2-8-2022

Harnessing the 4DEE Framework to Redesign an Introductory Ecology Course in a Changing Higher Education Landscape

Nathan Ruhl
Rowan University, ruhl@rowan.edu

Patrick Crumrine
Rowan University, crumrine@rowan.edu

Jennifer Oberle
Rowan University, kilic@rowan.edu

Courtney Richmond
Rowan University, richmond@rowan.edu

Shelly Thomas
Rowan University, thomassh@rowan.edu

See next page for additional authors

Recommended Citation

Ruhl, N., Crumrine, P., Oberle, J., Richmond, C., Thomas, S., and Wright, S.. 2022. Harnessing the Four-Dimensional Ecology Education Framework to redesign an introductory ecology course in a changing higher education landscape. Ecosphere 13(2):e03857. 10.1002/ecs2.3857

Authors
Nathan Ruhl, Patrick Crumrine, Jennifer Oberle, Courtney Richmond, Shelly Thomas, and Sara Wright

esa ECOSPHERE

ECO-EDUCATION

Harnessing the Four-Dimensional Ecology Education Framework to redesign an introductory ecology course in a changing higher education landscape

N. Ruhl ,[1,]† P. Crumrine,[1,2] J. Oberle,[1,3] C. Richmond,[1] S. Thomas,[1] and S. Wright[1]

[1]*Department of Biological Sciences, Rowan University, Glassboro, New Jersey 08028 USA*
[2]*Department of Environmental Science, Rowan University, Glassboro, New Jersey 08028 USA*
[3]*Department of Biology, Rutgers University, Camden, New Jersey 08102 USA*

Citation: Ruhl, N., P. Crumrine, J. Oberle, C. Richmond, S. Thomas, and S. Wright. 2022. Harnessing the Four-Dimensional Ecology Education Framework to redesign an introductory ecology course in a changing higher education landscape. Ecosphere 13(2):e03857. 10.1002/ecs2.3857

Abstract. As higher education undergoes rapid and fundamental change, eco-educators need to be prepared to promote the inclusion of the ecological sciences in the biological sciences curriculum of the future. Here, we present an instructional alignment for an introductory ecology course, which is informed by and integrated with the Four-Dimensional Ecology Education (4DEE) Framework. Our instructional alignment was created collaboratively among faculty involved in teaching the course and emphasizes the relevance and utility of the ecological sciences. We believe that this approach positions the ecological sciences for continued success and inclusion in the biological sciences curriculum of tomorrow.

Key words: Course-based Undergraduate Research Experience; ecology curriculum; ecology education; Four-Dimensional Ecology Education Framework; introductory ecology; undergraduate ecology.

Received 13 January 2021; revised 21 June 2021; accepted 8 July 2021. Corresponding Editor: Jennifer H. Doherty.

† **E-mail:** Ruhl@Rowan.edu

Introduction

The COVID-19 pandemic has accelerated the pace of change in higher education and highlighted unanswered questions about the future of higher education. A conservative assumption is that the future will bring smaller budgets, an increased exploration of virtual education (de Wit 2020), and the continuation of blended instructional formats that include asynchronous and synchronous components (Neuwirth et al. 2020). Eco-educators are likely to experience pressure to cut costs through curricular reform, create educational pathways such as certifications that do not require the same investment of time and money as two- and four-year degrees, and further streamline degree progression requirements via integration or reduction of content. These pressures are not new (Fleischner et al. 2017, Cooke et al. 2020), have been intensified during the COVID-19 pandemic, and are unlikely to lessen in the future after the pandemic has resolved.

In this atmosphere of educational and economic uncertainty, reeling from a global pandemic and facing the progressive march of global climate change, instructors of ecology must continue to promote the significance, relevance, and utility (Cahapay 2020) of ecological education. Ecological science is of obvious significance as a core discipline within the biological and environmental sciences and is increasingly important for sustainability initiatives. Ecology is relevant as a foundational topic for students pursuing interdisciplinary careers related to understanding the environment of the past (geology), the place of humans in the environment (geography and environmental studies), the impact of human actions on the environment (environmental science), and the health of both humans and nonhumans alike (e.g., public and global health, zoology, botany, agriculture, conservation). Ecology has clear utility for personalized medicine (Vrancken et al. 2019), addressing global pandemics (Gibb et al. 2020), and reducing carbon dioxide emissions that contribute to climate change (Brando et al. 2019).

