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Article

Effects of a Research-Infused Botanical Curriculum on Undergraduates' Content Knowledge, STEM Competencies, and Attitudes toward Plant Sciences

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In response to the American Association for the Advancement of Science's Vision and Change in Undergraduate Biology Education initiative, we infused authentic, plant-based research into majors' courses at a public liberal arts university. Faculty members designed a financially sustainable pedagogical approach, utilizing vertically integrated curricular modules based on undergraduate researchers' field and laboratory projects. Our goals were to 1) teach botanical concepts, from cells to ecosystems; 2) strengthen competencies in statistical analysis and scientific writing; 3) pique plant science interest; and 4) allow all undergraduates to contribute to genuine research. Our series of inquiry-centered exercises mitigated potential faculty barriers to adopting research-rich curricula, facilitating teaching/research balance by gathering publishable scholarly data during laboratory class periods. Student competencies were assessed with pre- and postcourse quizzes and rubric-graded papers, and attitudes were evaluated with pre- and postcourse surveys. Our revised curriculum increased students' knowledge and awareness of plant science topics, improved scientific writing, enhanced statistical knowledge, and boosted interest in conducting research. More than 300 classroom students have participated in our program, and data generated from these modules' assessment allowed faculty and students to present 28 contributed talks or posters and publish three papers in 4 yr. Future steps include analyzing the effects of repeated module exposure on student learning and creating a regional consortium to increase our project's pedagogical impact.

INTRODUCTION

In their seminal *Vision and Change in Undergraduate Biology Education* document, the American Association for the Advancement of Science (AAAS) challenged institutions to reform the ways in which they teach science, technology, engineering, and mathematics (STEM) subjects, creating educational experiences 1) centered on students, 2) rich in inquiry-driven approaches, and 3) full of relevant content (AAAS, 2011). AAAS and the National Science Foundation (NSF) further recommended that all undergraduate students engage in authentic research through faculty-mentored projects and/or classroom laboratory activities (Woodin *et al.*, 2009). Ideally, all undergraduate biology majors would participate in a formal original research experience (Meers *et al.*, 2004; AAAS, 2011); the National Research Council's Committee on Undergraduate Biology and Education (NRC, 2003) identified the development of research experiences as a key pedagogical priority for tertiary educators. Many institutions agree that research-based learning should become the curricular standard in undergraduate education (Council on Undergraduate Research [CUR], 2005), and some use a formal course sequence to let students participate in faculty-supervised research (Malachowski, 2003). However, mentoring every student through a thesis project can be difficult due to budgetary and time constraints (Nadelson *et al.*, 2010). At R1 institutions, undergraduates are frequently mentored by graduate students (i.e., Edwards *et al.*, 2011), but providing sufficient

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numbers of research experiences might be particularly challenging at non-R1 institutions, where faculty teaching and service loads are already heavy (Karukstis *et al.*, 2009).

To involve all biology majors at our public liberal arts college in research-based learning, we began infusing plant-based research throughout our courses, starting in students' sophomore years (when all students are required to take a plant biology course) and continuing for the duration of their undergraduate educations. Our vertically integrated research modules are unique teaching and learning tools, exposing classroom students to the same research theme during multiple classes (lower- and upper-division courses). By using modules based on our undergraduate research students' work and giving classroom students some autonomy in pursuing research questions of interest to them, we hoped to increase student interest in the scientific process. Our research-centered teaching approach was designed to help faculty members balance conflicting demands on their time (Laursen *et al.*, 2012), increase productivity by allowing faculty members to gather data while simultaneously immersing their classroom students in STEM research (e.g., Gardner *et al.*, 2011), and create a positive-feedback loop between teaching and research. In this paper, we describe how we designed, executed, and assessed a new plant-based curriculum, letting all sophomores do authentic research and allowing many students to investigate additional topics during upper-division classes.

