartite integration model of social influence (TIMSI), which provides a framework for understanding the psychological mechanisms linking educational experiences and persistence outcomes (Estrada *et al.*, 2018a; Estrada *et al.*, 2011). The TIMSI is a model of social influence that describes how a person's orientation toward a social system (e.g., a STEM field or community) can predict the conditions under which they would conform to the norms and expectations of the influencing agents (e.g., instructors, mentors, peers, or the design of learning contexts).

The TIMSI describes three orientations that influence persistence outcomes: efficacy, identity, and values. These three social influence mechanisms have been shown to contribute to integration and predict persistence in STEM (Estrada *et al.*, 2011; Estrada *et al.*, 2018b). Scientific self-efficacy indicates that a student feels capable of performing the actions needed to succeed in a STEM course, major, or career. Scientific identity indicates that a student perceives science as part of their identity and feels they belong to a scientific community. Students internalize scientific values when they authentically agree with the values of the scientific community, such as building new knowledge to solve global challenges, the thrill of discovery, and the importance of discourse. According to the TIMSI, these three factors—independently and collectively—contribute to social integration into STEM communities. STEM social integration (or STEM persistence) is measured by assessing a student's intention to pursue further academic or career goals in STEM. It can also be represented by behaviors, such as submitting applications for graduate school or getting a science-related job (Estrada *et al.*, 2018a; Estrada *et al.*, 2011).

Previous TIMSI research has examined the impact of science training programs and mentorship on integration and long-term persistence for STEM students who are from HECs and HICs (Estrada *et al.*, 2011; Estrada *et al.*, 2018b; Hernandez *et al.*, 2020). However, because most TIMSI studies have focused on how scientific self-efficacy, identity, and values explain persistence over long periods (e.g., semesters or years), less is known about how students change or grow with respect to TIMSI mechanisms as a result of curricular interventions (Estrada *et al.*, 2011; Estrada *et al.*, 2018a; Hernandez *et al.*, 2020).

CUREs as Curricular Interventions

Encouragingly, education research has identified several interventions that improve STEM performance and retention for students from HECs. One of the most effective approaches is improving the situational factors connected to scientific self-efficacy, identity, and values (Estrada *et al.*, 2011). Course-based undergraduate research experiences (CURE) can be considered curricular interventions that address many of these situational factors because they engage students through active learning, provide opportunities to practice skills, and introduce students to the value of participating in science by engaging in meaningful data collection that can contribute to new knowledge for addressing relevant scientific and global challenges (National Academies of Sciences, Engineering, and Medicine, 2017). These approaches increase confidence and provide students with a sense of belonging in STEM (Shuster *et al.*, 2019; Borlee *et al.*, 2023).

CUREs are grounded in active learning, which has long been known to enhance the performance and retention of all students and is especially beneficial to students from HECs (Hake, 1998; Haak *et al.*, 2011; Schwartz *et al.*, 2011; Freeman *et al.*, 2014; Hood *et al.*, 2020; Theobald *et al.*, 2020a). According to Freeman *et al.* (Freeman *et al.* 2014), "Active learning engages students in the process of learning through activities and/or discussion in class, as opposed to passively listening to an expert. It emphasizes higher-order thinking and often involves group work." Recent studies highlight the feasibility and importance of incorporating active-learning practices that have long-lasting effects on students and, in particular, the practices that reduce the inequities that result from students feeling disengaged and excluded from STEM (Freeman *et al.*, 2014; Thiry *et al.*, 2019; Theobald *et al.*, 2020b; Handelsman *et al.*, 2022).

CUREs package the best of active learning and scientific objectives together, with a phenomenal track record of improving the retention of diverse students in STEM. Although each CURE is unique in scope and format, CUREs commonly center on iterative scientific research that addresses a relevant problem (Auchincloss *et al.*, 2014; Corwin *et al.*, 2015; Buchanan and Fisher, 2022). CUREs give students ownership of their experiments, the opportunity to disseminate their results, and the chance to make new discoveries (Auchincloss *et al.*, 2014; Corwin *et al.*, 2015; Buchanan and Fisher, 2022). Evidence suggests that CUREs improve outcomes for all students (Rodenbusch *et al.*, 2016) and can have especially positive effects on students from HECs (Hurtado *et al.*, 2009; Olson *et al.*, 2019; Shuster *et al.*, 2019; Evans *et al.*, 2021; Waddell *et al.*, 2021). CUREs enable students to be scientists in a community of peers, thereby increasing their opportunity to identify as scientists, regardless of ethnicity or background. CUREs also make research experiences available to all students equally (Hurtado *et al.*, 2009; Hanauer *et al.*, 2022). In one study, students in CUREs gained significantly more scientific self-efficacy, scientific identity, and career intent than students in a non-CURE control group (Newell and Ulrich, 2022).

CUREs scale more effectively than research experiences in faculty research laboratories (Auchincloss *et al.*, 2014). The course-based nature of CUREs means they can be available to all students, regardless of background or experience. In contrast, faculty research laboratories are small, exclusive, and typically limited to one or a few experienced students. Furthermore, at some undergraduate institutions such as community colleges, faculty research programs may not be an option, so CUREs may be the only way for students to participate in research. In some cases, CUREs lead to more positive outcomes than research in faculty laboratories. For example, research in individual faculty laboratories can influence scientific identity and intent to pursue graduate study among women and Asian students less positively than members of other demographic groups (Aikens *et al.*, 2017), whereas CUREs have positive effects on students of all demographic groups (Rodenbusch *et al.*, 2016; Olson *et al.*, 2019; Evans *et al.*, 2021).

Several CURE programs, such as the Science Education Alliance–Phage Hunters Advancing Genomics and Evolutionary Science program, the Genomics Education Partnership, and the Undergraduate Research Consortium in Functional Genomics, set a standard for quality and impact, demonstrating that research courses can nurture creativity, reinforce diverse talents, diminish the stigma of failure, foster community, and teach principles of equity and inclusion in science (Lopatto *et al.*, 2008; Jordan *et al.*, 2014; Shaffer *et al.*, 2014; Hanauer *et al.*, 2017; Olson *et al.*, 2019; Evans *et al.*, 2021; Waddell *et al.*, 2021). They also allow students to take project ownership and develop identities as scientists in a community of peers (Hanauer *et al.*, 2017). Other studies showed that taking a CURE early in college increases the likelihood that a student will remain in a STEM major until graduation and complete college (Rodenbusch *et al.*, 2016), suggesting that CUREs have a significant impact on students' academic trajectories well beyond the research course itself. Previous studies have examined the role of CUREs in improving TIMSI outcomes in upper-division courses (Shuster *et al.*, 2019; Borlee *et al.*, 2023). However, to our knowledge, no studies have examined CUREs across multiple institutions while also considering student demographics and course characteristics associated with student gains in TIMSI factors and persistence. Enter Tiny Earth: the vehicle for this study.

The Tiny Earth CURE

Tiny Earth is an international, student-driven approach to antibiotic discovery that addresses a pressing global health crisis, antibiotic resistance, which is predicted to cause 50 million deaths per year by 2050 (World Health Organization, n.d.). The world's population needs a new approach to antibiotic discovery because few new structural classes of antibiotics have been discovered since the 1980s. The Tiny Earth CURE leverages a ubiquitous yet not fully mined natural resource (soil bacteria from around the world) and an untapped workforce (college students) to crowdsource antibiotic discovery. An estimated 16,000+ students per year in 33 countries enroll in a Tiny Earth course, each taught by a trained instructor at their college or university. The students' collective search forms a massive international network focused on antibiotic discovery. Tiny Earth's "studentsourcing" approach could provide an antidote to the pharmaceutical industry's approach, which has largely abandoned the discovery of new antibiotics and instead focuses on synthetic derivatives of known antibiotics or treatments for chronic diseases that are more profitable than infectious diseases.

The twin goals of Tiny Earth are to discover new antibiotics from soil bacteria and encourage diverse students to persist in STEM. To take advantage of the many pedagogical and inclusive features of CUREs, Tiny Earth embodies the hallmarks of a CURE: scientific research, iteration, ownership, relevance, discovery, and dissemination (Auchincloss *et al.*, 2014; Corwin *et al.*, 2015; Buchanan and Fisher, 2022). As described previously (Hurley *et al.*, 2021), Tiny Earth students engage in replicated, hypothesis-driven research to discover antibiotic-producing bacteria from soil, thereby addressing a relevant and pressing public health conundrum: rising antibiotic resistance with few new classes of antibiotics in the research pipeline. Students demonstrate ownership by choosing their soil sources, growth media, and research questions. They document their research findings in a shared, international database and communicate their research findings at international and regional Tiny Earth symposiums or local undergraduate research forums. Students also have the option to send their candidate antibiotic producers to the Tiny Earth Chemistry Hub (TECH) at the University of Wisconsin-Madison, where scientists sequence genomes and elucidate structures of secondary metabolites from the isolates. TECH currently stores 4300 of these isolates and has discovered 28 putative new molecular structures. Each of these research activities is designed to enable students to grow in scientific self-efficacy, identity, and values and contribute to discovering new antibiotics. A detailed version of the Tiny Earth research flow was published previously (Hurley *et al.*, 2021).

Tiny Earth makes research accessible in several ways, which opens a pathway toward equity in STEM. Students enroll in Tiny Earth at institutions representing every type of minority-serving and Carnegie classification. Tiny Earth is also designed to be flexible. For example, Tiny Earth Partner Instructors (TEPI) teach it as a standalone course or integrated as the laboratory component of a course such as Introductory Biology or Microbiology. It is taught in a range of class sizes, from a few students to several hundred. In 2020, the TEPI community created more adaptations to enable remote and hybrid teaching formats in response to the COVID-19 pandemic (González-Orta *et al.*, 2022) and incorporated content based on principles of antiracism, justice, equity, diversity, and inclusion (AJEDI) (Miller *et al.*, 2022).