The COVID-19 pandemic is a prime example that illustrates many of the core conceptual underpinnings of ecology, and it underscores the imperative nature of ecology's inclusion in 21st-century health education (Beck et al. 2012, Sklar 2020). Nonetheless, ecology suffers from a poorly articulated vision of relevance (Belovsky et al. 2004) and non-ecologists often do not appreciate the application of this discipline beyond being a pathway for those who desire to become ecological scientists. It is for these reasons that ecology suffers from a perception that it is not as important as other biological disciplines, seeding the sentiment that ecology can be removed from the pre-medical curriculum (Alpern et al. 2009). Our view is that ecology is significant because it informs society as it faces global environmental crises (e.g., climate change, pandemics), relevant because it enables important and rewarding careers, and useful because it guides policy, decision making, and the development of practical solutions to modern problems. Moving forward, eco-educators must ensure that their field experiences and lessons clearly encourage their students to make these connections.

The Four-Dimensional Ecology Education (4DEE) Framework is a tool for eco-educators that is endorsed by the Ecological Society of America (2018) and clearly articulates the significance and relevance of ecology (Klemow et al. 2019). Four-Dimensional Ecology Education envisages ecological concepts, practices, and human–environment interactions as being unified under the umbrella of "cross-cutting themes." Each of these four dimensions of eco-education is further defined by elements of ecology (21 different elements in total). The 4DEE framework draws on the Next-Generation Science Standards (NGSS Lead States 2013) and recommendations from the National Research Council (2012), which outlines science education as being composed of practices, cross-cutting concepts, and core ideas. In addition to being a guide for eco-educators, 4DEE is intended to define and summarize the field of ecology for students, stimulate professional certification efforts, lead to formalization and validation of best practices in ecology education, and ultimately enhance ecological literacy (Klemow et al. 2019).

The 4DEE Framework informs, unifies, and supports educators as they teach ecological science, but it does not clearly (1) articulate a pathway to achieving these goals in a rapidly changing higher education landscape or (2) demonstrate the relevance and utility of ecology as an embedded part of the scientific endeavor. Here, we combine concepts from Vision and Change (AAAS 2011) with those of NGSS and 4DEE to create a robust introductory ecology course that emphasizes the relevance and utility of ecology as part of a scaffolded introductory biology sequence. Because our course draws on Vision and Change, it is (partially) assessable using existing tools (Summers et al. 2018, Clemmons et al. 2020), which we believe will help us to ensure the continued inclusion of ecology (and field-based studies in general; Fleischner et al. 2017) in the general biology curriculum.

Institutional Context and our Collaborative Approach to 4DEE Integration

Rowan University is the fourth fastest-growing university in the United States (Chronicle of Higher Education 2019), and our institution has been evolving in ways that many other higher education institutions are now experiencing—a shift toward online courses, increasing class sizes, incorporating certificates into degree programs, streamlining degree progressions, increasing access to higher education, hyper-efficient use of resources (e.g., >90% space utilization), and changing student demographics. Our focus on first-generation (at least 32.5%) and transfer (28.5%) students has led to deep ties with two of our local two-year community colleges, which changed their names to reflect the relationship (Rowan College of South Jersey, RCSJ; Rowan College at Burlington County, RCBC). These partner institutions have adjusted their course offerings to be similar to our introductory courses, which facilitates a smooth transition for transfer students. We also offer select upper level courses, taught by faculty from Rowan University, on the community college campuses.

The Rowan University introductory biology curriculum features a non-traditional scaffolded four-semester course sequence in biology that emphasizes skill development and prominently features ecological science: (1) Introduction to Evolution and Scientific Inquiry, (2) Introduction to Genetics, (3) Introduction to Cell Biology, and (4) Introduction to Ecology. This course sequence was adopted in 2006 following faculty participation in the Faculty Institutes for Reformed Science Teaching (FIRST II; Lundmark 2002) with the intent to better prepare students to succeed in upper level biology elective courses. Completing the first three courses in the sequence is required prior to taking any advanced biology courses, and most advanced courses require all four introductory courses as a prerequisite. Transfer students who enter our program with a more typical two-semester introductory biology sequence take a specialized course focused on skill development (Biological Skills for Transfer Students) before taking the fourth and final course in our core sequence (Introduction to Ecology).

