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SYMPOSIUM

Authentic Research in the Classroom Increases Appreciation for Plants in Undergraduate Biology Students

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Synopsis Engaging students in authentic research increases student knowledge, develops STEM skills, such as data analysis and scientific communication, and builds community. Creating authentic research opportunities in plant biology might be particularly crucial in addressing plant awareness disparity (PAD) (formerly known as plant blindness), producing graduates with botanical literacy, and preparing students for plant-focused careers. Our consortium created four CUREs (course-based undergraduate research experiences) focused on dual themes of plant biology and global change, designed to be utilized by early and late-career undergraduates across a variety of educational settings. We implemented these CURES for four semesters, in a total of 15 courses, at four institutions. Pre- and post-course assessments used the Affective Elements of Science Learning Questionnaire and parts of a “plant blindness” instrument to quantify changes in scientific self-efficacy, science values, scientific identity, and plant awareness or knowledge. The qualitative assessment also queried self-efficacy, science values, and scientific identity. Data revealed significant and positive shifts in awareness of and interest in plants across institutions. However, quantitative gains in self-efficacy and scientific identity were only found at two of four institutions tested. This project demonstrates that implementing plant CUREs can produce affective and cognitive gains across institutional types and course levels. Focusing on real-world research questions that capture students’ imaginations and connect to their sense of place could create plant awareness while anchoring students in scientific identities. While simple interventions can alleviate PAD, implementing multiple CUREs per course, or focusing more on final CURE products, could promote larger and more consistent gains in student affect across institutions.

Introduction

A decade ago, the American Association for the Advancement of Science’s seminal *Vision and Change* document challenged institutions to reform biological pedagogy, creating undergraduate educational experiences centered on students, rich in inquiry-driven approaches, and imbued with relevant content (AAAS 2011; McLaughlin and Metz 2016). As society navigates complex issues, from climate change impacts to a global pandemic, AAAS’s clarion call has gained increased urgency. Undergraduate STEM programs must think creatively as they reconcile limited resources of time and personnel with the need to both instill skills (e.g., critical thinking, analytical ability, and communication) and impart content knowledge.

Since *Vision and Change*, course-based undergraduate research experiences (CUREs) and other authentic research opportunities have emerged as effective teaching strategies that promote learning gains in undergraduate biology students (Brownell et al. 2012; Auchincloss et al. 2014; Linn et al. 2015). CUREs often connect to broad research questions with implications that extend beyond the classroom, providing opportunities to contextualize course content by developing research questions, testing hypotheses, and generating and analyzing novel data. Students participating in CUREs increase their understanding of the process of science, exhibit enhanced data analysis skills (Brownell et al. 2015), and are more likely to graduate in STEM fields (Rodenbusch et al. 2016). Furthermore, research experiences create an opportunity for undergraduate students to develop a sense of scientific identity and to become integrated into a scientific community of practice (Gardner et al. 2015), and might benefit faculty efforts to balance effective teaching and research programs (Laursen et al. 2012).

CUREs connect key concepts and ideas with inquiry, enhance students' self-efficacy in STEM, promote an enduring understanding of content, and cultivate a sense of belonging and scientific identity (Kinner and Lord 2018; Cooper et al. 2020). The focus on collaborative skill-building may also increase retention of underrepresented groups in STEM (Hernandez et al. 2018; Malotky et al. 2020). CUREs provide opportunities and access to research experiences for more students than traditional mentor-apprenticeship undergraduate models (Bhattacharyya et al. 2020) and require students to integrate curricular content with science process skills essential to STEM career success (Linn et al. 2015). For example, one authentic research-based curriculum improved students' knowledge and awareness of plant science content, improved scientific writing and statistical knowledge, and increased students' interest in conducting research (Ward et al. 2014).

Implementing pedagogies that engage students and connect them to authentic research has particular relevance in the plant sciences. Although plants provide much of the food, fuel, fiber, and medicine required by human societies, the number of undergraduate programs and courses that provide botanical training has decreased substantially over the past two decades (Drea 2011; Kramer and Havens 2015; Crisci et al. 2020). At the same time, in response to the many intersections between botany and various pressing global challenges (e.g., climate change, food systems, biological invasions, and human health), there is an increasing demand for STEM professionals with botanical expertise (Uno 2009; Kramer and Havens 2015). However, an overall lack of awareness of or appreciation for plants, originally termed "plant blindness" (Wandersee and Schussler 2001; Allen 2003) and more recently "plant awareness disparity (PAD)" (Parsley 2020), contributes to gaps in the botanical capacity of STEM graduates, impairing institutions' ability to address these challenges. PAD is prevalent among undergraduates, even in biology programs (Schussler and Olzak 2008; Batke et al. 2020; Colon et al. 2020). Consequently, curricular reform through the implementation of immersive CUREs provides an excellent opportunity for students to cultivate self-efficacy, improve conceptual understanding, and gain key content knowledge while increasing awareness of the roles of plants in biological systems.