A free, week-long TEPI training workshop guides college instructors to learn the pedagogical principles and laboratory practices that undergird the Tiny Earth CURE. Based on the National Institute on Scientific Teaching model (Handelsman *et al.*, 2004; 2007; Miller *et al.*, 2008; Pfund *et al.*, 2009), the TEPI training immerses instructors in the scientific teaching

BOX 1. *Recommended learning objectives for the Tiny Earth CURE*

Module 1: Isolating bacteria from soil

- Apply aseptic and serial dilution plating techniques to obtain isolated bacterial colonies from soil.
- Develop hypotheses about how bacteria from various soil environments vary in growth, diversity, and abundance on various laboratory media.
- Design experiments, gather and analyze data, and summarize findings.
- Estimate the number of microorganisms in a sample.

Module 2: Screening bacterial isolates for antibiotic production

- Screen bacterial isolates for antimicrobial activity against a panel of safe relatives of known pathogens or other environmental microbes.
- Develop hypotheses about bacterial interactions and antibiotic production using various media.
- Design experiments, gather and analyze data, and summarize findings.
- Explain how bacteria harness nutrients from their environment to grow.
- Explain the importance of studying clinically relevant microbes, distinguishing between pathogenic, attenuated, and nonpathogenic microbes.
- Propose narrow-spectrum antibiotics by leveraging the differences between gram-positive and gram-negative bacteria.

Module 3: Characterizing the antibiotic-producing bacterial isolates

- Integrate molecular, morphological, and biochemical characterization methods to establish a putative taxonomic identity for one or more environmental bacterial isolates.
- Analyze and interpret biochemical test data to infer physiological, physical, and/or pathogenic properties of isolates.
- Justify why the 16S rRNA gene is a suitable molecular target to group and identify bacteria.
- Explain how taxonomic identity can be useful for prioritizing antibiotic-producing bacterial isolates for future study.

Module 4: Advancing the antibiotic discovery pipeline

- Extract metabolic compounds from bacterial isolates and design experiments to test the compounds for antimicrobial activity.
- Gather, visualize, and interpret data; communicate findings.
- Explain the processes of antibiotic discovery and resistance development in pathogen populations.
- Propose a candidate antibiotic that would be effective against bacteria but safe for humans; explain how the antibiotic would target bacterial functions not found in humans.

principles, AJEDI practices, and experimental tools needed to implement the Tiny Earth curriculum at their college or university. They receive a published student research guide with protocols, recommended student-learning objectives (Box 1), instructor resources, facilitated work time with colleagues, and a dedicated mentor who previously taught the course in a similar context. Box 2 presents a typical TEPI training schedule, described further in Hurley *et al.* (2021). Since 2013, Tiny Earth has trained more than 800 TEPIs who teach an estimated 16,000+ students annually.

Current Study

Despite the promising outcomes of CUREs, there is a gap in understanding the mechanisms underlying these benefits across diverse student demographics and course types. In this study, we apply the TIMSI (Estrada *et al.*, 2011) to 1) explore student gains in scientific self-efficacy, identity, and values orientation during 57 implementations of Tiny Earth CUREs; 2) examine whether student demographics or course characteristics influence those gains; and 3) understand whether and how the TIMSI factors, student demographics, and course

BOX 2. *Sample training schedule for Tiny Earth Partner Instructors (TEPIs)*

- **Pretraining:** Interactive welcome tutorial
- **Monday:** Welcome, overview of Tiny Earth, and laboratory 1 (isolating bacteria from soil)
- **Tuesday:** Scientific teaching, inclusive learning, and laboratory 2 (screening bacterial isolates for antibiotic production)
- **Wednesday:** Course design, syllabus development, and laboratory 3 (characterizing the antibiotic-producing bacterial isolates)
- **Thursday:** Active learning experiences, Tiny Earth database, and laboratory 4 (advancing the antibiotic discovery pipeline)
- **Friday:** Group presentations and lessons from veteran TEPIs
- **Post-Training:** Mentor pairings, network activities, and teaching Tiny Earth

characteristics correlate with gains in social integration (i.e., persistence) into the scientific community. The study extends prior TIMSI research (Shuster *et al.*, 2019; Borlee *et al.*, 2023) by longitudinally tracking scientific self-efficacy, identity, and values orientation in 57 Tiny Earth CUREs from beginning to end at 40 U.S. colleges and universities. Moreover, this study examines longitudinal change in a sufficiently large sample of courses to examine the impact of course characteristics and student demographics.

Given the positive influences of STEM research experiences and CUREs, we predicted that Tiny Earth students would show gains with respect to TIMSI factors and STEM persistence during a semester. We also predicted that TIMSI gains would correlate with STEM persistence. In this study, we further investigated whether student demographics or course characteristics influenced TIMSI outcomes.

Research Questions

While participating in a Tiny Earth CURE:

1. What, if any, gains do students experience in the TIMSI mechanisms of scientific self-efficacy, identity, or values? We hypothesized that students in the Tiny Earth CURE experience gains in scientific self-efficacy, identity, and values orientation (H1).
2. What, if any, student demographics or course characteristics influence gains in the TIMSI mechanisms? We hypothesized that students of all demographic groups in the Tiny Earth CURE experience positive gains in TIMSI mechanisms (hypothesis 2a, H2a). Furthermore, we hypothesized that students across all course characteristics in Tiny Earth experience gains in TIMSI mechanisms (hypothesis 2b, H2b).
3. What, if any, gains do students experience in their intent to persist in science careers? We hypothesized that students in the Tiny Earth CURE increase their intent to persist in science careers (H3).
4. What, if any, ways do student demographics, course characteristics, and changes in the three TIMSI mechanisms associate with changes in students' intent to persist in science careers? We hypothesized that these factors influence persistence outcomes in some manner and let the findings emerge from the data (H4).

Answers to these research questions will advance knowledge regarding student outcomes when participating in a CURE such as Tiny Earth, including who benefits and in what contexts.

MATERIALS AND METHODS

Participants

The current study used data from a large, national longitudinal study of undergraduate students taking a course incorporating the Tiny Earth CURE curriculum. The data were collected from 2131 undergraduate students grouped into 57 biological science college classrooms across the United States. Participants were omitted from the analytical sample if they did not respond to survey questions concerning the relevant variables ($n = 703$) or if they were not undergraduates while enrolled in the course ($n = 112$). As a result, the final analytical sample included 1316 students grouped within 57 Tiny Earth courses at 40 colleges and universities. The institution types ranged from 2-year colleges to 4-year universities and included institutions categorized as private and public, rural and urban, majority- and minority-serving. See Supplemental Table S6 for institutional descriptions.

TABLE 1. Tiny Earth student demographics ($N = 1316$, $J = 57$, $n_j = 23.09$)

Student characteristics	Frequency (%)
Gender	
Woman[a]	801 (60.87%)
Man	307 (23.33%)
Transgender, nonbinary, or gender-fluid (TNG)	15 (1.14%)
Prefer not to say (PNTS)	193 (14.67%)
Race and Ethnicity	
White, not Hispanic[a]	563 (42.78%)
Hispanic or Latine	240 (18.24%)
Asian[a]	247 (18.77%)
Black or African American	62 (4.71%)
Middle Eastern or North African[a]	34 (2.58%)
Native Hawaiian or Pacific Islander	5 (<1%)
American Indian or Alaska Native	0 (0%)
Multiracial	154 (11.70%)
Prefer not to say (PNTS)	3 (<1%)
Academic Rank (Year in School)	
First-year[a]	127 (9.74%)
Sophomore	391 (29.98%)
Junior	411 (31.52%)
Senior	375 (28.76%)
Prefer not to say (PNTS)	12 (<1%)
Generation Status	
Continuing-generation[a]	700 (53.19%)
First-generation	616 (46.81%)

Note: Demographic information about Tiny Earth students who responded to both pre- and postsurveys (i.e., T1 and T2, respectively) includes gender identity, racial and ethnic identity, academic rank (year in school), and continuing- or first-generation status.

[a] This category serves as a reference or comparison for regression models.

For the analytical sample, we asked students to self-identify their race and ethnicity, gender, generation status, and academic rank (year in school). Students represented a diversity of demographics. The largest racial/ethnic groups were of white, non-Hispanic (43%), Asian (19%), Latine (18%), or multi-racial (12%) descent. The majority self-identified as women (61%). Nearly half were first-generation college students (47%), and most were in their sophomore (30%), junior (32%), or senior (29%) year of college. See Table 1 for complete demographic data.