Eco-education at Rowan University is centered on the Introduction to Ecology course. This course is required for biology majors (both BA and BS), biology minors, and Environmental Science (BS) majors. Owing to our emphasis on skill development across the introduction to biology core sequence and our small classrooms, we have kept the instructor-to-student ratio comparatively low (~1:24). Our Introduction to Ecology course has, for many years, been structured around a semester-long inquiry-based learning experience, where students designed and conducted independent research projects and presented their results in oral and written forms. These student research projects were often focused on detecting the response of a plant species to different resources or conditions and usually took the form of seedlings being grown for a few weeks in control and experimental treatments. As the number of students and sections has increased, both the student experience (larger groups) and the quality of the experiments (fewer replicates) were in decline due to space and budgetary limitations.

The limitations to the independent research projects and the need to adapt to the changing landscape of higher education, including offering sections virtually due to the COVID-19 pandemic, were the primary catalysts for the decision to redesign the course (Fig. 1). The need for our curriculum to serve students with varied career interests, including many students desiring health-related careers, and a desire to incorporate pedagogical innovations, were also important factors in our efforts. Our course redevelopment began in earnest at the start of summer 2020, amid the COVID-19 pandemic, with the installation of a course coordinator (Ruhl) and the formation of a committee of full-time faculty involved in teaching the course to provide input (Fig. 1).

Throughout our collaborative process (Fig. 2), the course coordinator served as the go-between for the committee, our preparatory laboratory staff, and departmental leadership. The committee met on a weekly basis for about 10 weeks to consider changes to the course proposed by the course coordinator, who also served as the leader of the committee. As a group, we acknowledged that change was needed, committed to being open to the perspectives and ideas of everyone involved, and agreed to be respectful to those who shaped the course in the past, our individual workloads, and instructional freedom. The responsibility of keeping to these principles fell to all members of the committee, but it was especially important for the coordinator (the agent of change) and the senior faculty (who designed the previous version of the course) to be committed to them.

Our alignment articulates the desired traits for our course, and so serves as a guide or scaffold for our instructors as they build their courses, but it does not specify the exact way in which instructors must teach the course. Each learning objective in the alignment is a brick to be used in