The Consortium Exchanging Research Experiences for Undergraduate Students (CEREUS), a collaboration among four southern Appalachian colleges and universities [Appalachian State University (ASU), East Tennessee State University (ETSU), University of North Carolina Asheville (UNCA), and Warren Wilson College (WWC)], began in 2015. Since then, we have created and implemented new inquiry-based, botanically infused CURE modules that investigate global change in the southern Appalachians. Many undergraduates at these institutions are from the southeastern USA and come to college with meaningful personal and cultural connections to this region. Thus, we implemented a curriculum focused on southern Appalachian plant species and ecosystems in 15 introductory, intermediate, and advanced undergraduate courses (Table 1). We chose global change as a unifying theme because the southern Appalachian region is rich in species diversity and endemism and harbors a variety of unique ecosystems (Jenkins et al. 2015), such as the high-elevation spruce-fir forests that are predicted to shift under or be threatened by climate and/or land use change (Griep and Collins 2013). Although dramatic climate change responses remain undocumented in much of the region (Warren and Bradford 2010), there is evidence of changes in winter weather (Eck et al. 2019), recent warming in the southern portion of its range (Laseter et al. 2012), and changes in phenological patterns (Flood et al. 2018). Along with these climate-associated shifts, the term "global change" includes phenomena like the expansion of non-native plants, which can displace or hybridize with native species in this region (e.g., Zaya et al. 2015).

Our first objective was to create botanical CUREs that honed collaborative skills; cultivated positive student attitudes toward plants and STEM; were infused with skill development in higher-order cognitive processes, quantitative literacy, and analytical techniques; and could be adopted in a variety of institutional settings. Our second objective was to use a combination of quantitative and qualitative measures to evaluate relationships between this curricular engagement and student outcomes across institutions and course levels: introductory (first year/sophomore courses for majors), intermediate (sophomore/junior courses for majors), and advanced (courses aimed at senior-level majors). These assessments focused on scientific values, scientific identity, self-efficacy in science, and self-reported perceptions and knowledge of plants.

Materials and methods

Program description

From 2015 to 2018, the CEREUS faculty developed and implemented four plant-focused CUREs spanning multiple scales of biological organization (Fig. 1) that contained approaches adaptable for introductory, intermediate, and advanced level courses. CUREs, ranging in duration from 2 to 15 weeks, were presented to students at two large public universities (ASU, Appalachian State University; ETSU, East Tennessee State University), a public liberal arts university (UNCA; University of North Carolina Asheville), and a private liberal arts college (WWC; Warren Wilson College). Each CURE was taught at multiple

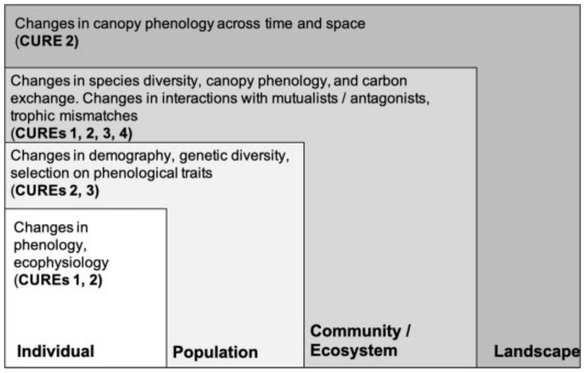

Fig. 1. Schematic diagram illustrating how CUREs evaluate global change effects at different levels of the biological hierarchy from individuals to ecosystems.

institutions. However, to ensure that CUREs aligned with faculty expertise and institutional course offerings, not all CUREs were implemented at all sites (Table 1).

Each CURE included an out-of-class data analysis and culminated in a final product. These products varied among instructors and courses and included laboratory reports (written in the style of peer-reviewed manuscripts) or conference-style oral presentations. Although field and laboratory methods were standardized across courses and institutions, students were charged with formulating their own hypotheses and using experimental design principles to test those hypotheses. Individual students or groups of students collected data, which were then compiled within courses (and sometimes across years/institutions) and/or shared with national data repositories to create multi-tier datasets appropriate for various lines of investigation.

Since faculty and institutional resistance to change can be barriers to CURE adoption (Bell et al. 2017), we prioritized developing CUREs that could be tailored to meet the learning targets of faculty who were willing and able to include CEREUS modules in their courses. While it would have been informative to compare indicators of student affect and PAD between CURE courses and a non-CURE control course, we did not include a control group in this study. Preliminary work indicated wide-ranging benefits of botanical CUREs, which made intentionally denying CUREs to some students ethically questionable. In addition, since some courses were taught as a single section per year, the use of a control group was impractical.