Authentic Undergraduate Research in the Classroom

Course-based original research is a proven approach to teach students content (Karukstis, 2004; Kauffman and Stocks, 2004; Ruiz-Primo *et al.*, 2011), model research skills and the scientific process (Kardash, 2000; Bowen and Roth, 2002; Deb-Burnman, 2002; AAAS, 2011; Kazempour *et al.*, 2012), help students understand the nature of science (NOS; Handelsman *et al.*, 2007; Schussler *et al.*, 2013), and increase matriculation into STEM graduate programs (Lopatto, 2003). Undergraduates who participate in research are better prepared for STEM careers (Ernsting and Akrabawi, 2007) and are able to take more creative approaches to problem solving (DeHaan, 2011). Research infusion can also shift the tenor of STEM courses, eliciting student engagement (Gardner *et al.*, 2011) and improving attitudes toward both STEM disciplines and scientific research (Nadelson *et al.*, 2010; Brownell *et al.*, 2012).

Course-based research experiences should be designed so they are not just modifications of traditional "cookbook" labs, with prescribed procedures and known outcomes (Brownell *et al.*, 2012). Instead, course modules should be created and evaluated using sound scientific principles (Handelsman *et al.*, 2004) and should meet a number of criteria (e.g., Lopatto, 2003). First, they should be student-centered, inquiry-rich (AAAS, 2011), and not based on an apprentice model (Wei and Woodin, 2011). Second, they should play a central rather than a peripheral role in undergraduate science curricula (AAAS, 2011). Finally, such research experiences should begin early in students' course work (NRC, 2003; CUR, 2005; AAAS, 2011), as they communicate high learning expectations (Chickering and Gamson, 1989; Handelsman *et al.*, 2007) and shape students' career trajectories (Holbrook and Tibbs, 1995; Chen *et al.*, 2005; Harrison *et al.*, 2011). Pedagogical research has found positive associations between first- and second-year research experiences and students' grades (Barlow and Villarejo, 2004; Kinkel and Henke, 2006; Junge *et al.*, 2010), on-time graduation rates (Kinkel and Henke, 2006), and continuity in STEM disciplines (Barlow and Villarejo, 2004; Kinkel and Henke, 2006; Summers and Hrabowski, 2006; Gilmer, 2007; Carter *et al.*, 2009).

Challenges: Curricular Inertia, Plant Blindness, and Plant Interest

Although the pedagogical advantages of a research-rich curricular approach have been well-documented (e.g., Herron, 2009; Baker, 2010; Mathews *et al.*, 2010), practical barriers to involving all students in authentic research remain (Sunal *et al.*, 2001; Tagg, 2012). Obstacles include constraints related to faculty time, motivation, and expectations (Doyle, 2002; Henderson and Dancy, 2006), student time and preparation (McGinn and Roth, 1999), and funding to support projects (Beath *et al.*, 2012). Some faculty members actively resist adopting a research-based model of pedagogy (Benvenuto, 2002), perhaps due to misperceptions about reduced rigor, loss of content knowledge, or the ways in which students construct knowledge (e.g., Kirschner *et al.*, 2006). Faculty opposition might be more common at comprehensive or R1 universities, where professors' evaluations rely heavily on research productivity (Anderson *et al.*, 2011) and professional identities are divorced from pedagogical activities (Brownell and Tanner, 2012), but resistance can be found across all institutional types (Smith and Lenhoff, 2002).

Plant biology courses might be particularly appropriate for curricular reform, as undergraduate students are less aware of or interested in botanical than zoological topics (Uno, 2007). Plant blindness, the ignorance of botanical facts and concepts, is prevalent among undergraduate students, even biology majors (Wandersee and Schussler, 1999; Allen, 2003; Schussler and Olzak, 2008). In addition, students often express little interest in plants, a challenge that might be exacerbated by the lack of engaging botanical exercises in first- and second-year majors' courses (Bidwell, 2013). Plant prejudice, which is frequently conveyed implicitly, is common in general biology courses (Hershey, 1993). This impediment to botanical engagement, which persists although the nation's botanical capacity does not meet job demand (National Fish and Wildlife Foundation, 2013), might be ameliorated by the incorporation of early-career, research-rich experiences with plants.

Study Goals

Each of our six goals was designed to lead to an assessable outcome, allowing us to determine the efficacy of this hybrid teaching–research approach.

