UNDERGRADUATE EDUCATION

Coordinated Distributed Experiments in Higher Education: A Low Barrier to Entry and Potential for Student Projects

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Abstract

This mixed-methods research focused on the implementation of a coordinated distributed experiment (CDE) investigating local adaptation in common milkweed (*Asclepias syriaca)*, a host plant for the monarch butterfly population. Faculty participants were recruited from the Ecological Research as Education Network (EREN) who recruited their former undergraduate students. Quantitative data were drawn from the Milkweed Local Adaptation (MLA) CDE database across the three project years. Qualitative data included faculty survey responses, semi-structured interviews of faculty and former undergraduates, and review of undergraduate research posters, papers, and curricula using rubrics aligned with 4DEE and Next Generation Science Standards (NGSS) benchmarks. Analysis of the MLA CDE database illustrates a decline in both participating institutions and in counts of milkweed stems over the project (2018–2020). Qualitative data analysis revealed that CDEs: (1) offer opportunities for higher education faculty and their students to be part of research including developing skills of data collection, analysis, and interpretation; (2) have unexpected challenges; and (3) can inspire undergraduate students to develop independent research projects or curricular modules for use in formal 6–12 classrooms. Broader ecological educational implications of our

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outcomes for higher education faculty and their undergraduate students include: (1) recommendation that faculty members involved ought to be proactively informed about potential challenges and provided with guidance on how to mitigate them; (2) mitigating challenges with model studies to try to estimate the sample size and redundancy likely to produce robust data; and (3) proactive use of the educational network to understand institutional use of the CDE project with undergraduates.

Key words: Common milkweed; Coordinated distributed experiments; EREN; Four-dimensional ecological education; Next Generation Science Standards; Undergraduate research.

Introduction

Our project used a coordinated distributed experiment (CDE) design modeled after Fraser et al. (2013) with participants from the Ecological Research as Education Network (EREN) to test for local adaptation of *Asclepias syriaca* to distinguish the variables most likely to affect the success rate for habitat restoration. EREN, an NSF research network, enhances undergraduate education and advances science through authentic experiments distributed across institutions where these experiments can be powerful tools for answering ecological research questions across large geographic areas and spans of time (Fraser et al. 2013). In this paper, we describe the implementation of a CDE with a focus on the educational opportunities and challenges intertwined with higher education participant involvement, with limited focus on the actual experimental data.

Coordinated distributed experiments are a way to combine research and instruction in higher education settings where teaching is considered a priority over research, as a unique way for students to gain scientific experience (Jensen-Ryan et al. 2020) and to increase sample size or run an experiment in different environments (Bragg et al. 2016). Research suggests that CDEs are valuable for faculty in higher education, especially early career, as they promote development of new concepts, leadership and communication skills, peer networking and promoting independence and engagement (Pastor et al. 2020). Graduate students benefit from CDEs through collaborative projects where they can take the lead to organize and initiate projects (Wilkins et al. 2020). Undergraduate researchers are the "boots on the ground" in many published CDE studies (Colautti et al. 2014, Bowne et al. 2018); however, no mention is made of the challenges CDEs present for higher education faculty or educational opportunities afforded undergraduate students, gaps we address through the following research question: *What are the educational opportunities and challenges faculty, and their undergraduate students face with CDEs?*

Methods

CDE context

The Milkweed Local Adaptation (MLA) CDE used complementary investigative approaches to study local adaptation of common milkweed (*A. syriaca*), a host plant for declining monarch butterfly population. In 2017, we recruited 29 participants from EREN (higher education participants) or state secondary science education networks represented by geographic location in Fig. 1.

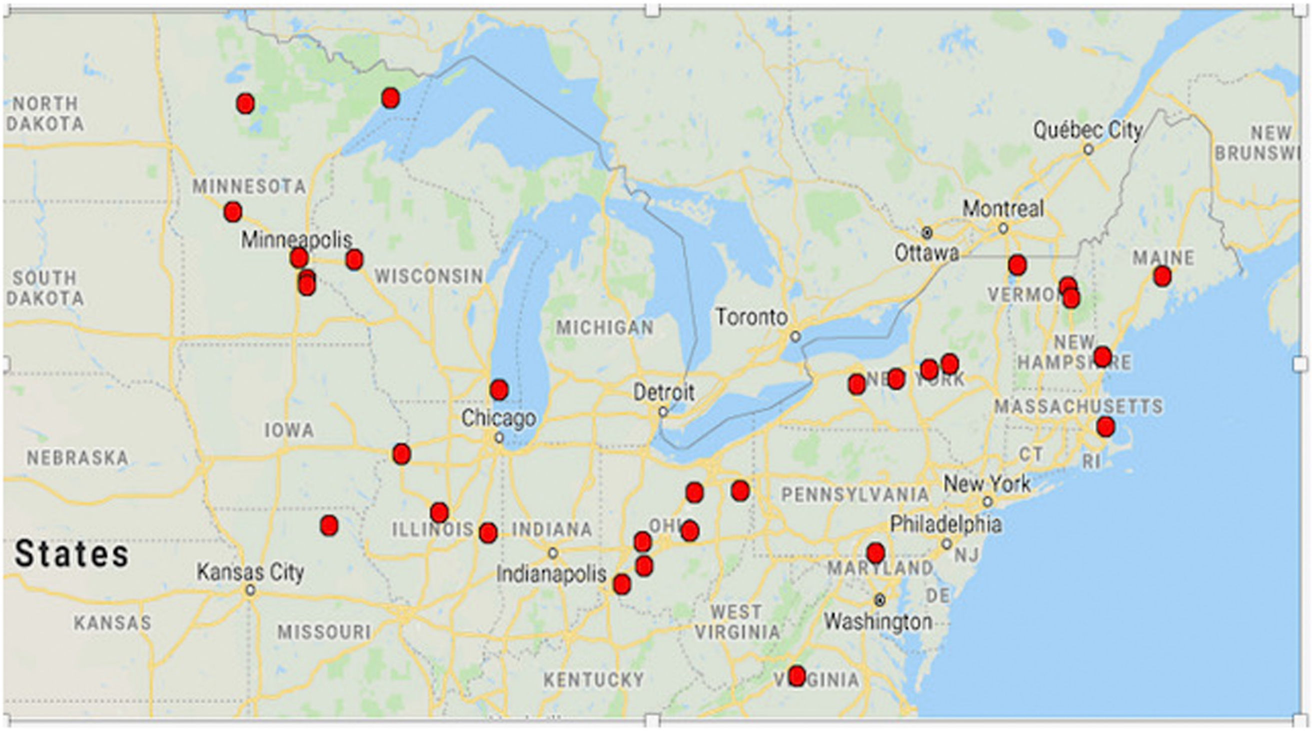

Fig. 1. Locations of participants in the MLA CDE.