TEPIs provided information about the context in which they implemented the Tiny Earth course at their institution. Their implementations represented a range of course sizes and types. Most Tiny Earth courses were medium-sized (i.e., $20 \leq n_j < 100$ enrolled students; 46%) or small (i.e., $n_j < 20$ enrolled students; 42%). Courses were evenly split between lower- or upper-division. Most (77%) instances were taught in-person; the rest were hybrid. None were taught fully online during the term of the study. Most (68%) course implementations included a combination of lecture and laboratory

TABLE 2. Tiny Earth course characteristics ($J = 57$)

Class characteristics	Frequency (%)
Class Size (Enrollment Number)	
High enrollment ($N \geq 100$)	7 (12.28%)
Medium enrollment ($20 \leq N < 100$)[a]	26 (45.61%)
Low enrollment ($N < 20$)	24 (42.11%)
Division (Course Level)	
Lower[a]	28 (49.12%)
Upper	26 (45.61%)
Not reported	3 (5.26%)
Delivery Modality	
In-person[a]	44 (77.19%)
Hybrid	12 (21.05%)
Remote/virtual	0 (0.00%)
Not reported	1 (1.75%)
Course Type	
Combined laboratory + lecture[a]	39 (68.42%)
Laboratory only	14 (24.56%)
Not reported	4 (7.02%)
Course Format	
Tiny Earth as a standalone course	9 (15.79%)
Tiny Earth integrated into a biology course	10 (17.54%)
Tiny Earth integrated into a microbiology course[a]	34 (59.65%)
Not reported	4 (7.02%)

Note: Course characteristics for the Tiny Earth courses in the study included class size, division, delivery modality, type, and format. Class sizes were categorized into low enrollment ($N < 20$), medium enrollment ($20 \leq N < 100$), and high enrollment ($N \geq 100$). Division categories described the course level, indicating whether the course was intended as a lower-division course for first- or second-year students, or an upper-division course for junior or senior students. Delivery modality categories described the extent to which the course was fully in person, fully remote, or a combination ('hybrid'). Course type categories differentiated which courses were taught as a laboratory-only configuration or part of a lecture-plus-laboratory combination. The format category designated whether Tiny Earth was taught as a standalone course (e.g., a first-year research seminar or independent study) or integrated into another microbiology or biology course (e.g., as the part of an introductory biology curriculum).

[a] This category serves as a reference or comparison for regression models.

components; the rest were classified as laboratory-only courses. Most instances integrated the Tiny Earth curriculum into a microbiology course (60%), whereas others integrated it into a biology course (18%) or taught it as a standalone course (16%; see Table 2).

Procedure

US college biology and microbiology instructors were recruited to apply to attend a free, week-long training program about teaching the Tiny Earth CURE. Instructors who intended to implement Tiny Earth as a course at their college or university were selected from the pool of applicants. After completing the TEPI Training (described above) and enrolling students in their Tiny Earth course, TEPIs helped researchers recruit students to participate in the study. Student recruitment involved providing the TEPI with a Google slide containing a brief study description and an anonymous Qualtrics survey link. Each instructor was asked to distribute the research study invitation to their Tiny Earth class of students (e.g., via email or a learning management system).

Student participants enrolled in a Tiny Earth course were recruited into the study every term from Fall 2020 through Spring 2023, resulting in six total cohorts. The students completed a precourse survey at the beginning of an academic term (time 1, T1) and a postcourse survey at the end of the same term (time 2, T2). Student participants in cohorts 1 to 4 received a $10 gift card for completing each survey as an incentive, and those in cohorts 5 and 6 received $10 gift cards for completing all postcourse surveys. The study was approved by the University of California, San Francisco Institutional Review Board (IRB #19-28867) and in consultation with all institutions in which data were collected.

Measures

Scientific Self-efficacy. We used a three-item scale adapted from a previous study (Estrada *et al.*, 2011) to assess the students' confidence in their ability to function as a scientist in a variety of tasks (e.g., "Create explanations for the results of the study"). Student participants rated each statement with a five-point Likert scale from 1 (*not at all confident*) to 5 (*absolutely confident*). Responses were averaged to derive composite scores to indicate their overall scientific self-efficacy at each timepoint ($\alpha_{T1} = 0.89$ and $\alpha_{T2} = 0.87$). A gain score was calculated as the difference between the participants' T1 and T2 survey responses (i.e., positive scores indicate higher self-efficacy postcourse than precourse).

Identification as a Scientist. We utilized a four-item scientific identity scale adapted from a previous study (Estrada *et al.*, 2011) to assess the degree to which participants identified as scientists. Participants were asked to assess their agreement on a Likert scale of 1 (*strongly disagree*) to 5 (*strongly agree*) with a series of statements (e.g., "Being a scientist is an important reflection of who I am"). Responses were averaged to derive composite scores to indicate their overall scientific identity at each timepoint ($\alpha_{T1} = 0.87$ and $\alpha_{T2} = 0.89$). A gain score was calculated as the difference between the participants' T1 and T2 scores.

Internalization of Scientific Community Values. We used a four-item scale from a previous study (Estrada *et al.*, 2011) to measure the extent to which participants endorsed values of the scientific community, such as discovery and experimentation. Participants rated the degree to which statements applied to them (e.g., "A person who thinks it is valuable to conduct research that builds the world's scientific knowledge") on a scale from 1 (*not at all like me*) to 6 (*very much like me*). Responses were averaged to derive composite scores to indicate their overall scientific values at each timepoint ($\alpha_{T1} = 0.87$ and $\alpha_{T2} = 0.88$). A gain score was calculated as the difference between the participants' scores at T1 and T2.

Scientific Career Persistence Intentions. A seven-item scale adapted from previous research (Woodcock *et al.*, 2012) assessed participants' intention to pursue a scientific career. Participants rated students' intention to persist (e.g., "To obtain a biomedical science-related undergraduate degree") on a scale from 0 (*definitely will not*) to 10 (*definitely will*). Responses were averaged to derive a composite score ($\alpha_{T1} = 0.83$ and $\alpha_{T2} = 0.86$). A gain score was calculated as the difference between the participants' scores at T1 and T2.

Student Demographics. In this study, the participants comprised undergraduate students enrolled in Tiny Earth courses at U.S. institutions. Participants were asked to provide their demographic information for four categories: *gender, race and ethnicity, college generation status,* and *academic rank*. Each category also included a response option called "prefer not to say" (PNTS).

Because we did not have hypotheses about which groups might grow more than others, all categorical variables were dummy-coded into a set of contrast variables to facilitate comparisons with the largest group (e.g., women for the gender identity variable), the group of substantive interest (e.g., first-generation for the generation status variable), or both where possible. See Table 1 for a complete list of focal and reference groups for each student demographic characteristic.

Gender analysis categories included women, men, and other. Students who reported "other" were provided the option to elaborate, which resulted in a group with three identities: transgender, nonbinary, and gender-fluid (TNG). Women served as the reference group.

For *race and ethnicity* analysis, students identified as American Indian or Alaska Native, Asian, Black or African American, Hispanic or Latine, Middle Eastern or North African multiracial, Native Hawaiian or Pacific Islander, or white (not Hispanic). White (not Hispanic) served as the reference group. Approximately one-third of the multiracial group ($n = 90$) also included those who selected both white and Hispanic/Latine.

Students were also categorized according to *generation status* (first-generation or continuing-generation) and *academic rank* (first-year, sophomore, junior, or senior). Continuing-generation and first-year students served as the reference group.

Course Characteristics. Research participants were undergraduate students enrolled in 57 Tiny Earth classes at 40 U.S. colleges and universities. Information on five course-level variables (size, level, modality, type, and format) was collected directly from instructors for the semester in which their Tiny Earth course was included in the study. As with student demographics, course-characteristic categorical variables were dummy-coded using the same criteria to identify the reference group within each variable. See Table 2 for a complete list of focal and reference groups for each course characteristic.

Courses were classified based on *size*: low enrollment (fewer than 20 students), medium enrollment (20 or more but less than 100; reference group), or large enrollment (100 or more). The *division* variable distinguished lower-division courses (i.e., intended for first- and second-year students; reference group) from upper-division (i.e., intended for junior and senior students). The *delivery modality* variable differentiated courses taught fully in-person (reference group), hybrid (i.e., partially in-person and partially online or remote), or fully online or remote. The course *type* variable distinguished courses taught in a laboratory-only format from those that combined lectures with a laboratory component (reference group). Course *format* differentiated Tiny Earth CUREs taught as standalone courses (e.g., as a first-year seminar or independent research credit), integrated into a biology course (e.g., the laboratory component of an introductory biology course), or integrated into a microbiology course (reference group).

Statistical Assumption Tests. All analyses were conducted in Stata v.18 (StataCorp, 2023). We conducted a preliminary analysis to check the tenability of statistical assumptions to 1) understand whether our statistical models would produce accurate and unbiased statistical results, 2) test longitudinal measurement properties of outcomes to determine whether the outcomes exhibited consistent measurement properties over time, and 3) test the cross-group measurement invariance of all outcomes at each timepoint as a function of gender and race/ethnicity to determine whether the outcomes exhibited consistent measurement properties across demographic groups.

Here, we briefly summarize the comprehensive assumption checks included in the Supplemental Materials and Supplemental Tables. Overall, our analyses provide robust evidence for the validity of most statistical assumptions and the presence of longitudinal measurement invariance across time for each construct. First, missing data analyses revealed that the pattern of missingness was consistent with Conditionally Dependent Missingness (Little, 1995); thus, our planned analyses were robust to missing data bias. Second, there was no evidence of extreme outliers. Third, the assumption of independent observations was tenable despite the nested nature of the data. All outcome measures (e.g., change in scientific self-efficacy) exhibited minimal, nearly zero intraclass correlations (ICC), which indicate the proportion of total variance due to nesting (ICC range, <0.0001 to 0.009). Given the extremely small ICCs, a multilevel modeling approach is unnecessary. However, to protect our results from even trivial influence due to clustering, our analytical approach used a cluster-robust estimating technique to control for the minimal nesting effect on the data (see Supplemental Materials for full details). Fourth, distributional assumptions were violated (i.e., normality for all and homoskedasticity for scientific self-efficacy and values). Therefore, our analytical approach used a robust estimator to account for violations of some distributional assumptions. Fifth, examination of the linearity assumption revealed negative associations between each gain-scored outcome and T1 scores (e.g., negative correlation between change in scientific self-efficacy and T1-scientific self-efficacy), indicating a potential regression to the mean effect. Therefore, we included T1 baseline scores as control variables in our analyses. Sixth, all scales exhibited acceptable psychometric properties regarding longitudinal measurement invariances from T1 to T2 and cross-group measurement invariance.