Table 1 CEREUS CURE utilization by institution, course, and course level (introductory, intermediate, or advanced)

School	Course	CURE(s)	Class size	Course level
ASU	Introduction to Botany[a]	1, 2	65	Introductory
	Global Change Ecology	1, 2, 4	20	Advanced
	Systematic Botany	3	20	Advanced
	Plant Physiology	2	24	Advanced
ETSU	Principles of Organismal Biology	2, 4	125	Introductory
UNCA	Plants and Humans	2, 4	20	Introductory
	Experimental Design & Analysis	2, 4	20	Introductory
	Cellular & Molecular Biology	3	20	Introductory
	Forest Ecosystems	1, 2, 4	15	Advanced
	Principles of Botany	1, 2, 3	20	Intermediate
	Plant Physiology	2, 4	15	Advanced
	Field Botany	1, 2	15	Advanced
WWC	Ecology	2	20	Intermediate
	Genetics[a]	3	18	Intermediate
	Applied Ecology[a]	4	20	Intermediate

When multiple CUREs were presented in a course, they were presented sequentially not simultaneously.
aCourses where CURE(s) were implemented, but not formally assessed pre- and post-CURE.

CURE 1: native community responses to non-native invasive plants

In this field-based CURE, we established permanent forest plots to monitor the efficacy of removal techniques (mechanical and chemical) and removal timing (annually and every 3 years) in reducing the cover of non-native invasive plants and promoting native community recovery. Plots were established using Global Invader Impact Network (GIIN; Barney et al. 2015) protocols. Students who participated in this CURE learned skills in plant identification, quantitative data collection, and statistical analysis. In addition, long-term data were uploaded to the national GIIN database.

CURE 2: Phenology as an indicator of species and community responses to climate change

This set of field-based CUREs focused on understanding relationships between plant phenology and climate. Phenology gardens, planned landscapes used to monitor the timing of biological phenomena (de Beurs et al. 2013), were established at UNCA, ASU, and WWC. Each garden contained sets of native perennial herbaceous species (grown in replicate plots) collected from the same field populations, to allow comparisons of source and site effects. Phenology trails, along which native and non-native trees and shrubs were tagged, were established at all four institutions, using protocols published by the USA National Phenology Network Nature's Notebook program (Denny et al. 2014).

Students learned skills associated with phenological research, such as plant identification, data management, and climatological and ecological data analysis. They used established protocols to monitor plant phenology on campus trails and managed areas located in campus centers. Student-generated data were shared with the USA National Phenology Network's Nature's Notebook Program (https://www.usanpn.org/natures_notebook).

CURE 3: characterizing population genetic diversity in a changing world

This laboratory-based set of CUREs was intended to overcome anti-botanical bias in pre-professional students by highlighting laboratory applications in plant science. It focused on how genetic diversity affects, and is affected by, global change (Pautasso et al. 2010; Dawson et al. 2011; Pauls et al. 2013). Such diversity is manifest at the species and population levels, where it can serve as an indicator of evolutionary histories, such as founder events (Uller and Leimu 2011), bottlenecks (Aguilar et al. 2008), habitat fragmentation (Jacquemyn et al. 2012), and overharvesting (Pinsky and Palumbi 2014).

Students explored connections between population genetics, conservation biology, and natural resource management. Undergraduates learned about the natural history and biology of charismatic southern Appalachian native plants, including American ginseng (*Panax quinquefolius* L.), a medicinal plant with significant cultural history in the region, and carnivorous pitcher plants (*Sarracenia* spp.), as well as non-native invasive plants (e.g., Asian bittersweet, *Celastrus orbiculatus*) that have altered southern Appalachian communities. Laboratory experiences focused on using research approaches and tools used in cellular, molecular, and conservation biology, including DNA extraction, polymerase chain reaction (PCR), and microsatellite analysis.

CURE 4: investigating carbon exchange in urban and other forests

This field-based CURE focused on providing students with community/ecosystem-wide perspectives on the influences of climate change on carbon dynamics and productivity. Permanent 20 × 20 m plots were established at ASU, UNCA, and WWC. Research and classroom students used NSF-EREN protocols (http://erenweb.org/project/carbon-storage-project/) to make annual measurements of tree diameter growth increments and community composition. Allometric equations for southern Appalachian tree species (Martin et al. 1998) permit estimates of tree biomass growth; these were coupled with data on tree wood density (Clark and Schroeder 1985) to let students estimate carbon storage per year (Kurz and Apps 1999). Students were able to discern the role of environment and history in determining community composition by comparing forest plots on slopes with different orientations (Cantlon 1953; Gilliam et al. 2014), and could also relate interannual changes in weather to those in carbon storage with data from campus weather stations.

Quantitative analyses of student engagement

To assess the effects of CUREs on student learning, we used a non-experimental pre- and post-test design to evaluate indicators of self-efficacy in science, science values, scientific identity, and indicators of PAD. The Affective Elements of Science Learning Questionnaire, whose 35 questions use a five-point Likert scale (range: strongly disagree to strongly agree), was used to test distinct constructs: students' beliefs about their own ability in science, students' value of science (including scientific knowledge and the process of science), and the degree to which students perceive themselves as members of the scientific community (Williams et al. 2011). Because each construct was represented by multiple survey items, responses were summed, and an average score was calculated for items related to each measure.