Twenty of the original participants were from higher education institutions with the remaining nine participants teaching science at the secondary level in public schools. In this paper, we report only educational outcomes related to higher education and undergraduate participants.

Milkweed Local Adaptation protocol training occurred in summer 2017 with a focus on milkweed/monarch biology and life cycles, and CDE data collection protocols participants would later translate into their higher education biology or ecology classrooms. The CDE protocol used a series of technical methods to test for the presence, scale, magnitude, drivers, and constraints of local adaptation across the species range, investigating both biotic and abiotic contributions to the patterns observed. The first step in the MLA project was to develop a plot for the milkweed (MW) plants. Participants harvested MW seeds from their local area in the fall of 2016 and sent them to the primary PI for counting, massing, and redistribution of seeds. Local seeds accompanied with seeds from four nonlocal source populations were distributed to each participant. The instructions for developing the plot (2018) specified that the planting site needed to be available for long-term data collection (3+ years) and should contain enough space to plant 20 plants in pots 1 m apart. Site preparation started with mowing any vegetation down. Pots were used rather than direct field planting to contain the roots and to help ensure that we knew which stems belonged to each milkweed plant. Secondly, the pots would let us remove the plants from the field when the experiment was finished. Participants were to dig holes for the pots, reserving the soil from each hole for the pot. The pot was then placed in the hole with the reserved soil used to fill the pot and to fill in the area in the hole around the pot. The rim of the pot was left visible above the ground, and a flag was placed near the stem to maintain visibility as vegetation returned. To help control weeds within the pots, participants placed weed suppression material around the stem, using staples to affix it to the soil and minimize chances that wind would displace it. For the sake of consistency between projects, we recommended that investigators develop a rectangular numbered layout for their plot. Row 1 had plants 1–4, row 2 plants 5–8, row 3 plants 9–12, row 4 plants 12–16, and row 5 plants 17–20. Each numbered plant represented a position within the plot. Milkweed seedlings (grown in the greenhouse) were planted in late spring after 4–6 days of slow acclimation to the outdoors.

MLA measurement data collection took place at each site from 2017 to 2020 where the protocol ideally used three undergraduate students to take independent measurements on each plant. Instruction for data collection included written documents with illustrations and step-by-step video guides. Whole plant measurements (number of stems, nodes, leaves, fruits, flowering umbels, and total fruit mass), largest stem measurements (height and diameter), and largest leaf (length, width, and area) were completed at the time seedlings were planted into the field. Measurements were repeated annually in the fall (when plants had reached maximum height) and spring, with some sites also collecting peak summer data.

Data collection and analysis

To answer the research question, our study featured a mixed-methods design of quantitative and qualitative data collection and statistical analysis (Patton 2015) bounded by the experiences of higher education faculty and undergraduate students of the faculty (Merriam 1998). Mixed-methods design allows for more complete analysis of research data than quantitative or qualitative data collection and analysis alone (Wisdom and Creswell 2013). Quantitative data included milkweed stems counted and institutional involvement over the 3 years of the project. Qualitative data collected included survey responses (10), 45-minute interviews of faculty (9), four former undergraduates (4), review of undergraduate (5) research products (posters, theses, papers, and curricula). We conducted semi-structured interviews with higher education faculty and undergraduates (Rubin and Rubin 2004) asking questions related to their participation within the project as well as opportunities and challenges they faced. Interviews were transcribed verbatim. Appendix S1 details information about each participant's background, institution, courses taught, and location of MLA plot with all participants coming from either private or public 4-year undergraduate institutions (Appendix S1).

We used analytic induction (Erickson 2011) to analyze the qualitative data within a grounded theory framework (Bryant and Charmaz 2007). Grounded theory is a well-known analytical approach in qualitative research that seeks to discovery theory or constructs within a data set, through systematic and nuanced inductive analysis of a data set [in our case: interview transcripts and survey open item text (Bryant and Charmaz 2007; Chun et al. 2019)], a method of analysis used in previous work (Koomen et al. 2014, 2016). Analytic induction is recursive, integrated, and progressive, but not necessarily constant (Erickson 2011). In our analysis, we systematically sorted the text into coding domains or relationships, reviewed all relevant data for each assertion or theory and then moved on to another assertion. The research team used Google Jamboards to highlight assertions and identify any inconsistencies or negative case analysis (Creswell 1998). Throughout the analysis process, we discussed similarities and differences in the themes to achieve acceptable interrater reliability (Baker et al. 1996). Due to our small participant number (10), quantitative survey data were analyzed using descriptive statistics only.

We examined research projects and curricula completed by undergraduate students using different benchmarks for ecology learning at the college level (Klemow et al. 2019) and for K12 students (NGSS 2013). The 4DEE Framework (Klemow et al. 2019) includes 21 elements divided into four dimensions of core ecological concepts, ecology practices, human–environment interactions, and crosscutting themes that provide recommendations, not mandates, for instructors developing and teaching general ecological content at the college level. The Next Generation Science Standards (NGSS) (2013) is a comprehensive vision for science learning and proficiency for students in K12 science classrooms. The NGSS benchmarks are represented by three equally important dimensions: science and engineering practices, disciplinary core ideas, and crosscutting concepts that serve to guide teachers to develop a cohesive understanding of science overtime with K12 students.

Using relevant content in ecology for both the Klemow et al. (2019) and NGSS (2013) we developed two rubrics, without a continuum of scales, to understand if the products (research projects or curricula) aligned with some of the expectations of the 4DEE or NGSS benchmarks, based on prior work of the authors (Koomen et al. 2016, 2021*a*,*b*). As these rubrics are emerging tools of criteria-based evaluation (Bennett 2016) and our undergraduate population was small (8), we focused on a few of the benchmarks across dimensions of each Framework, rather than every element, to help us to understand some of the ways the research projects or curricula were aligned with educational expectations for each framework. The 4DEE (see Table 5) rubric used the words "appropriate" and "sufficient" developed in tools published by McNeill and Krajcik (2012) as benchmark learning criteria, while the NGSS (2013) rubric (see Table 6) delineated only the alignment of curricula to the NGSS, without learning criteria.