Analytical Approach to Testing Research Questions and Hypotheses. As detailed below, regression analysis addressed research questions and hypotheses. As noted above, the effect of nesting was extremely small in our gain-score outcomes, and preliminary analysis showed that multilevel modeling approaches to model the between-cluster variance component failed to converge. Therefore, for each analysis, cluster- and heteroscedastic-robust standard errors were estimated for these models to account for minimal clustering effects corrections for distributional assumptions (Over *et al.*, 1996; Raudenbush and Bryk, 2002). See Supplemental Materials for a complete discussion of robust estimation. In addition, T1 baseline levels of scientific self-efficacy, identity, values, and persistence intentions (centered for the analysis) were

TABLE 3. Overall change in students' scientific self-efficacy (E), identity (I), values (V) orientation, and persistence intentions (P) while participating in the Tiny Earth CURE

Measure	T1 Average	T2 Average	Change overall
Scientific self-efficacy	3.45 ± 0.06	3.82 ± 0.06	**0.37 ± 0.04**
Scientific identity	3.48 ± 0.08	3.76 ± 0.09	**0.29 ± 0.04**
Orientation to scientific values	5.10 ± 0.07	5.10 ± 0.07	– 0.00 ± 0.04
STEM persistence intentions	6.62 ± 0.20	6.59 ± 0.23	– 0.02 ± 0.05

Note: Using paired T1 and T2 surveys, the three orientations of the TIMSI that influence persistence in STEM were assessed: scientific self-efficacy; identity as a scientist; and orientation toward scientific community values, such as discovery and collaboration. Gains in E, I, V, and P were measured using paired T1 and T2 surveys during the semester in which the Tiny Earth students' course was included in the study. This table shows the average, paired gains in E, I, V, and P for all students who responded to both surveys ($N = 1316$; $p < 0.05$). Self-efficacy and identity were measured on scales from 1 to 5. Values were measured on a scale from 1 to 6. Persistence was measured on a scale from 1 to 10. T1, precourse survey administered at the start of the semester. T2, postcourse survey administered at the end of the semester. Scientific self-efficacy and identity measured on a scale from 1 to 5. Orientation to scientific values measured on a scale from 1 to 6. STEM persistence intentions measured on a scale from 0 to 10. ±, represent robust standard errors. Bolded values show significant gains.

included as predictors for their respective change outcomes to statistically control for any regression to the mean effects present in gain-scored outcomes. Furthermore, some students did not respond to all demographic variables (i.e., PNTS), and some instructors did not provide some requested information on course characteristics (i.e., not reported [NR]). We retained these persons and courses by including PNTS and NR categories in the regression models. No one taught in a fully online or remote modality, so that variable was removed from the analysis.

To test hypothesis 1 (*quantifying gains in TIMSI mechanisms*), we fitted a series of unconditional regression models (i.e., no predictors) to estimate the overall average gains in scientific self-efficacy, identity, and values orientation.

To test hypothesis 2, a and b (*testing student and course predictors of gains, respectively*), we fitted a series of multiple regression models predicting student gain scores in efficacy, identity, and values from student demographics and course characteristics, controlling for T1 baseline levels of efficacy, identity, or values (centered for the analysis). In these models, we interpret regression-based standardized beta (β) values as an effect size for group or course characteristic differences along a continuum from small ($\beta \leq 0.29$), moderate ($0.30 \geq \beta \leq 0.49$), to large ($\beta > 0.50$) (Cohen, 1988; Nieminen, 2022).

To test hypothesis 3 (*quantifying gains in science persistence intentions*), we fitted an unconditional regression model to estimate the overall average gains in science persistence intentions.

To test hypothesis 4 (*testing student demographics, course characteristics, and gains in TIMSI mechanisms as predictors of persistence intentions*), we used a multiple regression model to predict gains in science persistence intentions from student demographics, course characteristics, and gain scores of scientific self-efficacy, identity, and values, controlling for T1 baseline levels of persistence intentions (centered for the analysis). As mentioned above, we interpreted regression-based standardized beta (β) values as an effect size for this model. We binned the gains in each of the TIMSI mechanisms into three groups: average gains, representing those who reported average gains in self-efficacy, identity, or values; low gains, representing the lowest (-1 SD) gains in the TIMSI mechanisms; or high gains ($+1$ SD), representing the highest gains in the mechanisms. These three bins were then mapped onto gains in persistence intentions.

RESULTS

Results of Testing Our Hypotheses

Hypothesis 1 (H1): *Students in the Tiny Earth CURE experience gains in scientific self-efficacy, identity, and values orientation.*

Overall, the starting average levels of scientific efficacy, identity, and values were moderately high: averages ranged between 57 and 79% of the maximum possible score. After the course, *scientific self-efficacy* and *scientific identity* showed a significant average gain score (consistent with our hypothesis), whereas the average gain score in *scientific values* was negligible (inconsistent with our hypothesis). See Table 3.

Hypothesis 2a (H2a): *Students across all student demographic groups in Tiny Earth show gains in TIMSI mechanisms.*

Consistent with our hypothesis, the analysis revealed that students across all demographics exhibited significant gains in *scientific self-efficacy* (Figure 1A) and *scientific identity* (Figure 1B), with no meaningful group differences based on student demographics. The analysis also revealed that students across all demographics held steady for *scientific values* except first-year students exhibited a small decline ($\beta s \leq 0.10$) (Figure 1C). Supplemental Tables S5 to S7 provide further details of the regression model output.

Hypothesis 2b (H2b): *Students across all course characteristics in Tiny Earth show gains in TIMSI mechanisms.*

Consistent with our hypothesis, the analysis revealed that Tiny Earth students exhibited significant gains in *scientific self-efficacy* across all implementation varieties, with no meaningful differences based on course enrollment size or delivery modality. However, a few statistically significant differential effects were detected based on course type, division, and format. For example, students in laboratory-only courses exhibited higher gains than those in combined lecture-laboratory courses, and those in upper-division courses grew slightly more than those in lower-division. Furthermore, students whose Tiny Earth curriculum was integrated into biology courses exhibited higher gains in scientific self-efficacy than those integrated into microbiology courses or standalone courses (see Figure 2A; Supplemental Table S5).

Also consistent with our hypothesis, students exhibited significant gains in *scientific identity* across the assessed course characteristics, with no meaningful differences based

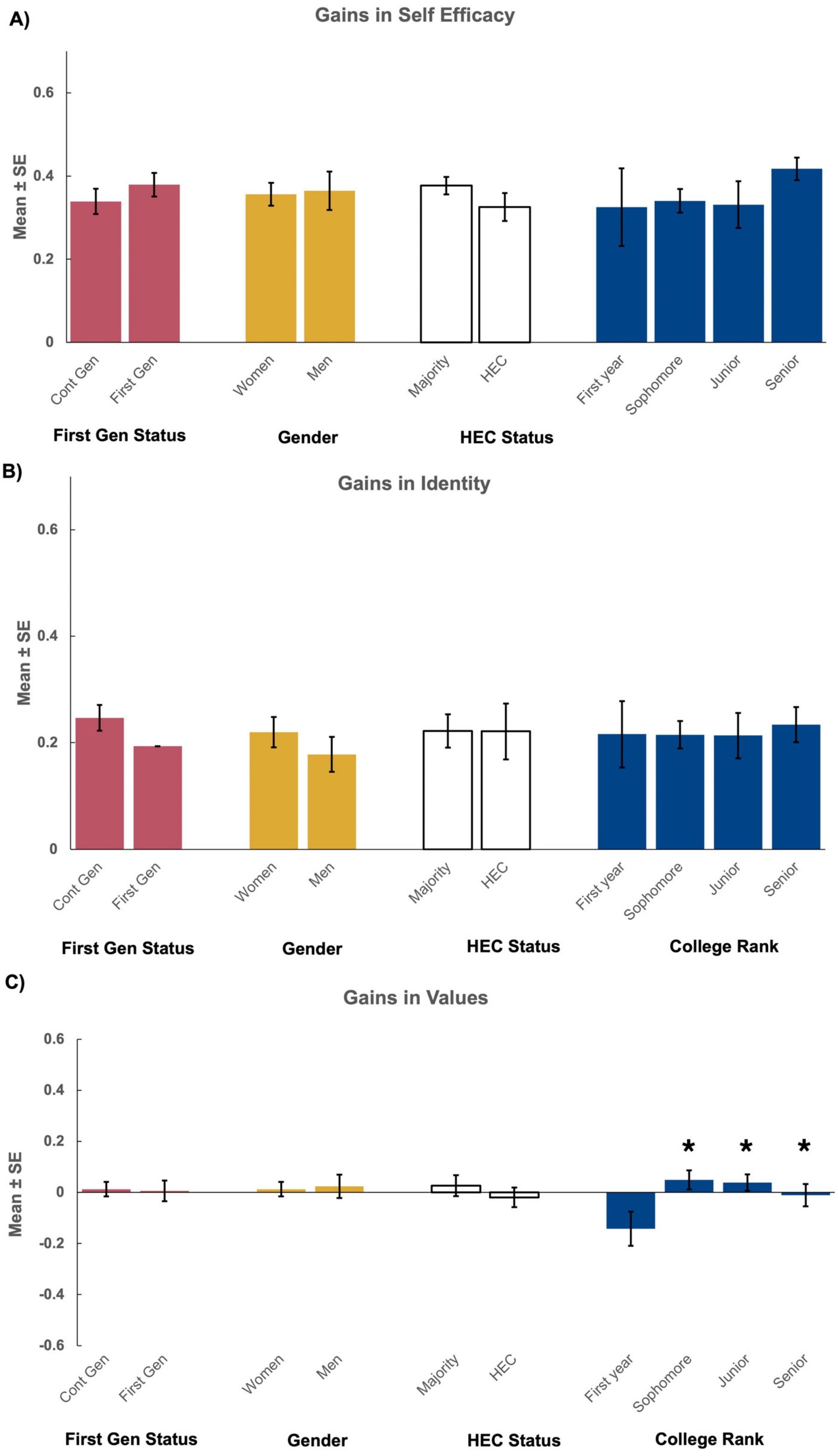

FIGURE 1. Mean student gains in (A) scientific self-efficacy, (B) scientific identity, and (C) orientation toward scientific values, differentiated by student demographics (N = 1,316). Self-efficacy and identity were measured on scales from 1 to 5. Values were measured on a scale from 1 to 6.