Students will:

1. gain understanding of basic botanical concepts (content knowledge);
2. enhance their abilities to analyze and present data (STEM literacy; Zollman, 2012);
3. improve their written scientific communication skills, including their ability to use related primary literature (STEM information literacy; Scaramozzino, 2010); and
4. demonstrate interest in, or at least increased awareness of, the plant sciences (plant attitude, plant blindness).

Undergraduate research mentors will:

5. use their work in designing modules and
6. produce more publishable/presentable research as a result of their collaborations with faculty and classroom students (increased productivity).

Study Design

Peer Mentoring and Vertical Integration. Our curriculum was designed to promote educational collaborations among different tiers of university students. Team-based research approaches to learning are highly effective, particularly for early-stage students (CUR, 2005), and research experiences that pair experts with novices enhance the learning of both parties (Stage *et al.*, 1998; NRC, 2003; Hannam and Muench, 2007). In our approach, undergraduates conducting independent botanical research were assigned to collaborate with the instructor supervising and students enrolled in a related course. During the semester, course-based researchers were mentored by both faculty and research students; groups of faculty members, research students, and classroom students worked together during the semester to synthesize a single research product (e.g., Gafney and Varma-Nelson, 2008). In our modified curriculum, research students gained leadership and mentoring experience while collecting enough data to publish their undergraduate theses in peer-reviewed scientific journals. After one or more semesters as mentors, researcher students presented their work at both an on-campus symposium (attended by students enrolled in our curriculum) and at regional and/or national meetings.

In our curricular design, we have infused botanical research vertically across an entire major to help undergraduates develop important research skills (CUR, 2005). Research projects are integrated throughout courses, first at the sophomore level and again in upper-division courses, allowing students to participate in components of one research theme over multiple years. All biology majors are required to take BIOL 211 (Principles of Botany, a sophomore course), giving them at least one independent exposure to this curriculum. This course is the first point at which students are exposed to the plant sciences in a rigorous and thorough way. In our modules, we use experimental designs developed during ongoing undergraduate research projects as a model system to explore basic botanical concepts (community ecology, taxonomy, physiology, and population genetics) and develop experimental analysis skills. While variations of this approach have been implemented at other institutions (e.g., Brame and Robinson, 2007; Baldwin, 2009; Kloser *et al.*, 2011; Goldey *et al.*, 2012) or created by disciplinary organizations (e.g., http://plantingscience.org from the Botanical Society of America), they have not integrated elements of student design, peer mentoring, and a botanical focus to elicit specific student knowledge, skill, and attitudinal responses.

New Curricular Modules. Our new curriculum aimed to infuse authentic, plant-based research into our courses to ameliorate curricular deficiencies, including compartmentalization of knowledge into cellular, physiological, or organismal subdisciplines; lack of intellectual engagement during laboratory periods; gaps between laboratory exercises and STEM competencies; and a dearth of research experiences in lower-division courses. Even at our small university, where undergraduate research features prominently in the mission statement (www.unca.edu/about/mission-unc-asheville), less than 15% of all biology majors participate in faculty-mentored research; this new curriculum was designed to let all students experience collecting, analyzing, interpreting, and presenting research data.

Revised laboratory exercises were designed to approach plant biology from multiple levels of the biological hierarchy, appealing to students interested in genes, cells, physiology, ecology, or evolution. Laboratory and field modules were based on current departmental research projects, an approach that has also been piloted at larger institutions (e.g., Kloser *et al.*, 2011), and took advantage of our region's (Southern Appalachian Mountains) rich plant diversity (Weakley, 2011). Per AAAS (2011) recommendations, course-based research projects were generated by students, allowed guided inquiry, and utilized regional questions to engage students in content. Our model also followed the suggestions of Kloser *et al.* (2011), including the creation of a long-term community ecology database, structured facilitation of students' hypothesis development (via faculty review of draft hypotheses), and reliance on institutional (faculty and student) research expertise in developing and implementing modules. Modules are described below, and their use is explained in Table 1.