Select items from a plant "blindness" instrument (Slough 2012) were included in pre- and post-surveys to measure self-reported botanical knowledge, personal involvement with plants, and cultural perceptions of plants. The three elements that contribute to PAD (knowledge, interest, and attitude) are distinct constructs, so results are reported independently rather than as an aggregate score (Slough 2012). Similar to the Affective Elements of Science Learning Questionnaire, items associated with each construct were measured on a five-point Likert scale, and an average score was calculated for each construct. Pre- and post-test survey data were collected for four semesters (Fall 2016, Spring 2017, Fall 2017, and Spring 2018) at all institutions using Google Forms. Entries with missing data were excluded from subsequent analyses.

Repeated measures ANOVAs were used to compare pre- and post-CURE indicators of self-efficacy, values, identity, and plant awareness described above. Because initial repeated measures ANOVAs showed significant differences ($\alpha = 0.05$) among institutions with respect to all variables (except plants and culture), pre- and post-CURE impacts were analyzed separately for each institution. UNCA was the only institution where CUREs could be implemented across all three course levels (introductory, intermediate, and advanced). To determine whether differences between pre- and post-CURE indicators of student affect and plant awareness varied among course levels at UNCA, we conducted repeated-measures ANOVAs that included the effects of time, course level, and time × course level. All statistical analyses were performed in JMP Pro 16.0.0 (SAS Institute, Cary, NC).

Qualitative analyses of student engagement

Qualitative data were collected as part of pre- and post-CURE surveys and through semi-structured (think-aloud) interviews with student participants throughout the study period. NVivo Qualitative Analysis Software (NVivo 12, QSR International Pty. Ltd.) was used to perform an inductive, emergent coding analysis on survey responses. Multiple research personnel coded survey responses identifying emergent patterns, themes, and categories (Patton 2002). There were three main sources of qualitative data. The first two sources were 30–45 min semi-structured interviews: (1) one-on-one interviews with student research interns who previously participated in courses with CEREUS modules and now working with faculty mentors on independent projects ($n = 10$) and (2) group interview with students in a WWC ecology course ($n = 17$). Respondents were asked how experiences with CEREUS courses and plant-based research impacted their personal and professional goals. Interviews were audio-recorded, and two trained graduate research assistants used emergent coding to evaluate all responses until acceptable inter-rater reliability (IRR) was reached (>90% agreement; Cohen's Kappa >0.80). Twenty unique codes emerged from interview data.

The third source of qualitative data was a series of open-ended questions on pre–post course surveys asking students about their views on science and the study of plants. Students provided short-answer responses to questions in each of these categories: self-efficacy, values, and identity. Open-response questions were evaluated and re-evaluated by two graduate assistants and one undergraduate research assistant until a subset (~800 statements) reached an acceptable IRR (>90% agreement; Cohen's Kappa >0.80), and the remaining responses were divided and evaluated by an individual research assistant. Open-response questions elicited from pre–post surveys resulted in over 4700 individual statements from students from all institutions over four semesters of data collection.

Results

Student awareness of and interest in plants

PAD is associated with a lack of consciousness of and interest in plants. Students' self-reported knowledge and perceptions of plants increased significantly between pre- and post-CURE exposure at all four colleges and universities (Table 2 and Fig. 2). We also observed a significant increase in post-test scores compared with pre-test scores for student self-reported measures for plant knowledge and personal involvement with plants. There was no significant difference between pre- and post-indicators of plants and culture (Table 2).

Comparisons among course levels indicated that students' self-reported plant knowledge and personal involvement with plants was higher in advanced courses than in intermediate or introductory courses (repeated measures ANOVA, course level effect knowledge $F_{2,114} = 4.573$, $P < 0.05$, personal involvement $F_{2,114} = 3.609$, $P < 0.05$). There were also significant course level × time interactions for both of these variables, indicating that the gain in knowledge and personal involvement with plants were greatest in UNCA's intermediate course (*Principles of Botany*).

Of the over 4700 statements evaluated from the pre- and post-surveys, 626 statements in the pre-CURE responses specifically referenced plants or plant sciences. The proportion of statements suggesting negative attitudes toward plants and plant biology decreased from the pre- (38%) to post-survey (24%); there was also a 15% decrease in statements explicitly describing a bias toward animals. When asked about how scientists study plants, 26% of pre-test responses referenced the use of general laboratory equipment (e.g., microscopes) or specialty tools for gardening/cultivation. There was very little reference (<2%) to the role of plants in studies of major biological disciplines, such as biochemistry, genetics, ecology, and physiology. The only major biological process mentioned in pre-CURE responses was photosynthesis (<1%).

By contrast, post-CURE survey responses showed an increase in the mention of plants in several areas of biology beyond photosynthesis (9%). Post-test responses also included more statements regarding the roles of plants in efforts to address problems facing humanity (from 1% in pre to 2% in post). There was also an increase in the number of responses describing the use of general laboratory equipment, such as microscopes, to study plants (from 26% in pre to 32% in post).