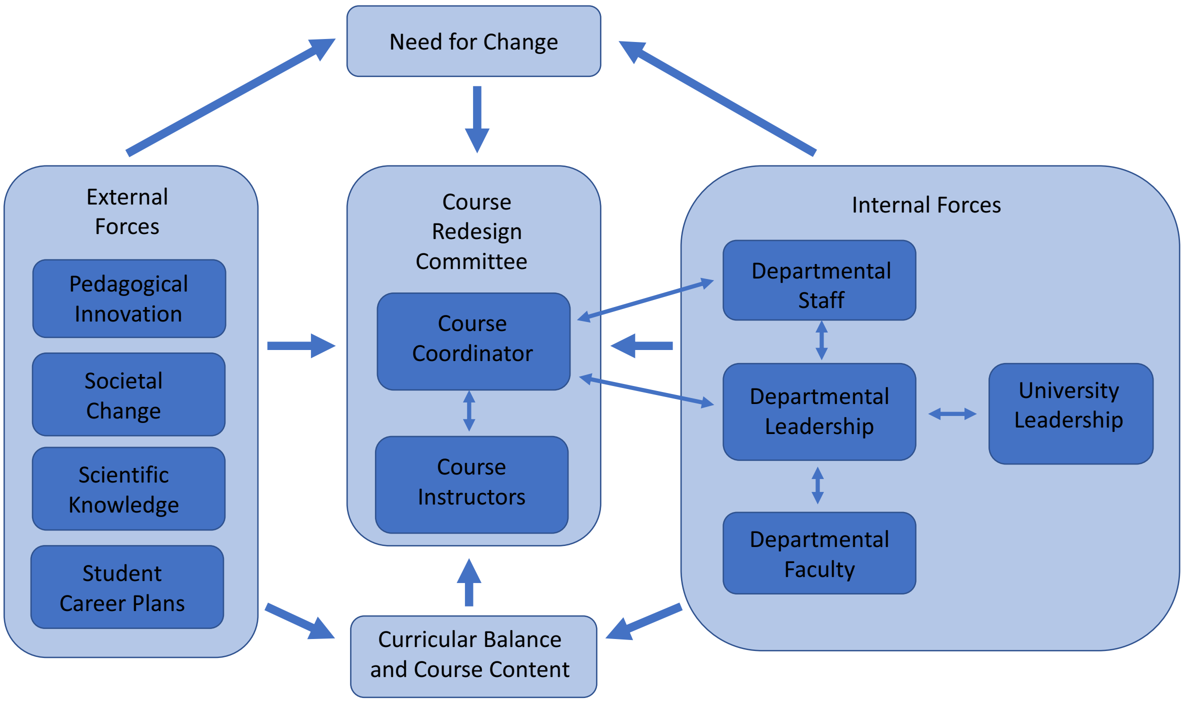

Fig. 1. Conceptual diagram of factors that influenced the redesign of the Introduction to Ecology course at Rowan University and the relationship between constituent groups. Students did not have direct input on the redesign of the course but did have a role in providing feedback on course materials. The redesign committee was initially composed of full-time faculty involved in the course and was later expanded to include part-time faculty involved in the course.

constructing a tower of ecological knowledge and scientific skills, but the order in which the bricks are laid depends on the bricklayer (instructor). This approach was born of necessity (managing the workload of adapting and creating course materials; resistance to change), the need to provide support to new instructors, a desire to spur innovation, and the expectation that the course would be taught using multiple instructional modalities (online, virtual/remote, in-person). While we incorporated flexibility, we also recognized that we needed to balance flexibility with assessable standards and provide students with an equitable experience across sections and instructional modalities. There were two key unifying factors for us: the 4DEE framework and the decision to develop our own Course-based Undergraduate Research Experience (CURE). Our discussions about how to alter our course were shaped and facilitated by the 4DEE framework, which served as a template and stimulus for debate on topics that should be emphasized or removed from the course. Our CURE, which is being developed for a future publication, is focused on the response of plants to urbanization and can be used for in-person, virtual/remote, and online courses. The CURE we are developing is similar in nature to the inquiry-based independent projects that we did in the past, which allowed us to conserve some course materials and avoid major changes to the balance of our curriculum between courses. The CURE additionally serves to both increase student access to the high-impact practice of an undergraduate research experience and provide faculty with a collaborative focus, which contributed to motivating and unifying faculty to engage in our redevelopment efforts.

We implemented the instructional alignment and CURE by having one faculty member (Ruhl) pilot the new course, build-out materials that met the learning targets of the instructional