Module 1. Transpiration, the loss of water from plants' photosynthetic tissues, happens when plants open their stomata for CO_2 uptake, and excessive transpiration can have negative consequences for plant fitness (Raven *et al.*, 2005). Environmental conditions affecting transpiration include CO_2 concentration, light, temperature, and wind speed (Welander and Ottoson, 1999; Bauerle and Bowden, 2011). Student hypotheses might focus on the effects of abiotic stresses on rates of plant transpiration or differences between the methodological approaches. Students applied different abiotic stresses to plants, then collected transpiration data using a handmade potometer and a LiCor 6400 portable photosynthesis system (LiCor Biosciences, Lincoln, NE). Our classroom data set now contains more than 4 yr of data on focal species that students can access for their statistical analyses.

Module 2. Nonnative invasive plants can alter successional trajectories, displace native species, and change forest structure (Flory and Clay, 2006; Vidra *et al.*, 2007; Heleno *et al.*, 2010). Approximately 10% of nonnative plants are ecosystem transformers or engineers (Richardson *et al.*, 2000), capable of actively suppressing native plants and initiating change in community composition or ecosystem function. Faculty and research students implemented four treatments (mechanical, chemical, mechanical plus chemical, and control) to remove nonnative invasive plants from two forested sites on campus. Module 2 allows classroom students to participate in larger-scale research with real-world applications, addressing a problem with major economic and ecological costs (Pimentel *et al.*, 2000). We now have 6 yr of data available for students to use in addressing their faculty-vetted hypotheses and have prepared a manuscript using these field-collected data. In addition, we have published a paper about a related project (Horton and Francis, 2014).

Module 3. American ginseng (*Panax quinquefolius*) is a medicinally important herb that has been collected from the

Table 1. UNC Asheville courses in which curricular modules are used and types of data generated by modules

Module	Course title, enrollment, description	Type of data generated
1. Effects of Abiotic Factors on Plant Transpiration	BIOL 211 (Principles of Botany), 75 biology, environmental studies majors	Photosynthetic responses of growth chamber–raised sunflowers (*Helianthus annuus*) to environmental changes
	BIOL 345 (Plant Physiology), 20 biology, environmental studies majors	Physiological attributes of invasive plant species, which typically show more rapid responses (van Kleunen *et al.*, 2011) and higher rates of photosynthesis than noninvasive plants (Shen *et al.*, 2011)
2. Community Responses to Non-Native Plant Removal	BIOL 211 (Principles of Botany), 75 biology, environmental studies majors	Responses of species-, community-, and ecosystem-level variables to removal treatments
	BIOL/ENVR 442 (Forest Ecology), 20 biology, environmental studies majors	Growth rates and patterns of trees in areas with and without invasive lianas
3. Genetic and Phytochemical Diversity of Wild Ginseng, a Threatened Natural Resource	BIOL 211 (Principles of Botany), 75 biology, environmental studies majors	Levels of intra- and interpopulation microsatellite diversity in populations with different sizes, harvesting histories, and levels of protection (Young *et al.*, 2012)
	BIOL 345 (Plant Physiology), 20 biology, environmental studies majors	Physiological responses of ginseng plants in different light environments
	BIOL 373 (Population Biology), 16 biology, environmental studies majors	Relationships between genetic diversity and demographic variables
4. Genetic Diversity and Seed Production in Virginia Spiraea, a Threatened Shrub	BIOL 211 (Principles of Botany), 75 biology, environmental studies majors	Estimates of genetic diversity and gene flow from microsatellite data

wild and exported to Asia for more than 200 yr (Case *et al.*, 2007; Wu *et al.*, 2010), and both aggressive harvesting and noncompliance with harvesting guidelines have resulted in its Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Appendix II listing (since 1973; Lim *et al.*, 2005; Schlag and McIntosh, 2006; Mooney and McGraw, 2007). Faculty and research students have begun to quantify and qualify medicinally active compounds (ginsenosides), identifying physiological and genetic factors correlated with these responses. To date, one paper about this module's results has been published in the peer-reviewed biological literature (Searels *et al.*, 2013).

Module 4. Virginia spiraea (*Spiraea virginiana*) is a federally threatened shrub endemic to the southern Blue Ridge and Appalachian Plateau (United States Fish and Wildlife Service, 1992). Virginia spiraea is adapted to low-competition, riparian scour-zone habitats (Ogle, 1991), and populations have declined because of habitat loss from anthropogenic alteration of flow regimes (Poff *et al.*, 2007). Faculty and research students have studied the effects of mowing on vegetative growth and reproduction of this species. We have also examined levels of genetic diversity within and among populations and collected data about pollen transfer and seed production, and we have published a paper about beaver browse on Virginia spiraea (Rossell *et al.*, 2013).