Participants provided the following statements post-CURE:

- *UNCA, Fall 2016.* "I do see myself having a job involving plants, animals, or the environment, regardless of whether or not it is deeply scientific or research-involved."
- *WWC, Fall 2017.* "I find science fascinating and feel capable enough when understanding scientific concepts. I thoroughly enjoy botany and look forward to continuing my education."
- *ETSU, Spring 2017.* "Science is an important part of society and I am very interested in science through all aspects, not just plants and animals."
- *ASU, Spring 2018.* "As I further my knowledge of botany, so does my support."

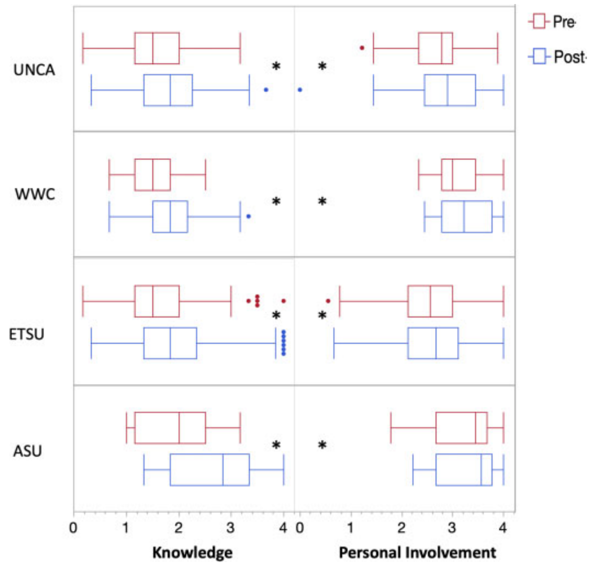

Fig. 2. Pre- and post-CURE indicators of student awareness and interest in plants at CEREUS institutions. Indicators range from 0 to 4 and values close to 4 signify greater plant interest and awareness than values close to 0. Vertical lines in each box indicate the median, and the length of each box corresponds to the interquartile range (IQR) between the 25th and 75th quartiles. Whiskers surrounding each box are 1.5 times the IQR. Pre- and post-indicators that differ significantly from one another (repeated measures ANOVA, $\alpha = 0.05$) are indicated with an asterisk (*).

Table 2 Summary of repeated measures ANOVAs comparing pre- and post-CURE mean indicators of student awareness and appreciation for plants at the four CEREUS institutions: ASU ($n = 15$), ETSU ($n = 436$), UNCA ($n = 117$), and WWC ($n = 31$)

Indicator	Institution	*F*-ratio	df_{num}	df_{den}	*P* value
Knowledge	ASU	25.79	1	14	**0.0002**
	ETSU	109.35	1	435	**<0.0001**
	UNCA	1001.01	1	116	**<0.0001**
	WWC	8.19	1	30	**0.008**
Personal involvement	ASU	5.30	1	14	**0.037**
	ETSU	15.55	1	435	**<0.0001**
	UNCA	12.31	1	116	**0.0006**
	WWC	6.49	1	30	**0.016**
Plants and culture	ASU	1.21	1	14	0.291
	ETSU	0.90	1	435	0.342
	UNCA	1.60	1	116	0.208
	WWC	0.45	1	30	0.510

Analyses that showed significant differences ($\alpha = 0.05$) are indicated in bold.

Affective elements of science learning

On average, student-reported self-efficacy increased significantly after CURE exposure at one of the four institutions (UNCA). Students' sense of scientific identity also increased between pre- and post-CURE surveys at ETSU, a large public university where CUREs were integrated into an Introductory Biology course. Indicators of student affect in STEM did not differ between pre- and post-CURE exposure at ASU and WWC (Table 3 and Fig. 3).

Because CUREs were not implemented across course levels at ASU, ETSU, and WWC, we were unable to compare student affect among levels at these schools. Repeated measures ANOVAs

Table 3 Summary of repeated measures ANOVAs comparing pre- and post-CURE mean indicators of student affect and learning in STEM at the four CEREUS institutions: ASU (n = 15), ETSU (n = 436), UNCA (n = 117), and WWC (n = 31)

Indicator	Institution	F-ratio	df_{num}	df_{den}	P value
Self-efficacy	ASU	0.48	1	14	0.500
	ETSU	2.48	1	435	0.116
	UNCA	7.65	1	116	**0.007**
	WWC	0.36	1	30	0.551
Identity	ASU	0.03	1	14	0.873
	ETSU	10.06	1	435	**0.002**
	UNCA	0.82	1	116	0.366
	WWC	0.65	1	30	0.428
Values	ASU	0.50	1	14	0.491
	ETSU	0.41	1	435	0.525
	UNCA	0.62	1	116	0.431
	WWC	0.65	1	30	0.428

Analyses that showed significant differences (α = 0.05) are indicated in bold.

evaluating course level effects at UNCA, however, showed no significant differences in CURE impacts among course levels with respect to self-efficacy (course level $F_{1,114} = 0.4944$, $P = 0.61$, time × course level $F_{1,114} = 1.7189$, $P = 0.18$), identity (course level $F_{1,114} = 0.1483$, $P = 0.86$, time × course level $F_{1,114} = 2.2697$, $P = 0.11$), or values (course level $F_{1,114} = 0.2363$, $P = 0.79$, time × course level $F_{1,114} = 1.7189$, $P = 0.9736$).