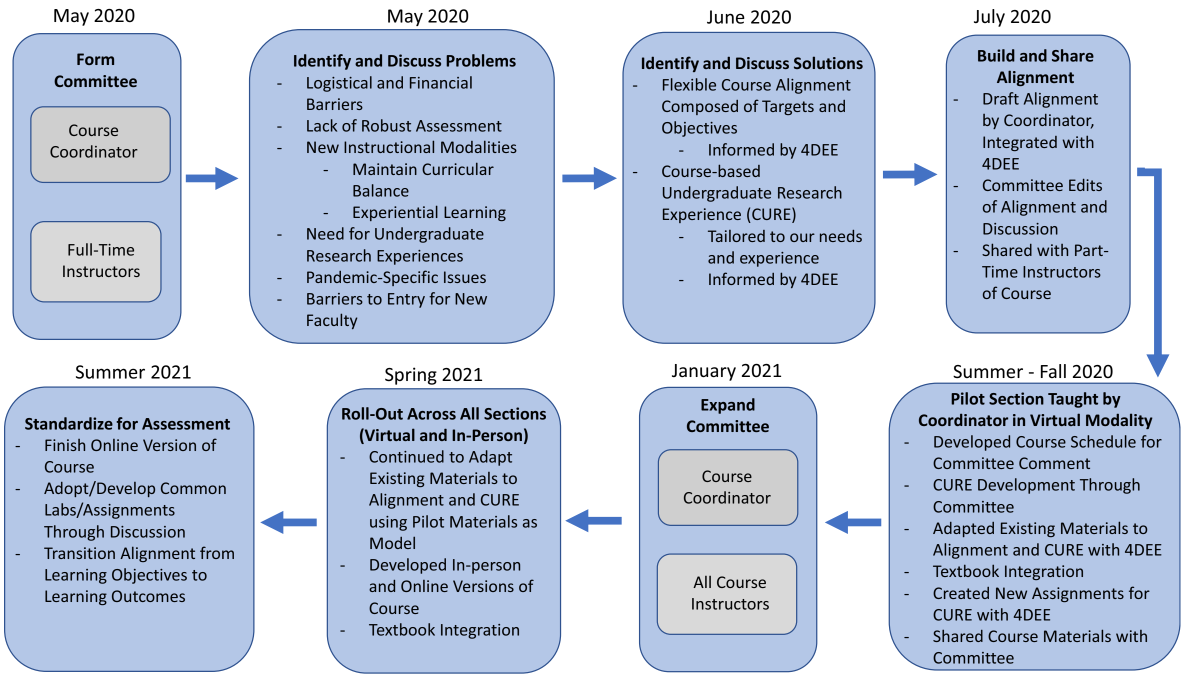

Fig. 2. Timeline of the collaborative redesign of the Rowan University Introduction to Ecology course.

alignment, and obtain faculty and student input on the course materials as they were developed. All of the materials from the pilot course (lectures and assignments/labs) were shared with the committee at the end of the semester, and the committee was expanded to include all instructors teaching the course (including contingent faculty). The instructional materials from the pilot course served as a resource for instructors as they adapted course materials to our course alignment and incorporated our new CURE. The CURE is implemented as a semester-long project embedded throughout the course and is the primary focus of the laboratory, so it serves as a balance to instructional flexibility that helps align sections while also simplifying the laboratory preparation requirements. As of this writing, all instructors are engaged in enhancing the materials for the CURE. We are also developing an online (asynchronous) version of the course (led by Wright), and we hope to come out of the summer (and the pandemic) with a common set of robust laboratories structured around our CURE.

Our Introduction to Ecology course was already an interesting case study for emphasizing the importance of the ecological sciences as part of an introductory biology curriculum, but by integrating the 4DEE framework and adopting a Course-based Undergraduate Research Experience (CURE), we believe we have positioned eco-education for continued success at our institution for years to come. Integration with 4DEE and the adoption of a CURE were both viewed positively by our university leadership, who supported our efforts to redesign the course. Integration with 4DEE was attractive to our leadership team because it could enable cross-institutional assessment and might lead to credentialing in the future. Our development of a CURE was also viewed positively because CUREs have a strong impact on student learning (Shapiro et al. 2015), degree completion rates (Rodenbusch et al. 2016), and might be particularly effective in the training of minority (non-white) students (Estrada et al. 2016). CUREs have also been shown to promote inclusivity for students (Bangera and Brownell 2014) and may provide both tangible and intangible benefits to faculty (Shortlidge et al. 2017). CUREs have been shown to increase cognitive and emotional connections to the subject matter (Cooper et al. 2019) and might therefore be useful for promoting the larger ecological literacy goal of the 4DEE framework. These benefits of including a CURE are synergistic with our institutional goals of increasing research activity on campus and promoting the professional development of faculty.

An Instructional Alignment for Introduction to Ecology at Rowan University

Our instructional alignment is composed of learning targets that emphasize different components of ecology education (concepts, practices, human–environment interactions) and includes coverage of the majority of the cross-cutting themes of 4DEE (Table 1 and Appendix S1). Most of the "Ecological Practices" of 4DEE are not unique to ecology, and we emphasize that fact by focusing on what we call "Transferable Practices." We use the "Transferable Practices" terminology to emphasize that our instructional focus is more closely aligned to teaching the practice of scientists (generally) than the practices of ecology, which is the focus of 4DEE. We explicitly teach our students core scientific practices through the lens of ecological science. For instance, we focus on the use of generally applicable scientific practices (e.g., experimental design, hypothesis construction and testing, statistical analysis, building predictive models) and follow-up by demonstrating their use within the discipline of ecology, positioning ecological practices as secondary to transferable practices. In another example, we characterize population ecology models (e.g., exponential or logistic growth) as examples of mathematical models

Table 1. Course-level learning targets for the Introduction to Ecology course at Rowan University, integrated with the 4DEE Framework, and emphasizing transferable practices, which is not a component of the 4DEE framework.