METHODS

Implementing Curricular Changes

Curricular modules were designed in the 2007–2008 academic year, and implementation of modules 1 and 2 began in Fall 2008. Modules 3 and 4 were added beginning in Fall 2009 and Fall 2010, respectively. Laboratory manuals for courses in which modules were used contained detailed instructions about scientific writing and statistical design/analysis, and they included the rubric (see Supplemental Material) used to assess student work. Undergraduate research students assisted in at least half of all sections in which these modules were used. Modules have now been used for 4 yr in BIOL 211 (Principles of Botany); therefore, assessment data are presented for this course only.

Assessment

Our curricular design incorporated ongoing formative assessments (e.g., Black *et al.*, 2003) to determine the success of this curriculum in teaching and reinforcing botanical knowledge, experimental design and analysis, and scientific writing. Student feedback and faculty reaction to that feedback were used to create more effective learning experiences (e.g., Brookfield, 1995; Moore and Kuol, 2005). Formative assessment data allowed us to modify curricular delivery to ensure that research experiences effectively reinforce classroom concepts, teach the scientific process, and affect student attitudes. Specific project goals were assessed as detailed in the following sections, using protocols approved by the University of North Carolina–Asheville's institutional review board.

Content Knowledge. Modifications of the Student Assessment of Learning Gains (SALG; www.salgsite.org) self-reporting instrument were administered via Moodle course-management software (https://moodle.org). The purpose of this assessment was to measure students' perceptions of the efficacy of curricular changes and the ways in which this curriculum influenced their learning. In addition, questions modified from the Biology Major Field Test, a standardized test developed by Educational Testing Services, were used to make direct measures of content knowledge. Students answered these questions in the first and last weeks of their enrollment in BIOL 211.

STEM Competencies

Experimental Design and Analysis. A modified SALG assessment, administered in pre- and posttest form on Moodle, allowed students to self-report changes in skill sets. Students used a 5-point Likert scale (strongly agree to strongly disagree) to rank their perceived understandings of:

- plant transpiration and the factors that affect it;
- the issue of, and biological effects of, invasive exotic plant species;
- collecting and analyzing population genetic data;
- posing a hypothesis and executing an experiment related to that hypothesis; and
- analyzing data and interpreting the results of statistical analyses.

Scientific Communication. We also developed a standardized grading rubric to evaluate students' data analysis and presentation. This rubric, tested for intergrader reliability, was used to assess students' ability to construct hypotheses, choose the correct statistical analysis, and interpret results of statistical analyses in their first and fourth journal-style paper. The rubric was also used to evaluate students' scientific writing, including their use of the primary scientific literature and overall compliance with scientific writing norms. BIOL 211 is a writing-intensive course, and such courses have been shown to improve students' use of disciplinary conventions and comprehension of the scientific literature (Brownell *et al.*, 2013).

Attitudinal Shifts. Students answered questions modified from the FLAG Biology Attitude Scale Assessment (www.flaguide.org/tools/attitude/biology_attitude_scale.php) on Moodle in the first and last weeks of BIOL 211. Students used a 5-point Likert scale (strongly agree to strongly disagree) to respond to the following statements:

- I understand the role, importance, and impact of plants and/or botany in my everyday life.
- BIOL 211 is the only plant/botany class I will take in college.
- I plan to take other science courses that include an opportunity to design and conduct experiments.
- I am doing or plan to do undergraduate research in the sciences.

Productivity: Publications and Presentations. Faculty members tracked the number of conference presentations and peer-reviewed publications coauthored by undergraduate research students each year.

All data were analyzed in SAS 9.2 (SAS Institute, 2011). Responses were compared over time (pre vs. post) and among cohorts (years) using analysis of variance (PROC GLM) followed by Tukey's post hoc tests. Year in school and gender were used as covariates in analyses.