Undergraduate student research posters are the main products we analyzed in this study, except for the two MLA and phenology curricula. Because the research posters were developed using Microsoft PowerPoint, we could not include them in this paper because of size and resolution challenges. Tables 1–4 represent abbreviated text from the posters with Appendixes S3–S6 illustrating poster figures (graphs, charts, and photos).

Results

In this section, we build a case through our findings that CDEs: (1) offer educational opportunities for higher education faculty and their students to be part of ongoing and authentic scientific research; (2) have unexpected challenges; and (3) can be vehicles to inspire undergraduate students to develop independent research projects or curricular modules. The text excerpts below represent most of the sentiments expressed by faculty participants, for brevity only a few are included.

Faculty interest and appeal of the project

Our analysis found that the CDE project was appealing to most of the higher education faculty because they saw the educational value of using a networked system (EREN) to focus on science and research skills with undergraduates. The CDE project offered opportunities for faculty to meet teaching and research goals at non-Research 1 institutions "where there's a low barrier to entry and there's a lot of potential for student projects" (Caris interview).

> *Being at a four-year comprehensive school my goal is to get students trained to become researchers. I was interested in the fact that my students are learning how to do high-quality research. (Kale interview)*

As a new assistant professor, Jocelyn used the data from the MLA to hone in on data analysis and draw evidence-based conclusions with students in her introductory biology courses.

> *I wanted them to get practice critically analyzing graphs and results and to identify possible alternative hypotheses and any weaknesses in the reasoning linking the evidence to the conclusions. (Jocelyn interview)*

Instructors used the MLA CDE project to highlight specific science content such as interdependent relationships in ecosystems and local adaptation.

> *When we talk about factors that disrupt monarch populations and actions people are taking to try to protect the populations, that relates to resilience of ecosystems and biodiversity and human interactions. I wanted students to have opportunities to learn about LA in an applied way, to make sense of data and use it to support their own arguments related to interdependent relationships. (Emery survey)*

Faculty planned strategically for the plots and ensured CDE protocols were followed

All higher education participants planned carefully where to place their plots, in consultation with administrators and ground's crews at their institutions.

> *I worked with the person that was head of grounds and we agreed on a place for me to put it, which was an out of the way place kind of behind the football stadium that met the criteria of being a low traffic area. I thought it would be a reasonably safe place, literally nobody goes [there] except us. (Kamal interview)*

All participants noted the ease of the milkweed adaptation protocol where instructions were "really clear, easy to follow" (Atticus interview), detailed (survey), and "pretty straightforward" (Jocelyn interview).

Survey responses helped us understand how higher education faculty taught the protocol to students: "We went through the protocols together. I demonstrated and had students practice with some plants we had on the green roof" and "for the plant course, we had each plant measured three times by different groups and averaged the values."

Challenges and constraints of MLA for faculty

Many participants faced challenges with working with campus facilities, grounds crews, or administration: "the hardest part was getting approval from the administration" (survey). However, even with that approval there was no guarantee that the site would be suitable for common milkweed as one participant noted in her survey response: “We had some challenging weather events, like drought and then floods in the plots.” Caris noted:

> *The summer of 2019 was really wet and there was a ton of standing water in our plots. We think that had a major effect on the plants' regrowth and so each year of the project, we had fewer and fewer plants grow back. We only had one semester, fall 2018 in which there were plants big enough for students in a class to measure, so that limited our incorporation of the project into class; combined with the poor regrowth rate we experienced in years 2 and 3 made it difficult to build a consistent lab module. (Caris interview)*

Herbivorous wildlife was a challenge, too.

> *Early on, we were very surprised. The MW plants were in the ground for maybe a week and some of the seedlings had been nipped off already, so we quickly installed some fencing and replanted it because we still were maintaining the leftovers. (Atticus interview)*

Kamal participated in the pilot study, where a few faculty at various institutions started a pilot plot attempting to flush out challenges and barriers before the CDE project lifted off.

> *The grounds crew and I talked and settled on a plot site. For the pilot study things went well. No real disruptions of the site. But the next year [2018] things started to go awry. The plot got mowed multiple times during the growing season. I put out larger stakes and put out flagging to make it clear with signs with my contact information. For a while, things were OK. That winter we had heavy snowfall. The ground's crew had to hire temporary workers to drive snowplows and they identified that parcel of land [plot site] as a place to dump the snow. They ended up driving snowplows through the plot multiple times. (Kamal survey)*

Quantitative data

Our analysis of the CDE database illustrates a decline in both participating institutions and in counts of milkweed stems over the years of the project (2017–2020). Fig. 2 illustrates institutional participation across the project with Fig. 3 documenting milkweed stem records.

Educational opportunities for undergraduates

This section highlights educational experiences and products for undergraduates representing two institutions: (1) a 4-year undergraduate private liberal arts college (PLA) in the Upper Midwest, professional home of one of the project PIs and (2), a state university (SU) that serves primarily undergraduate students in the Northeast US, the professional home of Caris and Havana. All three students from the PLA were summer research students. Octavia, a life science/secondary education double major, was paired with Jasmine (biology major) in the summer program. Billie was a biology/life science secondary education double major who participated two different summers in the project. Two of the students from the SU majored in biology with a double major in elementary (Kala) or secondary (Jade) education.

Private liberal arts college

Summer undergraduate research students developed two curricula drawn from the MLA: MAREN, [(Milkweed Adaptation Research and Education Network) Octavia] and the Phenology Project (Billie). Octavia developed the MLA curriculum of seven lessons designed for secondary biology teachers and their students. The lessons include monarchs and their decline, monarch population debate, milkweed as critical food for monarchs, evolutionary principles using MLA, data analysis of MLA, citizen science with monarchs and milkweed, and picking plants for the monarch highway. The lesson plans used the 5E Learning Model (Bybee et al. 2006) and addressed several NGSS standards (2013) in all three dimensions. The goals of the curricula were to:

> *bring biological principles and concepts into a real-world investigation. When students participate in these "authentic science" curricula, they make better scientific arguments, better understand biological principles, and integrate more sources and data into their arguments. (MAREN website)*

An overview of one lesson features MLA data as a tool to guide students in data entry, analysis, and interpretation (Appendix S2).