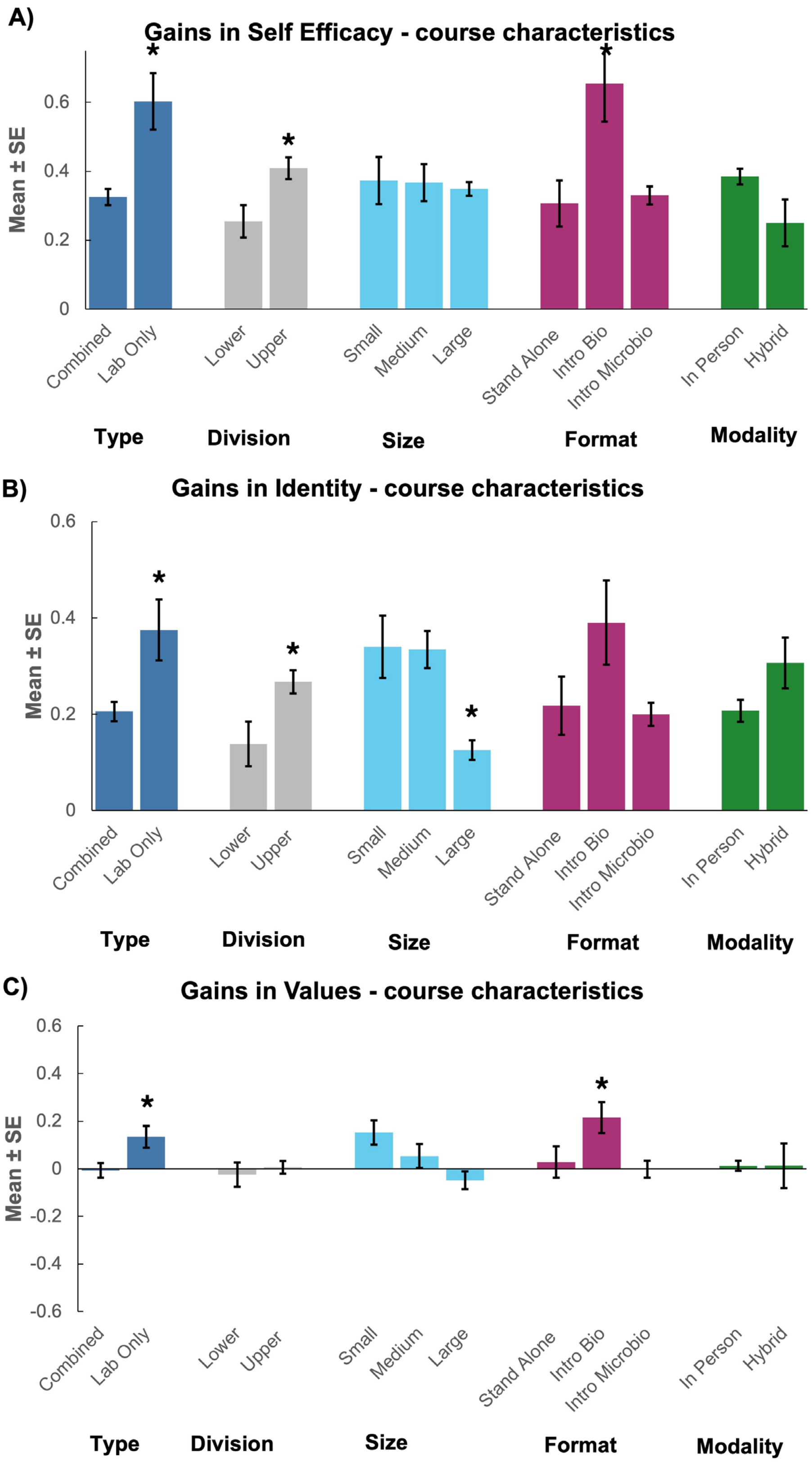

FIGURE 2. Mean student gains in (A) scientific self-efficacy, (B) scientific identity, and (C) orientation toward scientific values, differentiated by course characteristics (N = 1,316). Self-efficacy and identity were measured on scales from 1 to 5. Values were measured on a scale from 1 to 6.

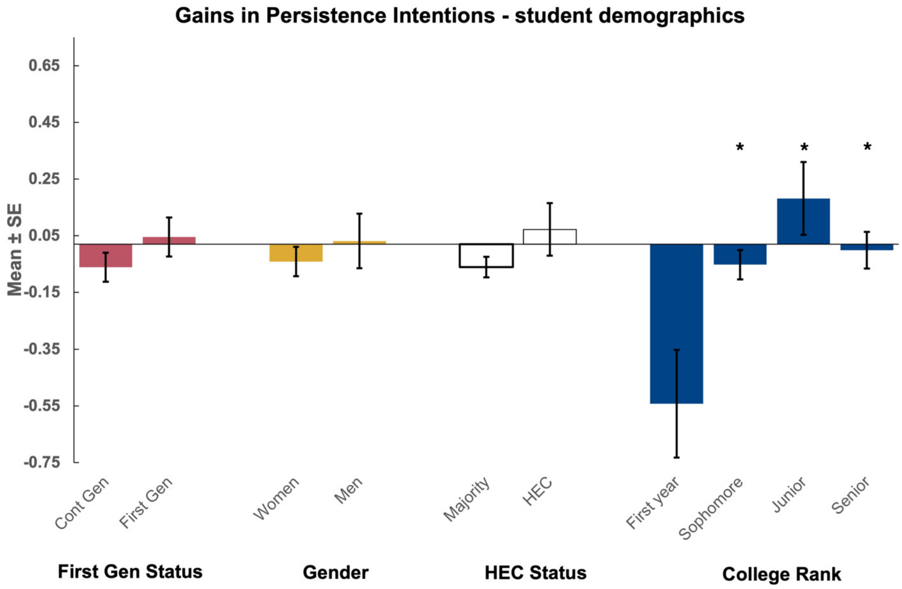

FIGURE 3. Mean student gains in intentions to persist in STEM, differentiated by student demographics (N = 1,316). Persistence was measured on a scale from 0 to 10.

on course format or delivery modality. However, statistically significant differential effects were detected based on course type, division, and enrollment size. Students in laboratory-only courses reported slightly higher gains in scientific identity than in combined lecture-plus-laboratory courses. Students' scientific identities in upper-division courses grew slightly more than those in lower-division. Students in large-enrollment courses grew slightly less than those in medium- and small-enrollment courses (see Figure 2B; Supplemental Table S6).

The analysis detected no meaningful differences regarding gains in *scientific values* based on course division, enrollment size, or delivery modality. However, a small statistically significant differential effect was detected based on the course type, where students in laboratory-only courses grew slightly more than in combined lecture-plus-laboratory courses, and format, with higher gains in biology than microbiology or standalone implementations (see Figure 2C; Supplemental Table S3).

Hypothesis 3 (H3)*: Students in Tiny Earth increase their intent to persist in STEM.*

Inconsistent with our hypothesis, the average *persistence intentions* held steady, rather than growing, over the semester (Table 3). The starting overall average level of scientific persistence intentions was moderately high (i.e., 61% of the maximum possible score).

Hypothesis 4 (H4): *Student demographics, course characteristics, and changes in the three TIMSI mechanisms influence students' intent to persist in STEM.*

Student gains in the three TIMSI mechanisms were uniquely and positively associated with statistically significant gains in persistence intentions. To understand the relationships, we first binned the gains in each of the TIMSI mechanisms into three groups: average gains, representing those who reported average gains in self-efficacy, identity, or values; low gains, representing the lowest (−1 SD) gains in the TIMSI mechanisms; or high gains (+1 SD), representing the highest gains in the mechanisms. These three bins were then mapped onto gains in persistence intentions. Students who reported gains in scientific self-efficacy, identity, and values showed corresponding gains in persistence intentions. Gains in scientific identity showed a somewhat stronger association with gains in persistence intentions compared with the associations with scientific self-efficacy and values (Figure 5; Supplemental Table S8).

The analysis revealed no meaningful group differences in persistence intentions gains based on student demographics, except first-year students showed a small decline, while sophomores, juniors, and seniors held steady (see Figure 3; Supplemental Table S3).

Furthermore, the analysis revealed that all course characteristics except delivery modality correlated with differential growth in persistence intentions. Students exhibited statistically significant gains in laboratory-only and biology-focused courses, whereas those in combined lecture-plus-laboratory, microbiology-focused, and Tiny Earth standalone courses held steady. Students in lower-division courses and those in large-enrollment courses exhibited a small statistically significant decline, whereas those in upper-division and small- and medium-enrollment sized courses held steady (see Figure 4; Supplemental Table S8).