	Emphasis		
Course targets for introductory ecology	Primary	Secondary	Tertiary
Introduction to the course and ecological science	Transferable Practices	Human–Environment Interactions	Ecology Concepts
Environmental change in space-time impacts natural selection	Cross-Cutting Themes	Ecology Concepts	Human–Environment Interactions
The abiotic environment has adaptive significance for organisms	Cross-Cutting Themes	Ecology Concepts	Human–Environment Interactions
The abiotic environment, species interactions, and intrinsic traits combine to govern how populations grow	Ecology Concepts	Cross-Cutting Themes	Human–Environment Interactions
Species interactions play a major role in shaping biological communities	Ecology Concepts	Human-Environment Interactions	Cross-Cutting Themes
Energy and elements move between organisms and the environment	Cross-Cutting Themes	Ecology Concepts	Human–Environment Interactions
Organisms interact with and impact the abiotic environment	Ecology Concepts	Cross-Cutting Themes	Human–Environment Interactions
Humans alter the environment and can use ecological knowledge to address problems	Human-Environment Interactions	Ecology Concepts	Ecology Practices
Students recognize themselves as scientists in training	Transferable Practices	Ecology Practices	N/A
Scientific communities are accessible and collaborative	Transferable Practices	Ecology Practices	N/A
Scientists manage, and ask questions of, data that vary in scope and scale	Transferable Practices	Ecology Practices	Cross-Cutting Themes
Scientists use universal principles to design experiments	Transferable Practices	Ecology Practices	Cross-Cutting Themes
Scientists use models to understand key drivers of biological and environmental processes	Transferable Practices	Ecology Practices	Ecology Concepts
Scientists communicate in a variety of ways	Transferable Practices	Ecology Practices	N/A

Notes: Except the first subject, course subjects are not presented in any particular order. The course outlined here is Introduction to Ecology, at Rowan University.

used in all scientific disciplines and which, in this case, have direct applicability for modeling disease transmission or the response of species (including humans) to anthropogenic climate change. We believe that this approach contextualizes ecology as being of equal importance to both other areas of biology and science more generally while better fitting an introductory course such as ours, which is taken by students with varied career plans in science.

Framing ecology within the broader conduct of science promotes ecological literacy by helping students, faculty peers, and institutional leadership recognize the significance, relevance, and utility of our discipline. Many of our learning targets have transferable practices as the primary emphasis and ecological practices as a secondary emphasis, but there are some targets for which the emphasis is squarely on the cross-cutting themes, ecological concepts, and human–environment interactions of 4DEE. We believe that it is important to emphasize the utility, relevance, and significance of ecology from the very beginning of the course, and so the only learning target with a fixed position in the course is the first one (Table 1). Our course starts by emphasizing that students will learn transferable practices, that ecology has utility for solving modern problems, and that ecology is a significant cross-disciplinary part of biology that is relevant to current societal contexts, including students' varied career goals. The learning targets in our alignment link multiple core dimensions of 4DEE (ecology concepts, ecology practices, cross-cutting themes, and human–environment interactions) with each other and/or broader science topics. Within each target (Table 1), we have developed several (3–9) more specific objectives (Appendix S2), which more thoroughly articulate the objectives for the course. In some cases, these objectives correlate with the 4DEE framework's broader objectives (Ecological Society of America 2018), and in other cases, they focus on course-specific objectives or transferable practices that reflect our desired outcomes for this particular course, as the fourth course in a 4-part introduction to biology series.

Eight of our fourteen learning targets (Table 1) link core ecology concepts and human–environment interactions. Nearly all core ecology concepts outlined in the 4DEE framework are represented in our learning objectives. Our learning objectives do not strongly emphasize behavioral ecology, landscape ecology, or biomes, but these topics are likely to be included by individual instructors (Appendix S1) and are well represented in our upper level courses (e.g., Advanced Ecology, Animal Behavior, Limnology, Pine Barrens Ecology, Stream Ecology). The human–environment interaction dimension is very well represented in our instructional alignment and was the primary area of topical expansion as we integrated with the 4DEE framework. We do not explicitly include ethical implications of ecological science as a learning objective, but we do expect that ethical considerations will naturally arise as students learn about human–environment interactions. The ethical dimensions of ecology are represented in our upper level course offerings (Environmental Science, Global Bioethics) and the courses of other departments.