Octavia (life science/secondary education double major) was paired with Jasmine (biology major) in the summer of 2017 to pilot common milkweed plant propagation in the greenhouse and later transplant the plants into a pilot field site on the college grounds. Octavia worked on the randomization of plants and layout of the field site. Jasmine completed the daily measurements of the plants in the greenhouse ("plant height, the number of leaf pairs, the width and length of leaves") and aspirated insects like aphids from the plants. Once the plants were transplanted to the field site, both research assistants completed the field measurements following the protocol. Both women presented the results of their summer research projects at an undergraduate symposium at the end of the summer. Octavia (Table 1; Appendix S3) focused on the MLA curricula, while Jasmine (Table 2; Appendix S4) compared rates of herbivory across two of the field sites at different geographic locations. Emery, along with Octavia, hosted a summer workshop for K12 teachers focused on the MLA project, protocols, and CDE that served as a pilot of the effectiveness of the curriculum with teachers. Jasmine presented data on the milkweed, chlorophyll, and cardenolides (toxic steroids) measurements.

> *Mine had to do more with the curriculum. Emery and I hosted a pilot workshop [for science educators from grades 6–12] just the day or two before that symposium. The teachers completed a survey about the curriculum and its usefulness. (Octavia interview)*

Octavia reflected on the impact of the summer research on her graduate studies in public health.

> *The summer research helped further cement my interest in not only research but really that high standard of very good quality research. I think it's a two for one deal when you participate in research as an undergrad because you are learning about and contributing to a field that you're interested in. But there are so many soft, like communication, and hard skills [how science is done] that you learn that are invaluable going forward. I carried so much of that with me in public health. It was especially useful to go through the IRB process for graduate school. (Octavia interview)*

Table 1. Abbreviated undergraduate research project text: Got Milkweed? Curriculum development for studying local adaptation in *Aslecpias syriaca*, by Octavia and Emery.

Canonical section of research poster	Descriptive text for canonical section
Introduction	Monarch butterfly populations have been sharply declining in the last 15 years (Inamine et al. 2016). One possible cause may be the decline of one of the monarch larvae's host plants, common milkweed. Determining whether or not common milkweed populations are locally adapted has implications for many conservation efforts to bolster the monarch population. However, studying local adaptation requires reciprocal transplant studies with multiple populations, often spanning the vast majority of the natural range of the species and is therefore difficult to conduct In middle and high school life science classes, finding hands-on labs to teach evolution is a rarity. Citizen science projects, where members of the community assist researchers in gathering data, can help students develop higher-level thinking skills and become scientifically literate (Lenz and Wilcox 2012). Using a distributed research model, this project aimed to create a lab curriculum that simultaneously eased the burden of gathering data to be used in studying local adaptation of common milkweed and yielded an authentic, hands-on research project for middle and high school life science students
Curriculum	The 5E Learning Model, based on the constructivist approach to learning, has students engage, explore, explain, elaborate, and evaluate their course material (Bybee et al. 2006). Each of the six individual lesson plans in the curriculum is structured around the 5E Learning Model; furthermore, the curriculum also contains on overarching 5E Learning Model, with students engaging with the material in the first lesson, "Monarchs and their Decline," all the way through evaluating their learning in the last lesson, "Citizen Science: Monarch and Milkweed Awareness." The curriculum is also based on the Next Generation Science Standards (NGSS), a unique approach to teaching science through a trifecta of different crosscutting concepts between branches of scientific study, science and engineering practices, and discipline-specific core ideas (Next Generation Science Standards)
Protocols and Pilot Study	To test written protocols, a pilot study of the student lab was conducted in the Natural Lands. Two 4 × 4 meter plots were planted, with 16 common milkweed plants each. While some seedlings were from the Natural Lands, other seedlings were from Virginia, New York, and Wisconsin. To test one of the possible extension teachers can add to the curriculum, plants in Plot 2 were treated with pesticide
Results	To determine the effectiveness of the curriculum, teachers and administrators from across the country were invited to participate in a workshop to learn about the curriculum and the associated lab. Surveys were sent out to participants before and after the workshop to determine how much they learned about monarch decline and related concepts, and the extent to which the workshop changed their teaching practices. For teachers who choose to participate in the research, spring and fall follow-up surveys will be sent to gather additional information to improve the curriculum and lab materials The pilot study led to significant revisions of protocols, including the procedure for seed germination and the size of pots used for transplanting. Although plants in Plot 2 were only treated with pesticide on two occasions, the difference in herbivory between the two plots was visibly noticeable
Conclusion	This curriculum and its associated lab will be successfully implemented in the fall of 2018, when teachers will begin collecting common milkweed seeds to be sorted by researchers and redistributed to participating schools. The field of ecology will benefit from the data gathered by students, who will, in turn, benefit from a robust curriculum and a hands-on lab to teach evolution and adaptation

Notes: Curriculum development for MLA, including pilot study with secondary teachers informing the curricula revisions. For better resolution, figures for the original research poster may be found in Appendix S3.

Jasmine's research poster focused on examining geographic variation and tolerance of milkweed to herbivory (Table 2; Appendix S4). Jasmine's study sought to test for latitudinal cline intolerance to herbivory where she used milkweed biomass of roots/shoots to understand resource allocation and variation in milkweed chlorophyll and cardenolide levels in response to herbivory.

Billie was a summer research student for two summers, and Jasmine was a research student for just one summer. Emery has lost contact with both former students, thus neither one was interviewed about their research and curricula projects.

> *They had to figure out how to focus and narrow down and to pick a question that's within the realm of questions that can be answered. They both went through the cycle of asking a question, gathering data, and interpreting the data. That last part of interpreting data is very important because without it it's not as impactful for undergraduates. They both presented at conferences at our institution at the end of the summer. (Emery interview)*

In the summer of 2019, Billie focused her research on science educators who were involved in the MLA CDE to address research questions related to MLA protocols and use of the MAREN curriculum ahead of developing a sister curriculum to MLA focused on phenology (Table 3; Appendix S5). Since the working hypothesis of the MLA CDE was that MW would exhibit local adaptation and since milkweed phenology is a candidate trait that will likely contribute to local adaptation, a sister phenology curriculum would complement the outcomes of the MLA.