Pre- and post-CURE qualitative surveys were used to confirm quantitative analyses and identify additional learning outcomes and/or themes that may not have been captured by the Likert-type questions. Student pre-CURE responses often included negative statements regarding their academic skills and abilities, as well as their confidence in explaining scientific ideas and participating in STEM. These responses also revealed little interest in plants and plant biology. Post-CURE survey responses indicated a marked increase in the mention of plants, however, and many students described specific experiences that increased their confidence and understanding of science.

Participants provided the following statements post-CURE:

- *ETSU, Fall 2017.* "I feel confident in my science abilities based on my success in my current science classes and hope to continue on into many more science related courses."
- *UNCA, Spring 2017.* "I want to be a scientist . . . I have had a lot of experience in interpreting scientific data and understanding the mechanisms that govern the world around me."
- *WWC, Spring 2017.* "Science (biology) is one of the few areas in school that makes sense to me, even though plants are a bit harder for me to understand. The interaction between all of the components makes a unique and easy to understand web."
- *ASU, Spring 2018.* "I feel very confident about my skills in the science field, but it does come with challenges of course. Sometimes it takes me a little longer to understand a concept than others depending on the subject matter."

Structured interviews with undergraduate research interns mirrored patterns from post-CURE student responses; they described gains in confidence and a sense of scientific identity. Additional themes emerged from interviews that were not evaluated in the questionnaire. For example, interviewees indicated the value of developing technical research skills. All students interviewed described positive relationships with faculty mentors, and more than half hoped to gain additional skills in data analysis and scientific writing. Six participants indicated an interest in pursuing a graduate degree in STEM.

Discussion

In recent years, CUREs have been championed as an innovation in STEM education because they can leverage existing faculty research interests, complement faculty scholarship, require fewer resources than traditional mentored research, and can reach large numbers of students (Alkaher and Dolan 2014). The CEREUS project described herein provides an example of how CUREs can be developed into transferable curricula that can be implemented across a diverse array of institution types, class sizes, and class levels to yield significant learning gains. We observed consistent gains with respect to plant awareness and interest in both large and small enrollment courses in multiple institutional settings. While there were consistent and significant gains across institutions with respect to PAD-mitigation, gains in STEM affect varied by institution. Students may come to college with more preconceived notions about themselves than preconceived notions about plants. This suggests that there may be fewer barriers to elevating student awareness and interest in plants than there are to moving the needle on students' sense of self. Consequently, establishing *a priori* learning targets and assessment strategies specifically aimed at promoting gains in self-efficacy and sense of identity should be part of future iterations of the CUREs presented here.

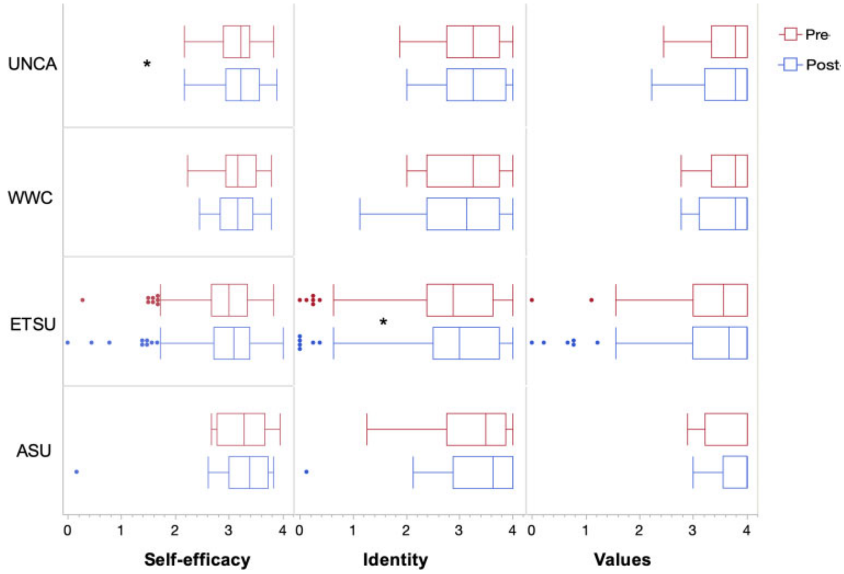

Fig. 3. Pre- and post-CURE indicators of student affect in STEM at CEREUS institutions. Indicators range from 0 to 4 and values close to 4 signify greater plant interest and awareness than values closer to 0. Vertical lines in each box indicate the median, and the length of each box corresponds to the interquartile range (IQR) between the 25th and 75th quartiles. Whiskers surrounding each box are 1.5 times the IQR. Pre- and post-indicators that differ significantly from one another (repeated measures ANOVA, $\alpha = 0.05$) are indicated with an asterisk (*).