RESULTS

To date, more than 300 classroom students have participated in these research projects, more than eight times the number of students who could be accommodated in traditional faculty-mentored research over the same period. We have disseminated our modules within our university, where versions have been utilized in the biology department (three faculty members), mathematics department (one faculty member), and environmental studies department (one faculty member), resulting in the exposure of an additional 60 undergraduate students to this hybrid teaching–research strategy. We have also modified the modules for our ongoing outreach at three local secondary schools, where 75 students have now participated. Since our project's inception, 15 research students have mentored in one or more semesters, and 21 research students have contributed to the modules. Data analyses are for the 2012 and 2013 cohorts, as earlier iterations of modules and instructional interventions, before formative assessments, did not produce equivalent learning and attitudinal gains.

Content Knowledge

After taking BIOL 211, in which these topics were taught via research-infused modules, students felt more confident in their knowledge of transpiration ($p < 0.0001$), genetics ($p < 0.0001$), and statistical analyses ($p < 0.0001$; Figure 1). However, they did not perceive gains in their understanding of invasive plants ($p = 0.93$) or their ability to construct hypotheses ($p = 0.25$). Classroom students demonstrated measurable gains in their actual content knowledge of plant transpiration ($p < 0.0001$), invasive species ($p < 0.0001$), and population genetics ($p = 0.011$). Students' content knowledge of statistics, as assessed by test questions, did not increase significantly ($p = 0.17$), although scores on one of the two questions improved significantly ($p = 0.0425$; Figure 2). In this and all other

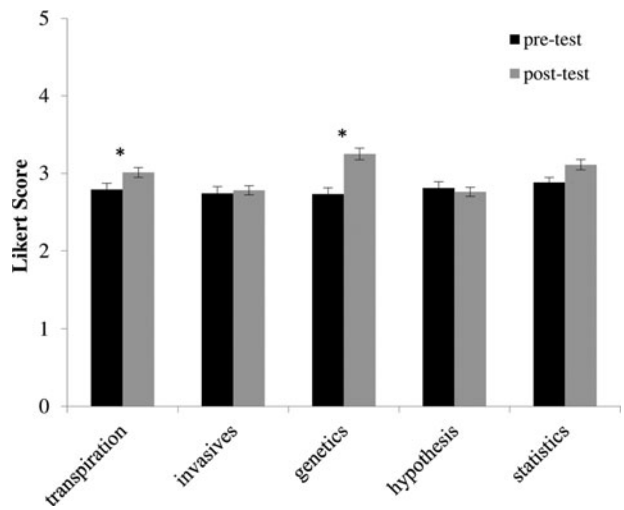

Figure 1. Mean (±1 SE) self-ranked knowledge of transpiration, invasive species, and population genetics on pre- and posttests. Results of Tukey's post hoc tests are shown; asterisks indicate statistically significant differences between means. Students also reported confidence in ability to generate hypotheses and analyze/interpret statistics. $n = 379$.

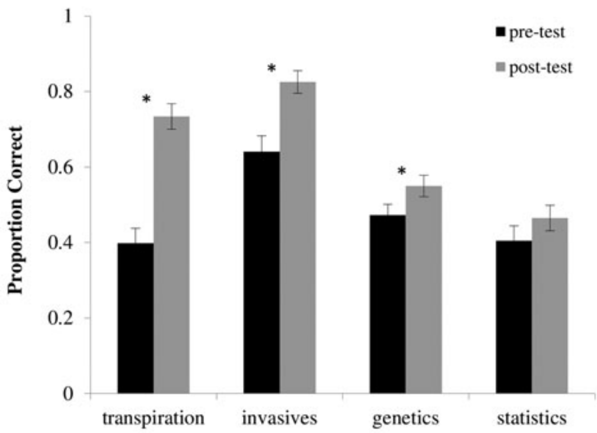

Figure 2. Mean (±1 SE) proportion of correct answers to questions about plant transpiration, invasive species, population genetics, and statistics on pre- and posttests. Results of Tukey's post hoc tests are shown; asterisks indicate statistically significant differences between means. Students were asked two questions per topic. $n = 270$.