Billie surveyed educators who expressed interest in the MLA project with questions about the MLA current and future curriculum (Table 3; Appendix S5). The results of her survey lead to the design of a new curricula and protocol called the Phenology Project, a series of citizen science investigative protocols that invite students and individuals to work together to address this question: *How does the developmental stage of common milkweed, its relative phenology, and geography affect its interactions with herbivores and pollinators?* The website includes information on milkweed identification, selection of sites for collecting data, protocols (with video demonstrations), and how to submit data collected. Recruitment for project participants began in summer 2022.

State university

As part of her research assistantship, Jade used the data collected at SU to develop an independent research project (Table 4; Appendix S6).

Jade explained more about her research in her interview:

> *We were looking at the common milkweed experiment to see how seeds from various locations across the Northeast were doing in our area. We had these different seed location numbers because we had to keep ourselves blind as to which seeds were from where because we didn't want to bias ourselves and make our own seeds do better. The MLA project was a really great opportunity to do something that could easily translate to a middle school or high school level for students to do real science, not just a lab where you're spoon feeding every single step of the way to them. (Jade interview)*

Table 2. Abbreviated undergraduate research project text: Geographic variation in milkweed tolerance against herbivory by Jasmine and Emery, Biology Department.

Canonical section of research poster	Descriptive text for canonical section
Introduction	Monarch migration patterns have begun to shift due to climate change, and there is concern regarding what milkweed resources are available in these regions. Assisted milkweed migration is a potential solution, but it is unknown whether milkweed can thrive in these new migration regions. It is expected that milkweed plants exhibit geographic variation in response to herbivory that effect their ability to relocate to new environments. Unlike resistance, which reduces herbivory, tolerance to herbivory is measured as the difference in fitness between damaged and undamaged plants. In a different species, *Lythrum salicaria*, there is evidence for a latitudinal cline in both resistance and tolerance to herbivory (Lehndal and Agren 2015) This study's aim is to test for a latitudinal cline in tolerance to herbivory. We hypothesize that resource allocation in plant roots is a mechanism of tolerance to herbivory and if there is geographic variation in root: shoot biomass ratios. The third hypothesis tested for geographic variation in milkweed cardenolide levels in response to herbivory
Methods	Common milkweed (*Aslecpias syriaca*) seeds were collected from 19 different populations. We grew approximately 16 plants from each population. To test for tolerance to both chewing and sucking herbivores, the 16 plants were divided into eight controls, four treated with monarch larvae herbivory, and four treated with aphid herbivory. The plants were placed into four temporally and spatially separated blocks. Each block had a total of approximately 76 plants that contain four plants from each population (two controls, one with monarch larvae, and one with aphids). The placement of each plant was randomized within the block, and experimental measurements for each block were recorded within the same 24-hour period Measurements were taken over the course of 5 weeks. Plant growth measurements included stem height, leaf number, and area of the largest leaf and were recorded twice before and after applying damage. Chlorophyll content and cardenolide concentrations of the largest, highest, and lowest leaves were measured once before and after applying damage. Aphids and monarch larvae were applied 2 weeks after initial growth measurements were taken and removed after they had damaged no more than 25% of the leaf tissue. After experimentation, plants were harvested, freeze-dried, and massed
Discussion	Our results indicate that milkweed stem height is significantly affected by the presence and type of herbivory (Fig. 1). The origin of the seed also has a significant effect on the percent growth of the stem height (Fig. 2), which indicates that milkweed growth patterns exhibit geographic and genetic variation The difference between damaged and undamaged plants' percent growth of the stem height is reflective of plant tolerance. However, there is not sufficient evidence that latitude predicts tolerance to aphid (Fig. 3) or monarch larvae herbivory. There is also no evidence for a relationship between a plant's tolerance to aphid herbivory and its tolerance to monarch larvae. This is likely due to this study's space limitations. There were only four replicates of each treatment per family. An increase in replicates to represent each family and gathering seedpods from a wider range of locations would provide further insight into the geographic variation of milkweed tolerance
Conclusion	We found that a common milkweed growth pattern exhibited geographic and genetic variation. However, we cannot conclude that there is a genetic correlation or latitudinal cline in milkweed tolerance to herbivory. Final plant biomass, root: shoot ratios, and levels of cardenolide production may predict milkweed's ability to tolerate herbivory. Further investigation and replication can provide more knowledge into milkweed's ability to relocate to novel environments in order to support recent changes in monarch butterfly migration patterns

Notes: Geographic variation in milkweed tolerance against herbivory. For better resolution, figures for the original research poster may be found in Appendix S4.