Variation among institutions

Gains in indicators of student STEM affect (self-efficacy, sense of identity, and values), were inconsistent across institutions (Fig. 3). At UNCA, exposure to one or more botanical CUREs was associated with significant quantitative increases in self-efficacy, but this pattern was not observed at other institutions. We also found that students' sense of scientific identity increased at ETSU, but not at the other institutions. These findings could be attributed to multiple factors. First, there could have been variation among faculty with respect to *how* various CURE elements (authentic problem solving, collaboration, elements of science, iteration, and discovery; Auchincloss et al. 2014) were executed. UNCA faculty and the institution have been engaged in intentional CURE programming for at least a decade (Ward et al. 2014). The process of implementing new CUREs may be more effective at institutions where *Vision and Change* pedagogies and the practice of CURE assessment are embedded in the institutional culture. Second, it is possible that students at WWC and ASU started with somewhat high levels of self-efficacy [mean (SE) at ASU = 3.3 (0.11); WWC = 3.2 (0.07)] compared with other schools [mean (SE) at ETSU = 2.9 (0.03); UNCA = 3.2 (0.04)], leaving little room for overall gain in this indicator of student engagement. At WWC (but not other instructions), we observed a significant negative correlation between self-efficacy pre-scores and overall gains (linear regression, $t = -2.24$, $P = 0.03$, $R^2 = 0.147$, $n = 30$), suggesting that the opportunity for self-efficacy gains was not uniform among students sampled at this site. Third, CUREs were assessed in all courses where they were implemented at UNCA and ETSU (Table 1), but this was not the case at ASU and WWC. It may be that the smaller number of student assessments at the latter schools hindered our ability to detect quantitative differences between pre- and post-CURE exposure.

Qualitative data from surveys and interviews across institutions provide helpful additional perspective on the quantitative results. Student responses revealed more frequent mentions of plants and growing confidence in their abilities to conduct and participate in science. In addition, semi-structured interviews showed language indicating increases in scientific identity. These interviews also uncovered themes not explicitly evaluated in the questionnaire, including perceived gains in technical skills, interests in scientific writing, positive mentor-mentee relationships, and effects of research participation on post-graduate and career goals. Such results are aligned with other analyses of CURE impacts (Corwin et al. 2015).

Comparisons across course levels

In our network, ETSU and UNCA were the only schools where CUREs were implemented and assessed in introductory courses, and course level comparisons were only done at UNCA. There, we found consistent gains in self-efficacy across course levels, but the gains were greatest in an intermediate course. This is similar to the findings of other studies that reported greater gains in non-introductory courses (Kinner and Lord 2018; Anderson et al. 2020).

It is particularly encouraging that these CUREs were effective in introductory courses. First-year courses often have high enrollments and emphasize the acquisition of content knowledge over skills, which can create obstacles to connecting students with the highly immersive experiences of "doing science" that may inform a student's choice of academic and/or career path. Here, we demonstrate that it is possible to impart some aspects of independent research in introductory courses, creating opportunities for students to gain access to the scientific enterprise and to build a sense of belonging (Cooper et al. 2020). This may be particularly important for students historically excluded from STEM career paths, including those with PEER—People Excluded because of Ethnicity or Race—identities (Asai 2020).

CUREs for PAD

Plants are often taken for granted. Nonetheless, in the coming years, they will play critical roles in efforts to address a variety of issues relating to global climate change, human health, and food security (Henkhaus et al. 2020). Future generations of scientists will, therefore, benefit from gaining an awareness of and an appreciation for plants (Montgomery 2021). We observed significant, positive increases in plant knowledge and awareness across all four CEREUS institutions, a pattern that contrasts with our observations of affective learning in STEM. This suggests that using botanical CUREs to deliver biological content knowledge and to develop skills in STEM is an effective way to alleviate PAD.

Course level-comparisons at UNCA revealed that student interest in plants increased the most in UNCA's intermediate *Principles of Botany* course. In this particular class, CUREs 1, 2, and 3 were each implemented one after the other, providing the opportunity to explore intersections among botany, ecology, genetics, climate science, and conservation biology. This repeated semester-long exposure to multiple CUREs might have piqued botanical interest by personalizing plant science. CURE implementation will continue with the goal of not only alleviating PAD, but of building an enduring love for plants (McDonough MacKenzie et al. 2019).

PAD is one factor that may exacerbate ongoing challenges associated with conserving non-timber plant species and protecting imperiled species from illegal trade activity (Margulies et al. 2019). Hence, we developed two CUREs (1 and 3) that focused explicitly on conservation; we hope that teaching conversation and botanical principles together will foster appreciation for plants as a taxonomic group worthy of protection (Balding and Williams 2016).