DISCUSSION

Too often, students complete gateway science courses valuing scientific approaches less than when they started, or they decide to leave STEM altogether (Estrada and Matsui, 2019). CUREs are designed to be the antidotes to STEM attrition. CUREs are designed to engage all students—HEC and HIC equitably—in authentic, relevant research investigation. The goal of CUREs is to provide scientific knowledge, skills, and

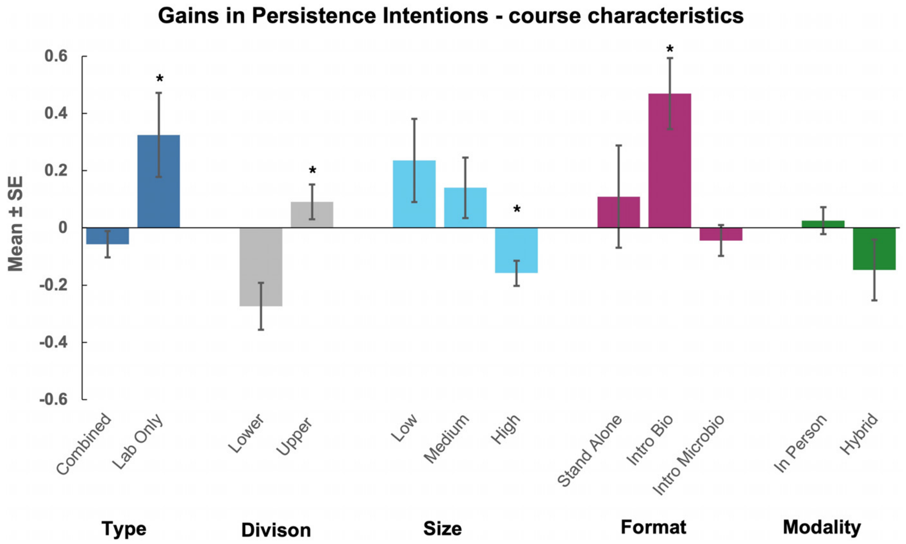

FIGURE 4. Mean student gains in intentions to persist in STEM, differentiated by course characteristics (N = 1,316). Persistence was measured on a scale from 0 to 10.

practices of science while creating a sense of belonging that encourages students to persist in science beyond the course, through graduation, and into their careers. Because they provide students with opportunities to experience agency and the thrill of discovery, CUREs tap into the factors that have been shown repeatedly to help students persist in STEM: building confidence, seeing themselves as scientists, and internalizing the value of evidence-based, rigorous practices emblematic of scientific discovery.

This study aimed to improve our understanding of the associations between participating in Tiny Earth, a science CURE with widespread and varied implementation, and the psychological processes leading to social integration among diverse students and types of Tiny Earth CURE courses. The study applied the TIMSI to understand how enrollment in Tiny Earth is associated with students' integration into the scientific community, measured through changes in scientific self-efficacy, scientific identity, and orientation toward scientific values during an academic term, and how these three psychological mechanisms of social influence relate to intentions to persist in STEM. We examined individual student differences and determined how course contexts relate to outcomes. This study

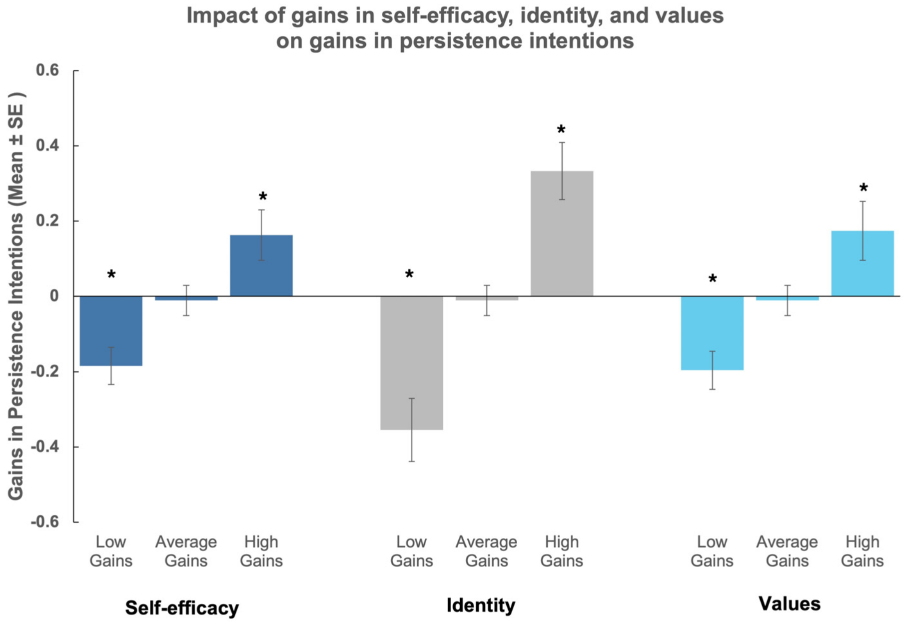

FIGURE 5. Relationship between gains in students' scientific self-efficacy, identity, and values with gains in intent to persist in STEM (N = 1,316).

builds on findings by others (Shuster *et al.*, 2019; Borlee *et al.*, 2023), who applied TIMSI to upper-division CUREs. To our knowledge, this is the first study examining these course variables on TIMSI factors in a CURE with a high number of students across a range of student demographics, course implementations, and institutions that allowed us to compare outcomes across those variables.

The main finding from this study is that, on average, students enrolled in a one-term Tiny Earth CURE gained confidence in and perception of themselves as scientists, yet held steady in their orientation toward scientific values and STEM persistence intentions. Specifically, we found that:

1. Tiny Earth students from historically excluded and included communities gained substantially in scientific self-efficacy and identity. These findings were not influenced by student demographics but were somewhat influenced by course type, division, and format.
2. Tiny Earth students from historically excluded and included communities held steady in their orientation toward scientific values. Scientific values outcomes were somewhat influenced by student year in school and course type.
3. Tiny Earth students from historically excluded and included communities held steady in STEM persistence intentions. Persistence outcomes were somewhat influenced by student year in school and course type, division, size, and format.
4. Gains in scientific self-efficacy, identity, and values orientation correlate with increases in intentions to persist in STEM. Scientific identity showed the greatest correlation with persistence intentions.

These findings are consistent with previous studies that apply TIMSI to research experiences showing gains in scientific self-efficacy and identity (Estrada *et al.*, 2011; Borlee *et al.*, 2023) but add a multidimensional approach that teases apart the differential impacts of individual student demographics and course implementation types. Also consistent with previous studies, higher gains in TIMSI factors correlated with higher persistence gains (Estrada *et al.*, 2011).

Another notable finding from this study showed that Tiny Earth students generally started their research experience scoring moderately high on the three TIMSI factors related to confidence and belonging in STEM and their intentions to persist in science, which suggests that students who enroll in a Tiny Earth course want to be there and participate in science. Despite the relatively high scores at start-of-term, however, we were still able to detect significant gains in students' scientific self-efficacy and identity during a one-term Tiny Earth course. The gains held across all student demographic variables and course characteristics, which indicate that a Tiny Earth research experience is robust enough to build confidence and belonging in STEM for everyone regardless of students' HEC status and the implementation context.

This study corroborates previous studies of CUREs that show their positive effects on students from historically excluded and included communities. In particular, Tiny Earth students from a breadth of backgrounds in a variety of educational contexts reported gains in their *scientific self-efficacy*. In STEM contexts, self-efficacy involves having confidence that one can perform the activities emblematic of scientific research and the motivation to pursue learning and discovery. The Tiny Earth curriculum, even when applied across a variety of institutions and with course variability, implicitly addresses self-efficacy by connecting motivating content (i.e., the thrill of discovery and solving a real-world global health crisis) with scaffolded learning (i.e., incremental steps toward designing and conducting experiments, progressively more sophisticated laboratory protocols, and troubleshooting).

We also found that *scientific identity* increased for all students across the various contexts in which they experienced Tiny Earth. HEC and HIC students showed similar gains across the board, with no differences between groups. These findings signal that the Tiny Earth curriculum provides equitable access for students to attain the benefits of research experience for developing and maintaining a positive scientific identity, regardless of race, ethnicity, gender, first-generation status, or year in school. Interestingly, several course characteristics—smaller size, upper division, laboratory-only, and those integrated into biology courses—showed greater positive benefits for students' scientific identity. Small and laboratory-intensive courses have been shown to benefit students in general (DeFeo *et al.*, 2020), so this result was not surprising.

Notably, this study found that Tiny Earth students remained consistent in their scientific values and persistence intentions over the course of the semester. Students are oriented toward scientific values when they internalize and value scientific experiences, such as building new knowledge to solve global challenges, the thrill of discovery, and the importance of discourse. Tiny Earth provides regular, intentional opportunities for students to engage with science practices, so we expected gains in this area. However, studies have shown values orientation to be a stubborn metric in which to detect changes, even when it remains predictive of persistence (Estrada *et al.*, 2011; Borlee *et al.*, 2023).

The one exception to consistent values scores happened with first-year students, which showed an unexplained, significant decrease in values orientation. This result could be explained in part by the Stages of Intellectual Development theory (Perry, 1999). The theory states that students early in college tend to hold views based on dualism (e.g., facts are right or wrong) or multiplicity (e.g., everyone's opinion is equal), compared with students later in college who learn to appreciate relativism (e.g., conclusions made through reasoning and evidence) and eventually commit to values and action after thoughtful consideration and critical thinking. The multiplicity stage, which many first-year students would be reaching, manifests as a distrust in authority, reason, abstraction, and science.