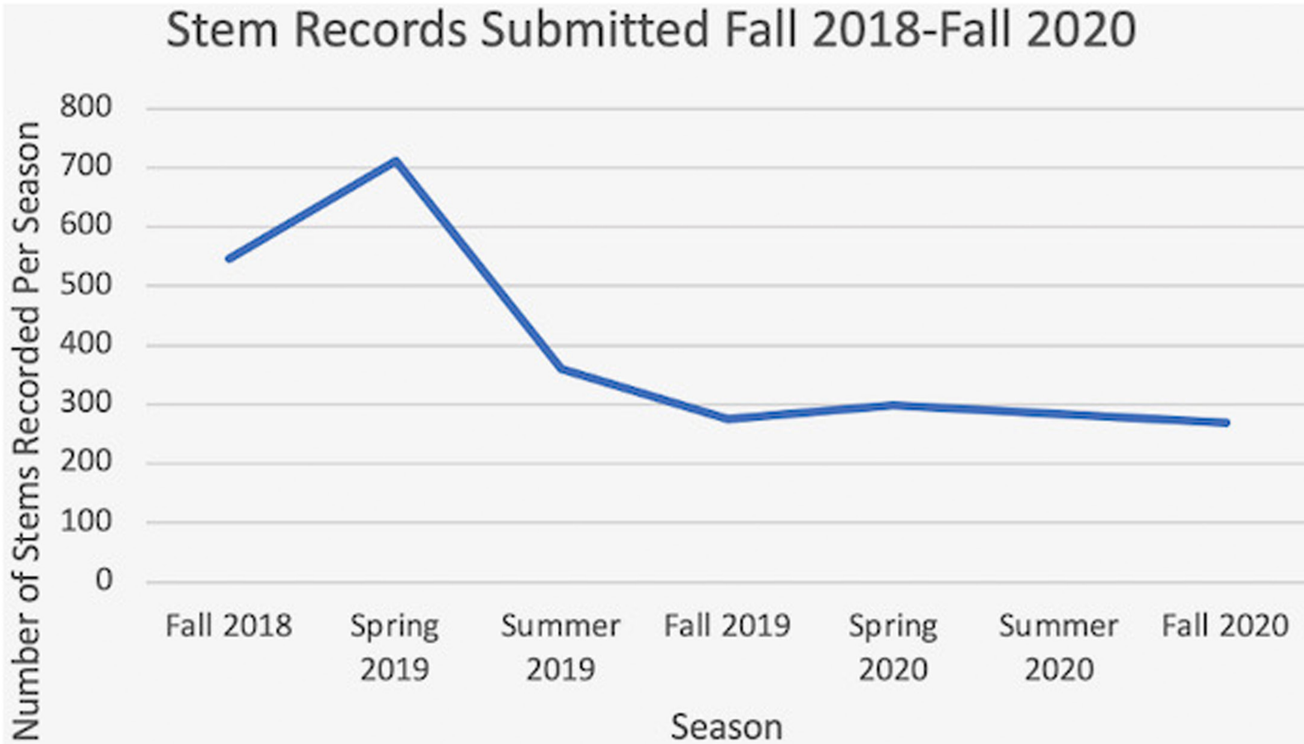

Fig. 2. Number of common milkweed stems counted across the same period.

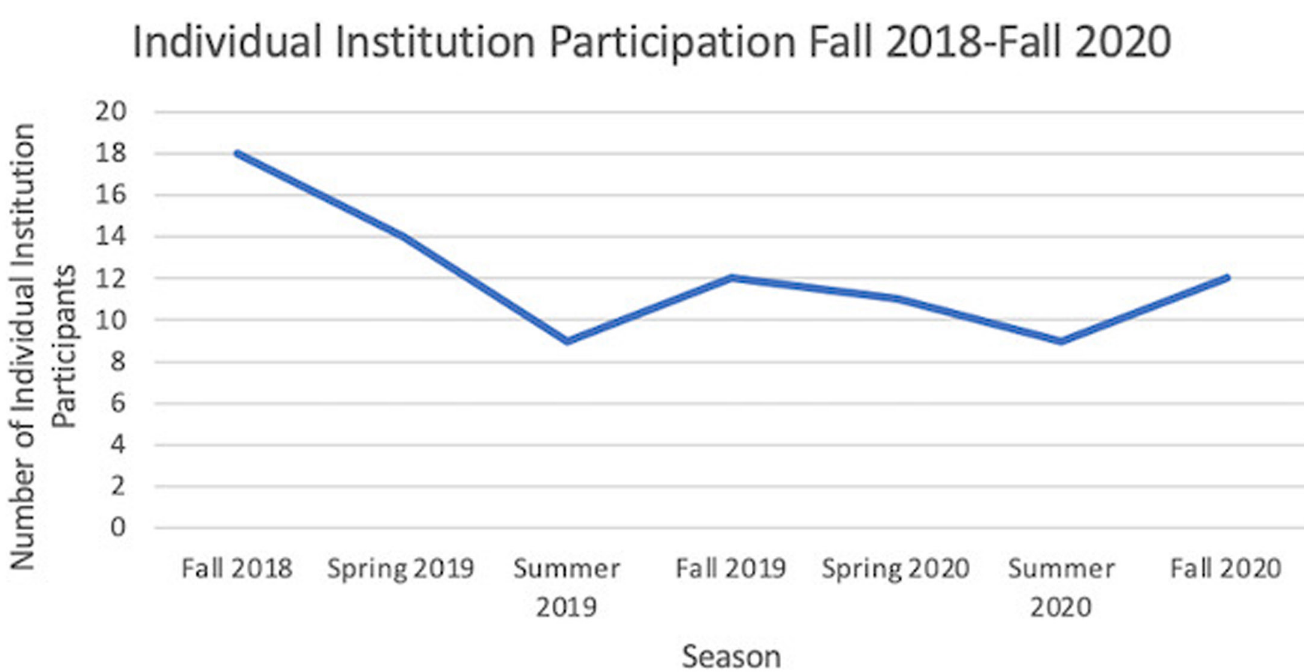

Fig. 3. Institutional involvement in the MLA from fall 2018 to fall 2020.

Table 3. Abbreviated undergraduate research project text: investigating local adaptation in milkweed: expanding curriculum involving authentic science, by Billie and Emery, Biology & Education Departments.

Canonical section of research poster	Descriptive text for canonical section
Introduction	The Milkweed Adaptation Curriculum was developed in 2016 to support teachers involving their students in data collection as part of a reciprocal transplant study investigating local adaptation in common milkweed, an important food source for monarch butterflies. The premise was that students benefit from participation in authentic science, including exposure to current debates and unanswered questions. Many educators expressed interest in the curriculum who were unable to participate in the reciprocal transplant study due to lack of time, space, or resources. This study introduces a sister curriculum using observations and simple experiments to promote inclusivity
Methods	• We surveyed educators who expressed interest in the reciprocal transplant study with questions about the current and future curriculum • We designed a complementary curriculum ○ That can be applicable year-round ○ Involves observational and experimental components ○ Techniques can be implemented in diverse contexts ○ Connects with and expands on upon other citizen science projects at the National Phenology Network • Justified the curriculum expansion with preliminary data to highlight the way research questions develop ○ Focuses on species interactions, herbivory, and phenology ○ Curriculum is easily modifiable to promote the authentic investigations of other questions generated in the classroom
Results	• Currently, no direct relationship between curriculum use and participation in experiment • Strong desire for more collaborations between educators and students at different institutions requests for more training and funds to support the use of protocols and data with students • Great interest in observational study with simple protocols • Enthusiasm for modifiable curriculum that promotes the generation of new research questions
Conclusion	The purpose of this study was to produce a sister curriculum that is easily modifiable for different educational levels and accessible for educators and students who do not have the space, time, or resources for a transplant study. This new curriculum supports experimental and observational interactions with milkweed plants through direct or technological interactions in order to provide students with research experience related to the milkweed adaptation curriculum. The curriculum and protocols focus on phenology because of phenological differences from plan to plant, which can create challenges for conservation efforts for milkweed

Notes: Billie's poster presented at college undergraduate research initiative. For better resolution, figures for the original research poster may be found in Appendix S5.