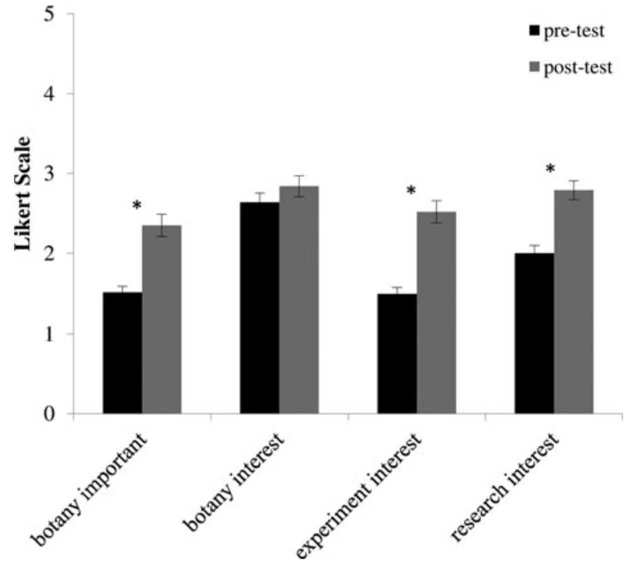

Figure 4. Mean (±1 SE) responses to questions about importance of botany, interest in taking additional botany courses, interest in participating in more course-based research experiments, and interest in doing independent undergraduate research. Results of Tukey's post hoc tests are shown; asterisks indicate statistically significant differences between means. $n = 379$.

analyses, no differences based on gender or year in school were observed ($p > 0.05$ for all).

Scientific Practice

Data Analysis and Presentation. Students exposed to our curriculum improved their ability to make statistically valid hypotheses ($p < 0.0001$) and to choose appropriate statistical analyses ($p = 0.0003$). They were also able to more accurately interpret statistical results ($p < 0.0001$; Figure 3).

Scientific Communication. Students' ability to use primary scientific literature to validate their arguments improved from the first to fourth papers (increase in rubric scores; $p < 0.0001$; Figure 3). Students' ability to follow scientific writing conventions improved significantly from the start to the end of BIOL 211 (significant changes in rubric scores; $p < 0.0001$), and they also produced better publication-quality figures at the course's end ($p < 0.0001$).

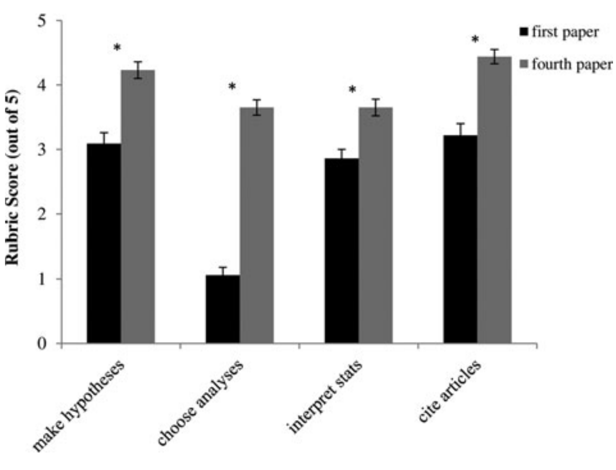

Figure 3. Mean (±1 SE) rubric scores on ability to make hypotheses, choose analyses, interpret statistics, and cite articles on first and fourth journal-style paper. Results of Tukey's post hoc tests are shown; asterisks indicate statistically significant differences between means. $n = 209$.

Attitudinal Shifts

Exposure to the revised curriculum increased students' awareness of the importance of plants and botany ($p = 0.013$), effectively ameliorating plant blindness. Intent to take additional plant courses (botanical interest) was unchanged ($p = 0.76$), although students did report increased interest in participating in course-based research ($p < 0.0001$) or independent undergraduate research ($p = 0.040$) after exposure to modules (Figure 4). During postcourse interviews, faculty-mentored research students reported increased understanding of both basic botanical concepts and their own research.