Consistent with previous research, when students reported larger gains in scientific self-efficacy, identity, and values (Figure 5), they were more likely to indicate larger gains in their intentions to persist in STEM. This study, therefore, provides further quantitative support for the TIMSI model as a predictor of persistence in STEM.

Limitations and Future Directions

This study is grounded in pre- and postmeasurements within an academic term and builds on previous studies involving the TIMSI model and upper-division CUREs. Because several of the most positive outcomes appeared in Tiny Earth courses integrated into biology courses, comparing student outcomes with biology courses that do not include Tiny Earth sections would further elucidate the effect that the Tiny Earth curriculum has on student gains within those contexts. We could find no previous studies that might explain why students in introductory biology–based Tiny Earth courses would report higher gains in scientific identity. We hypothesize that these gains could be results from students entering a relativistic stage of development that better aligns with science by happenstance during introductory biology, or it could simply be an anomaly of Tiny Earth's flexible implementation across course types.

An unanticipated outcome of this study was the high number of students who declined to identify their gender. Twenty-five percent of students selected PNTS for the gender identity item, in contrast to <1% for race/ethnicity and academic rank. The PNTS item is different from the "other" item on the instrument, from which we could extract a subset of students who specified their identity as TNG. Although the number of PNTS is substantial, we cannot interpret what it means in this context. As a research community, we need to explore better ways for respondents to claim their identity on their terms and ensure their contributions are not omitted from research.

CONCLUSIONS

The results of this study add to a growing literature that demonstrates that a sense of belonging can be fostered in core science courses. Higher education has the opportunity to use evidence-based interventions, such as active-learning strategies, AJEDI activities, and CUREs, which reliably engage talented students in STEM. One research group estimated that if every undergraduate in the United States could take a CURE, an estimated 200,000 more students would graduate college in STEM fields each year (Dolan and Weaver, 2021). Considering that several CUREs have been rigorously studied, optimized, and disseminated, there are many validated choices available (Buchanan and Fisher, 2022). If a federal agency or private foundation provided resources for training to teach a CURE for one instructor from each of the 4000 undergraduate institutions in the United States, positive transformation would occur. We estimate that such training could be accomplished for $25 million and eventually could result in every undergraduate having the option to take a research course. This seems like a modest investment to powerfully leverage CUREs to create a more sufficient, diverse, and robust STEM workforce.

ACCESSING MATERIALS

The Tiny Earth student research guide is available for purchase online at https://tinyearth.wisc.edu/students/. Some materials are available in previous publications (S. Hernandez *et al.*, 2020; González-Orta *et al.*, 2022; Miller *et al.*, 2022). To access the full set of instructor resources, apply to attend a TEPI Training at https://tinyearth.wisc.edu/tinyearth-partner-instructors/. Trainings are currently free for U.S. college instructors, except for travel to the training site. No promotion of the curriculum should be construed.

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REFERENCES

Aikens, M. L., Robertson, M. M., Sadselia, S., Watkins, K., Evans, M., Runyon, C. R., … Dolan, E. L. (2017). Race and gender differences in undergraduate research mentoring structures and research outcomes. *CBE—Life Sciences Education*, *16*(2), ar34. https://doi.org/10.1187/cbe.16-07-0211

Auchincloss, L. C., Laursen, S. L., Branchaw, J. L., Eagan, K., Graham, M., Hanauer, D. I., … Dolan, E. L. (2014). Assessment of course-based undergraduate research experiences: A meeting report. *CBE—Life Sciences Education*, *13*(1), 29–40. https://doi.org/10.1187/cbe.14-01-0004

Borlee, G. I., Kinkel, T., Broeckling, B., Borlee, B. R., Mayo, C., & Mehaffy, C. (2023). Upper-level inter-disciplinary microbiology CUREs increase student's scientific self-efficacy, scientific identity, and self-assessed skills. *Journal of Microbiology & Biology Education*, *25*(1), e00140–e00123. https://doi.org/10.1128/jmbe.00140-23

Buchanan, A. J., & Fisher, G. R. (2022). Current status and implementation of science practices in course-based undergraduate research experiences (CUREs): A systematic literature review. *CBE—Life Sciences Education*, *21*(4), ar83. https://doi.org/10.1187/cbe.22-04-0069

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences*. New York, NY: Lawrence Erlbaum Associates.

Corwin, L. A., Graham, M. J., & Dolan, E. L. (2015). Modeling course-based undergraduate research experiences: An agenda for future research and evaluation. *CBE—Life Sciences Education*, *14*(1), es1. https://doi.org/10.1187/cbe.14-10-0167

DeFeo, D. J., Bibler, A., & Gerken, S. (2020). The effect of a paired lab on course completion and grades in nonmajors introductory biology. *CBE—Life Sciences Education*, *19*(3), ar36. https://doi.org/10.1187/cbe.20-03-0041

Dolan, E. L., & Weaver, G. C. (2021). In: *A Guide to Course-Based Undergraduate Research: Developing and Implementing CUREs in the Natural Sciences*, ed. W.H. Freeman. New York, NY: Macmillan Learning.

Estrada, M., Eroy-Reveles, A., & Matsui, J. (2018a). The influence of affirming kindness and community on broadening participation in STEM career pathways. *Social Issues and Policy Review*, *12*(1), 258–297. https://doi.org/10.1111/sipr.12046

Estrada, M., Hernandez, P. R., & Schultz, P. W. (2018b). A longitudinal study of how quality mentorship and research experience integrate underrepresented minorities into STEM careers. *CBE—Life Sciences Education*, *17*(1), ar9. https://doi.org/10.1187/cbe.17-04-0066

Estrada, M., & Matsui, J. (2019). A longitudinal study of the biology scholars program: Maintaining student integration and intention to persist in science career pathways. *Understanding Interventions*, *10*(1).

Estrada, M., Woodcock, A., Hernandez, P. R., & Schultz, P. W. (2011). Toward a model of social influence that explains minority student integration into the scientific community. *Journal of Educational Psychology*, *103*(1), 206–222. https://doi.org/10.1037/a0020743

Estrada, M., Young, G. R., Nagy, J., Goldstein, E. J., Ben-Zeev, A., Márquez-Magaña, L., & Eroy-Reveles, A. (2019). The influence of microaffirmations on undergraduate persistence in science career pathways. *CBE—Life Sciences Education*, *18*(3), ar40. https://doi.org/10.1187/cbe.19-01-0012

Evans, C. J., Olson, J. M., Mondal, B. C., Kandimalla, P., Abbasi, A., Abdusamad, M. M., … Banerjee, U. (2021). A functional genomics screen identifying blood cell development genes in *Drosophila* by undergraduates participating in a course-based research experience. *G3*, *11*(1), jkaa028. https://doi.org/10.1093/g3journal/jkaa028

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences*, *111*(23), 8410–8415. https://doi.org/10.1073/pnas.1319030111

González-Orta, E. T., Tobiason, D., Gasper, B. J., Raja, A., & Miller, S. (2022). Rapid pivot of CURE wet lab to online with the help of instructor communities. *Journal of Microbiology & Biology Education*, *23*(1), e00250–e00221. https://doi.org/10.1128/jmbe.00250-21

Guimerà, R., Uzzi, B., Spiro, J., & Amaral, L. A. N. (2005). Team assembly mechanisms determine collaboration network structure and team performance. *Science*, *308*(5722), 697–702. https://doi.org/10.1126/science.1106340

Haak, D. C., HilleRisLambers, J., Pitre, E., & Freeman, S. (2011). Increased structure and active learning reduce the achievement gap in introductory biology. *Science*, *332*(6034), 1213–1216. https://doi.org/10.1126/science.1204820

Hake, R. R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics*, *66*(1), 64–74. https://doi.org/10.1119/1.18809

Hanauer, D. I., Graham, M. J., Arnold, R. J., Ayuk, M. A., Balish, M. F., Beyer, A. R., … Sivanathan, V. (2022). Instructional models for course-based research experience (CRE) teaching. *CBE—Life Sciences Education*, *21*(1), ar8. https://doi.org/10.1187/cbe.21-03-0057

Hanauer, D. I., Graham, M. J., SEA-PHAGES, Betancur, L., Bobrownicki, A., Cresawn, S., G., Zimmerman, … (2017). An inclusive Research Education Community (iREC): Impact of the SEA-PHAGES program on research outcomes and student learning. *Proceedings of the National Academy of Sciences*, *114*(51), 13531–13536. https://doi.org/10.1073/pnas.1718188115

Handelsman, J., Ebert-May, D., Beichner, R., Bruns, P., Chang, A., DeHaan, R., … Wood, W. B. (2004). Scientific teaching. *Science*, *304*(5670), 521–522. https://doi.org/10.1126/science.1096022

Handelsman, J., Elgin, S., Estrada, M., Hays, S., Johnson, T., Miller, S., … Williams, J. (2022). Achieving STEM diversity: Fix the classrooms. *Science*, *376*(6597), 1057–1059. https://doi.org/10.1126/science.abn9515

Handelsman, J., Miller, S., & Pfund, C. (2007). *Scientific Teaching*, 1st ed. New York, NY: Macmillan.