Kala used the MLA CS project at SU as part of her honors thesis where she developed a unit plan, suitable for 5th grade students, that blended MW with the fungus mycorrhizae. Kala's inspiration for this project originated in perceived misconceptions that K12 students might have about fungi (Bahar 2003). "Many students have a misconception that 'all fungus is bad'. In my unit. I wanted students to understand how fungi can be beneficial and are used to make medicine, food, and shelter for insects, not just that they decompose things" (Kala, Interview).

Table 4. Abbreviated undergraduate research project text: preliminary results of a common garden experiment with *Asclepias syriaca* (common milkweed) by Jade, Havana & Kala, Department of Biological Sciences at State University.

Canonical section of research poster	Descriptive text for canonical section
Research Approach & Methods	In October 2017, HM and MCFR collected seed pods from five individual milkweed plants from Wyman Meadows (Fig. 1A), a location roughly 4 miles east of the SU campus. Seeds were cold-stratified in moist sand for 1 month at 4°C. All seeds were referred to by a randomized location number, rather than location name, to prevent bias. Three hundred seeds were then planted in flats at random and grown for 6 weeks in the greenhouse (Fig. 1B) In early September, the cages were removed, and the stems were staked to provide stability (Fig. 1C). Size data were collected again in late September (Fig. 1D). Additional data collected at this time included number of fruits, number of flowers, number of leaves chewed, number of leaves with damage from specific invertebrates (weevils, miners, and snails), stem damage, number of curling leaves, number of leaves with spots, presence of certain invertebrates (monarch caterpillars, milkweed bugs, tussock moths, milkweed beetles, weevils, aphids, ants, ladybeetles, bees, spiders, snails, and Japanese beetles), and aphid color (if present). September data collection was completed with the assistance of HM's Plant Physiology class, Jade led the lesson (Fig. 1D)
Results	There was no significant difference in seedling growth between plots, so results from each plot have been pooled together. There were some differences in growth between seeds sourced from different locations. In May, on the day of transplant from greenhouse to field, seedlings from location 23 had a significantly taller stem height than the other locations' seeds (ANOVA, $F =$, $P =$; Fig. 2A). These initial greenhouse advantages were not observed in September (ANOVA, $F =$, $P =$; Fig. 2A). Seedlings from location 10 had significantly larger leaf length and width compared to seedlings from location 8 in May (ANOVA, $F =$, $P =$; Fig. 2B,C). Again, these advantages were not observed in September (ANOVA, $F =$, $P =$; Fig. 2B,C). After 4 months in the field, there was also no significant difference in stem height among locations (ANOVA, $F =$, $P =$)
Discussion	We successfully established 40 milkweed plants in two adjacent plots from four different locations in our common garden at BSU. There was no significant difference in growth between plots, supporting our hypothesis that the adjacent plots were similar in quality. The plants in both plots experience the same amounts of sunlight, rainfall, and soil composition, and each plot contained five plants from each location in a randomized arrangement Locations 10 and 23 experienced a slight, but significant, growth advantage in the greenhouse (Fig. 2A); however, this advantage was not observed after a full season of growth in the plots. As this is a new EREN initiative, we do not yet have other data from Got Milkweed? to analyze against our own. In similar studies growing grasses sourced locally and commercially, this phenomena was also observed. Initial advantages were present, but final advantages were not found based on seed source.[2] This may indicate that local traits for germination and initial growth have been selected for. The seeds are also sourced from locations that are of similar latitude and climate (Fig. 3), so this could indicate that they have evolved similar adaptations convergently We have several ideas for side projects within our plots. We established two plots so that we could carry out experiments with our plants. In November 2018, all plants in Plot 2 were treated with two teaspoons of soluble endomycorrhizae. We predict that the endomycorrhizae will promote more growth in Plot 2 this season. We also plan to do soil analyses later in the spring to determine nutrient availability, and presence or absence of endomycorrhizae in both plots. We will continue to monitor our plots and collect data as they grow back this year. We also want to explore aphid–plant interactions, as nearly all plants were colonized by large numbers of oleander aphids (Aphis nerii)

Notes: Poster presented at Northeast Natural History Conference. For better resolution, figures for the original research poster may be found in Appendix S6.

Table 5. Four-dimensional ecological education framework (Klemow et al. 2019).

Core ecological concept	Core ecological concept evidence
Organisms: habitat and niche with appropriate and sufficient evidence	Table 4; Appendix S6: Common milkweed is one of the primary food sources of monarch caterpillars. The overall mission of Got Milkweed? is to investigate the regional adaptations of milkweed plants. By planting these seeds under the same conditions and monitoring their growth over time, adaptations and advantages may begin to show between seed localities
Ecosystems: community competition with appropriate and sufficient evidence	Table 2; Appendix S4: Common milkweed (*Asclepias syriaca*) seeds were collected from 19 different populations. We grew approximately 16 plants from each population. To test for tolerance to both chewing and sucking herbivores, the 16 plants were divided into eight controls, four treated with monarch larvae herbivory, and four treated with aphid herbivory
Ecological practices	Ecological practice evidence
Natural history: making observations and connections with appropriate and sufficient evidence	Table 2; Appendix S3: Measurements were taken over the course of five weeks. Plant growth measurements included stem height, leaf number, and area of the largest leaf and were recorded twice before and after applying damage. Chlorophyll content and cardenolide concentrations of the largest, highest, and lowest leaves were measured once before and after applying damage
Quantitative reasoning and computational thinking: data skills with appropriate and sufficient evidence	Table 2; Appendix S4: Our results indicate that milkweed stem height is significantly affected by the presence and type of herbivory (Fig. 1). The origin of the seed also has a significant effect on the percent growth of the stem height (Fig. 2), which indicates that milkweed growth patterns exhibit geographic and genetic variation
Human–environment interactions	Human–environment interactions evidence
How humans shape and manage resources/ecosystems/the environment: conservation biology with appropriate and sufficient evidence	Table 1; Appendix S3: Monarch butterfly populations have been sharply declining in the last 15 years (Inamine et al. 2016). One possible cause may be the decline of one of the monarch larvae's host plants, common milkweed. Determining whether or not common milkweed populations are locally adapted has implications for many conservation efforts to bolster the monarch population. However, studying local adaptation requires reciprocal transplant studies with multiple populations, often spanning the vast majority of the natural range of the species and is therefore difficult to conduct
Crosscutting	Crosscutting themes evidence
Spatial and temporal: evolution with appropriate and sufficient evidence	Table 4; Appendix S6: By planting these seeds under the same conditions and monitoring their growth over time, adaptations and advantages may begin to show between seed localities. Locations 10 and 23 experienced a slight, but significant, growth advantage in the greenhouse (Fig. 2A); however, this advantage was not observed after a full season of growth in the plots. In similar studies growing grasses sourced locally and commercially, this phenomenon was also observed. This may indicate that local traits for germination and initial growth have been selected for. The seeds are also sourced from locations that are of similar latitude and climate (Fig. 3), so this could indicate that they have evolved similar adaptations convergently