Productivity: Publications and Presentations

Data generated by our course modules enhanced faculty and research students' productivity. Since modules were first piloted in 2009, faculty and students have presented talks or posters at statewide (Molecules in the Mountains, North Carolina Exotic Plant Pest Council), regional (Association of Southeastern Biologists, Big South Undergraduate Research Conference, Science in the Mountains, Southeastern Population Ecology Evolution and Genetics), and national (AAAS Vision and Change in Undergraduate Biology Education, Council on Undergraduate Research, Ecological Society of America) conferences, for a total of 27 contributed and nine invited presentations. Undergraduate students were authors on three peer-reviewed articles (*American Journal of Plant Sciences*, *American Midland Naturalist*, *Southeastern Naturalist*), two manuscripts in review, and three papers in preparation.

DISCUSSION

Our research-infused botanical approach overcame barriers of faculty time, student time and preparation, and funding to create sustainable curricular changes that continue to be implemented after external funding ended. Our new curriculum was effective in triggering statistically significant changes in students' content knowledge and STEM practices. It has also elicited significant changes in student attitudes toward plants, which may reduce plant blindness (Allen, 2003). Students' knowledge, skills, and attitudes improved over cohorts, perhaps because faculty members made incremental changes in response to formative feedback (Black *et al.*, 2003). Our curricular approach allowed 100% of all undergraduate students in our department to participate in authentic research, compared with 15% before these changes. Finally, this new curriculum enhanced the research productivity of both undergraduate research students and faculty.

Our curriculum had mixed effects on student's statistical knowledge and skills. On one hand, student content knowledge, as assessed from test questions, did not improve. On the other hand, their practical skills (hypothesis generation, choosing statistical tests, and interpreting results) did improve. Faculty members devote 1 h of laboratory time, multiple pages of laboratory manuals, many comments on draft papers, and significant time in face-to-face meetings to provide statistical instruction. However, these interventions do not seem sufficient to ameliorate all of the deficiencies in statistical knowledge and skills. To improve student understanding, our department has begun collaborating with a faculty member in the mathematics department to add a biology-based component to the STAT 185 (Introduction to Statistics) course, which is required for all natural science majors at UNC Asheville. We are also ensuring that statistical instruction is a formal part of all freshman and sophomore majors' courses in our department, so that students might benefit from repeated exposure to these concepts.

This curriculum also had mixed results on student awareness and interest in plant sciences. While students' plant blindness decreased, this change did not result in increased interest in taking additional plant courses. This failure to generate interest might be a consequence of BIOL 211's rigor and its anecdotal reputation as the most difficult of the four-course core sequence. Alternatively, we might be interceding in students' attitudes too late in their formal education, as much plant aversion seems to happen during K–12 education (Frisch *et al.*, 2010). Faculty members are taking a twofold approach to address these shortcomings. First, we are adding more plant-based research experiences to freshman biology courses, including an investigation of genetically modified organism foods in BIOL 116 (Cellular and Molecular Biology). Second, we are using our modules to do research-based outreach exercises with local high school students, whose curricula might unintentionally exacerbate plant blindness or prejudice (Hershey, 2005).

We are now entering our fourth year of collecting data on all modules, and some of the courses in which modules are used are only taught every other year. Thus, we are not yet able to test the specific effects of vertical integration or repeated exposure to the same botanical theme from different angles (genetics, physiology, ecology, etc.). Additionally, assessments to date have focused on a single, large-enrollment majors' course (BIOL 211). Future assessments will track cohorts of students through our curriculum and will test modules' effects both within and among individual classes.

Although modules were developed to be place based (AAAS, 2011), they should be flexible and adaptable for a variety of institutional types, including secondary schools and urban, suburban, or rural universities. Our department is developing additional modules to fit the changing research foci of faculty and research students and to divorce research from seasonal constraints (e.g., winter plant dormancy). Institutional support for our efforts, including monies to purchase supplies and expendables, has contributed to the curricular sustainability. We are also testing this proven pedagogical approach, already institutionalized at UNC Asheville, across diverse institution types (4-yr private liberal arts college, 4-yr public liberal arts college, one public comprehensive university) to ensure its transferability. Modules are being modified so that each contains multiple iterations, ensuring its applicability to students at different levels (first year to upper division). Our new place-based educational network (CEREUS: Consortium Exchanging Research Experiences for Undergraduate Students) will use regional environmental issues to impart botanical knowledge while advancing quantitative literacy, teaching scientific communication, encouraging higher-order cognitive processes, and improving student attitudes toward STEM and plants.

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