CURE implementation: feasibility, barriers, and benefits

Several factors made the student-centered CUREs described here easier to develop and implement. First, the emergence in recent years of large coordinated research and educational networks, such as the GIIN, the Ecological Research as Education Network (EREN), the USA National Phenology Network (NPN), and the SouthEast Regional Network of Expertise and Collections (SERNEC), has made it possible for students to compare a relatively small number of CURE-generated observations with large datasets collected nationwide. This sets the stage for students to enter into larger communities of practice to further develop their scientific identities, in addition to learning how to work with large datasets to evaluate research questions. Second, the project PIs are all botanists with strong interests in plant evolution and/or ecology and whose research dovetails with and informs CURE topics. Third, existing structures at some CEREUS institutions might have helped with CURE integration. For example, UNCA has a robust peer-tutoring system that supports first year students as they used the statistical program R to analyze data and write their first journal-style laboratory reports.

The CUREs described here are relatively low cost, but we also encountered limitations in the extent of institutional support for CURE implementation. Challenges included inconsistent staffing for CURE courses, finding sufficient faculty time to replace existing curricula with CUREs (or to integrate CUREs with existing curricula), and student resistance to grappling with the uncertainties of authentic scientific inquiry. Establishing a campus culture where *Vision and Change* principles are embraced and faculty are motivated and ultimately rewarded for teaching innovation is essential for CUREs to be implemented in a long term, vertically integrated, and consistent manner (McLaughlin and Metz 2016).

The CUREs resulting in significant increases in self-efficacy and identity also had substantial final products associated with them. For example, at UNCA, all students wrote drafts and final versions of a journal-style paper about CURE 1, and some were able to present CURE 3 products at the university's undergraduate research symposium. By contrast, at WWC, CURE 2 was integrated and assessed in a course with multiple pre-existing projects already embedded into the curriculum. Students engaged in the process of discovery, addressed a real-world problem, and evaluated hypotheses, but may not have had a strong sense of ownership for this research compared with their other coursework.

While the CUREs focused on student outcomes, one result of this work is the generation of a faculty community of practice. Faculty professional development experiences, such as the collaboration of faculty participating in the CEREUS consortium, result in faculty who are more well-equipped and able to catalyze organizational change and adopt long-term effective teaching practices (Steinert et al. 2019). In the process of developing and implementing CURES across the four institutions, a community of practice emerged and created a welcome space for participating instructors to share lessons learned. Expertise in the network includes both plant science and biology education research, which allowed faculty trained in botanical research to engage in the process of educational assessment. The network continues to be an interactive forum for constructive teaching and research dialogues. Members have also collaborated on conference presentations and CURE-implementation workshops, and continue to build a network of faculty supporting faculty. Beyond continued collaboration to refine the CUREs described here and to develop new curricular materials (Ward and Hove 2021), network members have established cross-institutional projects that involve co-mentoring undergraduates in their research laboratories to study American ginseng conservation genetics and southern Appalachian forest ecology (Caruso et al. 2021; Ward et al. in preparation). An additional legacy of this project is the establishment of longitudinal data sets that will document future patterns of phenology and forest growth. We are continuing to build these datasets and use them for future studies of responses to global change once we accumulate several more years of data. This will provide future generations of students with long-term "home-grown" data that can continue to be generated and analyzed over time.

Conclusion

The CEREUS program began with a desire to connect biology education, regional biodiversity, and authentic research experiences. However, student interviews revealed student interests in other areas, including how to pursue a science career, desire to gain technical and analytical skills, and to engage in science communication. Given the anticipated demand for STEM professionals in the coming years, especially in botany (Kramer and Havens 2015), extensions of these CUREs will explicitly connect individual research experiences to possible career outcomes. These modules could also be readily adjusted to culminate in final products involving science communication and outreach that extend beyond the traditional conference presentation or laboratory report formats.

The past decade has seen a push toward doing more experiential learning in STEM classrooms, with a subsequent increase in the use of CUREs. Our study demonstrates that CUREs can be implemented in a variety of class sizes, course levels, and institutional settings and that student engagement can be fostered through focusing on research questions that address real-world challenges that may connect to students' interests and experiences.

The current decade began with a year that brought with it myriad events that have challenged STEM educators, and humanity as a whole. Rarely does change come easily; nonetheless, shifting our educational practice has perhaps never been more critical. The work shared here expands upon existing research demonstrating the effectiveness of CUREs, but also highlights the importance of explicitly considering institutional culture and curricular structures throughout the process of CURE implementation. The consistent increases in student awareness and interest in plants also suggest that CUREs may be particularly valuable tools for alleviating PAD and for cultivating an engaged, botanically literate generation of scientists and scientifically-engaged members of our society.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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Conflict of interest

The authors declare no conflict of interest.

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