Our focus on transferable practices emphasizes the relevance and utility of ecological science as a core discipline of the biological sciences. We more narrowly define ecological practices than the 4DEE framework does, and we emphasize that many of the tools and methods of ecology are inextricably linked to other areas of science. All of the ecology practices from the 4DEE framework are ultimately included in our instructional alignment, but we treat the skills-based elements of ecology in a broader context than "ecology practices" articulates, and so we have additional learning targets that are not included in the 4DEE framework. These additional learning targets focus on the relevance and utility of ecology and include a focus on career preparation, tiered mentorship, and collaboration within the scientific community.

Using our Instructional Alignment for Introduction to Ecology

The instructional alignment that we have created (Appendix S2) serves as a resource for instructors at our institution as they develop and deliver their course. The learning targets that we present here work in our institutional and programmatic context, but may not translate directly to other institutions, so eco-educators should tailor their skills-integration strategy to their curricular and institutional context. We believe that a degree of horizontal course alignment (across sections) is beneficial both logistically and in terms of vertically aligning our scaffolded four-course introduction to the biological sciences, but we also recognize that students ultimately benefit when instructors are free to innovate, adapt materials, and teach to their strengths. Our course alignment strives to balance the benefits of consistency across course sections with those of instructional freedom, and while we have encountered some minor resistance to that perspective, we have also found that integration with the 4DEE framework helps to legitimize this perspective. Given the flexibility that we built into our instructional alignment, we believe that it is useful for eco-educators at other institutions, with appropriate modification to fit the institutional and/or programmatic context.

Early efforts to assess 4DEE are already appearing (Smith et al. 2019), and we anticipate further developments in this area. Our instructional alignment is partially assessable through existing tools (Summers et al. 2018, Clemmons et al. 2020) because it draws on Vision and Change, but it should be noted that our alignment is based on learning targets and objectives, not learning outcomes, and so is not yet as assessable as it will be in the future. Learning outcomes should be developed with specific assignments or lessons in mind and we did not have those specific assignments as we worked to pivot our course to incorporate 4DEE and a CURE. Assessment is one of our current priorities and, as we have built course materials for our course, we have done so with an eye toward transitioning our alignment from learning objectives to learning outcomes. We believe that our alignment will ultimately facilitate assessment between sections of our course after we transition it to learning outcomes, and because it is integrated with 4DEE, our final product will also be useful for assessing our course relative to those of other institutions.

Conclusion

The continued inclusion of ecological science in higher education relies on the ability of eco-educators to promote the significance, relevance, and utility of their educational offerings. We believe that the best pathway to promoting the ecological sciences and ecological literacy is through a focus on the relevance and utility of ecology. Integration with the 4DEE Framework offers many benefits, including an opportunity to emphasize the role of ecology in the undergraduate curriculum, and we expect those benefits to increase as assessment tools are developed and refined. We provide an example of how to collaboratively integrate the 4DEE framework and a CURE into an introductory ecology course through the creation of a course alignment that emphasizes the significance, relevance, and utility of ecology.

Literature Cited

Alpern, R. J., et al. 2009. Scientific foundations for future physicians. Report of the AAMC-HHMI Committee. Association of American Medical Colleges, Washington, D.C., USA.

American Association for the Advancement of Science (AAAS). 2011. Vision and change in undergraduate biology education: a call to action. American Association for the Advancement of Science, Washington, D.C., USA.

Bangera, G., and S. E. Brownell. 2014. Course-based undergraduate research experiences can make scientific research more inclusive. CBE-Life Science Education 13:602–606.

Beck, C., et al. 2012. Add ecology to the pre-medical curriculum. Science 355:1301.

Belovsky, G. E., et al. 2004. Ten suggestions to strengthen the science of ecology. BioScience 54:345–351.

Brando, P. A., L. Paolucci, C. C. Ummenhofer, E. M. Ordway, H. Hartmann, M. E. Cattau, L. Rattis, V. Medjibe, M. T. Coe, and J. Balch. 2019. Droughts, wildfires, and forest carbon cycling: a pantropical synthesis. Annual Review of Earth and Planetary Sciences 47:555–581.

Cahapay, M. B. 2020. Rethinking education in the new normal post-COVID-19 era: a curriculum studies perspective. Aquademia 4:ep20018.