Hernandez, P. R., Agocha, V. B., Carney, L. M., Estrada, M., Lee, S. Y., Loomis, D., … Park, C. L. (2020). Testing models of reciprocal relations between social influence and integration in STEM across the college years. *Plos ONE*, *15*(9), e0238250. https://doi.org/10.1371/journal.pone.0238250

Hood, S., Barrickman, N., Djerdjian, N., Farr, M., Gerrits, R. J., Lawford, H., … Hull, K. (2020). Some believe, not all achieve: The role of active learning practices in anxiety and academic self-efficacy in first-generation college students. *Journal of Microbiology & Biology Education*, *21*(1), 10. https://doi.org/10.1128/jmbe.v21i1.2075

Hurley, A., Chevrette, M. G., Acharya, D. D., Lozano, G. L., Garavito, M., Heinritz, J., … Handelsman, J. (2021). Tiny Earth: A big idea for STEM education and antibiotic discovery. *mBio*, *12*(1), e03432–e03420. https://doi.org/10.1128/mBio.03432-20

Hurtado, S., Cabrera, N. L., Lin, M. H., Arellano, L., & Espinosa, L. L. (2009). Diversifying science: Underrepresented student experiences in structured research programs. *Research in Higher Education*, *50*(2), 189–214. https://doi.org/10.1007/s11162-008-9114-7

Jordan, T. C., Burnett, S. H., Carson, S., Caruso, S. M., Clase, K., DeJong, R. J., … Hatfull, G. F. (2014). A broadly implementable research course in phage discovery and genomics for first-year undergraduate students. *mBio*, *5*(1), e01051–e01013. https://doi.org/10.1128/mBio.01051-13

Little, R. J. A. (1995). Modeling the drop-out mechanism in repeated-measures studies. *Journal of the American Statistical Association*, *90*(431), 1112–1121. https://doi.org/10.1080/01621459.1995.10476615

Lopatto, D., Alvarez, C., Barnard, D., Chandrasekaran, C., Chung, H.-M., Du, C., … Elgin, S. C. R. (2008). Genomics education partnership. *Science*, *322*(5902), 684–685. https://doi.org/10.1126/science.1165351

McLeod, P. L., Lobel, S. A., & Cox, T. H. (1996). Ethnic diversity and creativity in small groups. *Small Group Research*, *27*(2), 248–264. https://doi.org/10.1177/1046496496272003

Miller, S., Kerr, J., & Handelsman, J. (2022). AJEDI in science: Leveraging instructor communities to create antiracist curricula. *Journal of Microbiology & Biology Education*, *23*(1). https://doi.org/10.1128/jmbe.00248-21

Miller, S., Pfund, C., Pribbenow, C. M., & Handelsman, J. (2008). Scientific teaching in practice. *Science*, *322*(5906), 1329–1330. https://doi.org/10.1126/science.1166032

National Academies of Sciences, Engineering, and Medicine. (2017). *Undergraduate Research Experiences for STEM Students: Successes, Challenges, and Opportunities*. Washington, DC: National Academies Press. https://doi.org/10.17226/24622

Nemeth, C., Brown, K., & Rogers, J. (2001). Devil's advocate versus authentic dissent: Stimulating quantity and quality. *European Journal of Social Psychology*, *31*(6), 707–720. https://doi.org/10.1002/ejsp.58

Nemeth, C. J., & Kwan, J. L. (1987). Minority influence, divergent thinking and detection of correct solutions. *Journal of Applied Social Psychology*, *17*(9), 788–799. https://doi.org/10.1111/j.1559-1816.1987.tb00339.x

Newell, M. J., & Ulrich, P. N. (2022). Gains in scientific identity, scientific self-efficacy, and career intent distinguish upper-level CUREs from traditional experiences in the classroom. *Journal of Microbiology & Biology Education*, *23*(3), e00051–e00022. https://doi.org/10.1128/jmbe.00051-22

Nieminen, P. Y. (2022). Application of standardized regression coefficient in meta-analysis. *BioMedInformatics* *2*(3), 434–458. https://doi.org/10.3390/biomedinformatics2030028

Olson, J. M., Evans, C. J., Ngo, K. T., Kim, H. J., Nguyen, J. D., Gurley, K. G. H., … Banerjee, U. (2019). Expression-based cell lineage analysis in *Drosophila* through a course-based research experience for early undergraduates. *G3*, *9*(11), 3791–3800. https://doi.org/10.1534/g3.119.400541

Over, M., Jolliffe, D., & Foster, A. (1996). Huber correction for two stage least squares estimates. *Stata Technical Bulletin* *5*(29).

Paulus, P. B., van der Zee, K. I., & Kenworthy, J. (2016). Cultural diversity and team creativity. In: *The Palgrave Handbook of Creativity and Culture Research*, ed. V. P. Glăveanu. London, UK: Palgrave Macmillan, 57–76. https://doi.org/10.1057/978-1-137-46344-9_4

Perry, W. G., Jr. (1999). *Forms of Intellectual and Ethical Development in the College Years: A Scheme*. San Francisco, CA: Jossey-Bass.

Pfund, C., Miller, S., Brenner, K., Bruns, P., Chang, A., Ebert-May, D., … Handelsman, J. (2009). Summer Institute to improve university science teaching. *Science*, *324*(5926), 470–471. https://doi.org/10.1126/science.1170015

Raudenbush, S. W., & Bryk, A. S. (2002). *Hierarchical Linear Models: Applications and Data Analysis Methods*, 2nd ed. Thousand Oaks, CA: Sage.

Riegle-Crumb, C., King, B., & Irizarry, Y. (2019). Does STEM stand out? Examining racial/ethnic gaps in persistence across postsecondary fields. *Educational Researcher*, *48*(3), 133–144. https://doi.org/10.3102/0013189x19831006

Rodenbusch, S. E., Hernandez, P. R., Simmons, S. L., & Dolan, E. L. (2016). Early engagement in course-based research increases graduation rates and completion of science, engineering, and mathematics degrees. *CBE—Life Sciences Education*, *15*(2), ar20. https://doi.org/10.1187/cbe.16-03-0117

Rosenzweig, E. Q., Harackiewicz, J. M., Hecht, C. A., Priniski, S. J., Canning, E. A., Tibbetts, Y., … Hyde, J. S. (2021). College students' reasons for leaving biomedical fields: Disenchantment with biomedicine or attraction to other fields? *Journal of Educational Psychology*, *113*(2), 351–369. https://doi.org/10.1037/edu0000456

Schultz, P. W., Hernandez, P. R., Woodcock, A., Estrada, M., Chance, R. C., Aguilar, M., & Serpe, R. T. (2011). Patching the pipeline: Reducing educational disparities in the sciences through minority yraining programs. *Educational Evaluation and Policy Analysis*, *331*, 95–114. https://doi.org/10.3102/0162373710392371

Schwartz, D. L., Chase, C. C., Oppezzo, M. A., & Chin, D. B. (2011). Practicing versus inventing with contrasting cases: The effects of telling first on learning and transfer. *Journal of Educational Psychology*, *103*(4), 759–775. https://doi.org/10.1037/a0025140

Shaffer, C. D., Alvarez, C. J., Bednarski, A. E., Dunbar, D., Goodman, A. L., Reinke, C., … Elgin, S. C. R. (2014). A course-based research experience: How benefits change with increased investment in instructional time. *CBE—Life Sciences Education*, *13*(1), 111–130. https://doi.org/10.1187/cbe-13-08-0152

Shuster, M. I., Curtiss, J., Wright, T. F., Champion, C., Sharifi, M., & Bosland, J. (2019). Implementing and evaluating a course-based undergraduate research experience (CURE) at a Hispanic-Serving Institution. *Interdisciplinary Journal of Problem-Based Learning*, *13*(2). https://doi.org/10.7771/1541-5015.1806

Sommers, S. R. (2006). On racial diversity and group decision making: Identifying multiple effects of racial composition on jury deliberations. *Journal of Personality and Social Psychology*, *90*(4), 597–612. https://doi.org/10.1037/0022-3514.90.4.597

StataCorp. (2023). *Stata Statistical Software: Release 18*. College Station, TX: [Computer software]. StataCorp LLC.

Theobald, E. J., Hill, M. J., Tran, E., Agrawal, S., Arroyo, E. N., Behling, S., … Freeman, S. (2020a). Active learning narrows achievement gaps for underrepresented students in undergraduate science, technology, engineering, and math. *Proceedings of the National Academy of Sciences*, *117*(12), 6476–6483. https://doi.org/10.1073/pnas.1916903117

Theobald, E. J., Hill, M. J., Tran, E., Agrawal, S., Arroyo, E. N., Behling, S., … Freeman, S. (2020b). Active learning narrows achievement gaps for underrepresented students in undergraduate science, technology, engineering, and math. *Proceedings of the National Academy of Sciences*, *117*(12), 6476–6483. https://doi.org/10.1073/pnas.1916903117

Thiry, H., Weston, T. J., Harper, R. P., Holland, D. G., Koch, A. K., Drake, B. M., … Seymour, E. (2019). In: *Talking about leaving revisited*, ed. E. Seymour& A.-B. Hunter. Cham, Switzerland: Springer.

Waddell, E. A., Ruiz-Whalen, D., O'Reilly, A. M., & Fried, N. T. (2021). Flying in the face of adversity: A *Drosophila*-based virtual CURE (course-based undergraduate research experience) provides a semester-long authentic research opportunity to the flipped classroom. *Journal of Microbiology & Biology Education*, *22*(3), e00173–e00121. https://doi.org/10.1128/jmbe.00173-21

Woodcock, A., Hernandez, P. R., Estrada, M., & Schultz, P. W. (2012). The consequences of chronic stereotype threat: Domain disidentification and abandonment. *Journal of Personality and Social Psychology*, *103*(4), 635–646. https://doi.org/10.1037/a0029120

World Health Organization. (n.d.). *Antibiotic Resistance: Key Facts*. Retrieved May 18, 2025, from https://www.who.int/news-room/fact-sheets/detail/antibiotic-resistance