Chronicle of Higher Education. 2019. Fastest-Growing Colleges 2007-17. The Chronicle of Higher Education, Washington D.C., USA. https://www.chronicle.com/article/fastest-growing-colleges-2007-17/

Clemmons, A. W., J. Timbrook, J. C. Herron, and A. J. Crowe. 2020. BioSkills Guide: Development and National Validation Tool for Interpreting the *Vision and Change* Core Competencies. CBE-Life Sciences Education 19. https://doi.org/10.1187/cbe.19-11-0259.

Cooke, J., et al. 2020. Teaching and Learning in ecology: a horizon scan of emerging challenges and solutions. Oikos 130:15–28.

Cooper, K. M., J. N. Blattman, T. Hendrix, and S. E. Brownell. 2019. The impact of Broadly Relevant Novel Discoveries on Student Project Ownership in a Traditional Lab Course Turned CURE. CBE-Life Sciences Education 18:ar57.

de Wit, H. 2020. The future of internationalization of higher education in challenging global contexts. ETD Educacao Tematica Digital 22:538–545.

Ecological Society of America. 2018. 4-Dimensional Ecology Education Framework. Ecological Society of America, Washington, D.C., USA.

Estrada, M., et al. 2016. Improving underrepresented minority student persistence in STEM. CBE-Life Science Education 15:es5.

Fleischner, T. L., et al. 2017. Teaching biology in the field: important, challenges and solutions. BioScience 67:558–567.

Gibb, R., D. W. Redding, K. Q. Chin, C. A. Donnelly, T. M. Blackburn, T. Newbold, and K. E. Jones. 2020. Zoonotic host diversity increases in human-dominated ecosystems. Nature 584:398–402.

Klemow, K., A. Berkowitz, C. Cid, and G. Middendorf. 2019. Improving ecological education through a four-dimensional framework. Frontiers in Ecology and the Environment 17:71.

Lundmark, C. 2002. The FIRST Project for Reforming Undergraduate Science Teaching. BioScience 52:552.

National Research Council. 2012. A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. The National Academies Press, Washington D.C, USA.

Neuwirth, L. S., S. Jovic, and B. R. Mukherji. 2020. Reimagining higher education during and post-COVID-19: challenges and opportunities. Journal of Adult and Continuing Education. https://doi.org/10.1177/1477971420947738.

NGSS Lead States 2013. Next Generation Science Standards: For States, By States. The National Academies Press, Washington, D.C, USA.

Rodenbusch, S. E., R. Hernandez, S. L. Simmons, and E. L. Dolan. 2016. Early engagement in course-based research increases graduation rates and completion of science, engineering, and mathematics degrees. CBE—Life Sciences Education 15:ar20.

Shapiro, C., J. Moberg-Parker, S. Toma, C. Ayon, H. Zimmerman, E. A. Roth-Johnson, S. P. Hancock, M. Levis-Fitzgerald, and E. R. Sanders. 2015. Comparing the impact of course-based and apprentice-based research experiences in a life science laboratory curriculum. Journal of Microbiology & Biology Education 16:186–197.

Shortlidge, E. E., G. Bangera, and S. E. Brownell. 2017. Each to their own CURE: faculty who teach course-based undergraduate research experiences report why you too should teach a CURE. Journal of Microbiology & Biology Education 18. https://doi.org/10.1128/jmbe.v18i2.1260.

Sklar, D. P. 2020. COVID-19: lessons from the disaster that can improve health professions education. Academic Medicine 95:1631–1633.

Smith, M. K., C. Walsh, N. G. Holmes, and M. M. Summers. 2019. Using the ecology and evolution-measuring achievement and progression in science assessment to measure student thinking across the four-dimensional ecology education framework. Ecosphere 10:e02873.

Summers, M. M., B. A. Couch, J. K. Knight, S. E. Brownell, A. J. Crowe, K. Semsar, C. D. Wright, and M. K. Smith. 2018. EcoEvo-MAPS: an ecology and evolution assessment for introductory through advanced undergraduates. CBE-Life Sciences Education 17. https://doi.org/10.1187/cbe.17-02-0037

Vrancken, G., A. C. Gregory, G. R. B. Huys, K. Faust, and J. Raes. 2019. Synthetic ecology of the human gut. Nature Reviews Microbiology 17:754–763.

Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.3857/full