Note: Aligned assessment illustrating how students use their ecological knowledge with example evidence from research posters (Tables 1–4, and Appendixes S3–S6).

Analysis of undergraduate research projects and curricula

Our basic rubrics helped us understand the research project and curricula relative to the Klemow et al. (2019) and NGSS (2013) educational benchmarks. Table 5 illustrates each of the core dimensions of the 4DEE with a total of 6/21 (28.5%) elements within that Framework (Klemow et al. 2019) of text excerpts from the poster that we deemed appropriate and sufficient of benchmarks of the 4DEE learning criteria.

To look deeper at alignment with the NGSS (2013) three dimensions, we analyzed each of the seven lessons from the MAREN curricula. All lessons included alignment with the NGSS (2013) dimensions of science and engineering practices, disciplinary core ideas, and crosscutting concepts. Every lesson included at least two elements for each dimension. Table 6 features an overview of alignment of the seven lessons with NGSS standards.

Table 6. Overview of milkweed local adaption lessons, 5E learning model stage and alignment with NGSS middle school standards (NGSS 2013).

Title of lesson	Overview of lesson; Stage of 5E learning model	Embedded NGSS standards
Monarchs and Their Decline	Introduces students to the recent population decline of monarch butterflies with interpretation of graphs depicting decline. Explain	SEPs: asking questions and defining problems; analyzing and interpreting data DCI: LS2.A: interdependent relationships in ecosystems CC: patterns; scale, proportion, and quantity; stability and change
Monarch Population Decline Debate	Students debate the most likely cause of the decline and compare arguments from experts in the field using primary literature. Elaborate	SEPs: engaging in argument from evidence DCI: LS2.C: ecosystem dynamics, functioning, and resilience CC: patterns; cause and effect; stability and change
Milkweed: A Critical Food Source for Monarchs	Students will engage in a discussion of milkweed and its native range. Explore	SEPs: asking questions and defining problems DCI: LS1.B: growth and development of organisms; LS2.C: ESS3.D: global climate change CC: cause and effect
Local Adaptation of Milkweed: Evolutionary Principles	Students will learn basic evolutionary principles within the concept of local adaptation and apply them to MLA. Explain	SEPs: obtaining, evaluating, and communicating information DCI: LS2.A: interdependent relationships in ecosystems; LS3.A: inheritance of traits; LS3.B: variation of traits; LS4.B: natural selection; LS4.C: adaptation
Local Adaptation of Milkweed: Data Analysis	Students complete entry, representation, analysis, and interpretation of data and submit these data to CDE research project. Explain	SEPs: developing and using models; analyzing and interpreting data; using mathematics and computational thinking DCI: LS2.A: interdependent relationships in ecosystems; LS4.B: natural selection; LS4.C: adaptation CC: patterns; scale, proportion, and quantity
Citizen Science: Monarchs and Milkweed Awareness	Introduces students to their culminating task: a citizen science project bringing awareness of the monarch and common milkweed decline to their community. Evaluate	SEPs: developing and using models; analyzing and interpreting data; DCI: LS2.A: interdependent relationships in ecosystems; LS2.C: ecosystem dynamics, functioning, and resilience CC: patterns; scale, proportion, and quantity
Picking Plants for the 'Monarch Highway'	Students will process how a plants origin and current location can affect its phenology. Evaluate	SEPs: engaging in argument from evidence; obtaining, evaluating, and communicating information DCI: LS2.A: interdependent relationships in ecosystems; LS4.B: natural selection; LS4.C: adaptation CC: patterns; scale, proportion, and quantity

CC, NGSS Crosscutting Concepts; DCI, NGSS Disciplinary Core Ideas; LS, Life science; SEPs, NGSS Science & Engineering Practices.

Discussion

Findings from this study reveal important educational outcomes for the field of CDEs that offer opportunities for higher education faculty and their students to be part of ongoing and authentic research, have unexpected challenges, and can be vehicles to inspire undergraduate students to develop independent research projects or curricular modules that can be used in formal classrooms, outcomes that serve to answer our research question.

Offer opportunities for higher education faculty and their students to be part of ongoing and authentic research

The project included rigorous protocols to ensure a quality database of results that was adjudicated by faculty (Jensen-Ryan et al. 2020). Adhering to the project protocol gave faculty a specific structure to teach science skills associated with the nature of doing science and research (Linn et al. 2015), including identifying variables, collecting, and analyzing data, linking evidence to conclusions, and exploring alternative hypotheses, skills reported in the literature that are difficult for undergraduates (Eshach and Kukliansky 2016). Because there was a "low bar" to enter, this distributed and replicated project was a pragmatic way to engage students at undergraduate institutions in research, a finding that adds to the benefits of early career faculty (Pastor et al. 2020) and graduate student involvement in CDEs (Wilkins et al. 2020).

Distributed replicated projects like this one allow faculty who are not at an R1 institution to engage in authentic scientific research, to meet institutional research goals and offer faculty opportunities to teach and mentor undergraduate students while they develop research projects. Faculty often experience time-related conflicts between teaching and research (Wynn et al. 2018) that may be mitigated by combining research and teaching by engaging undergraduates in research (Rosenkrantz 2013, Jensen-Ryan et al. 2020), one of the goals of this project.

Unexpected challenges

Our analysis illustrates several challenges of this CDE project. Plot selection for some faculty was a challenge where many felt they had to jump through hoops with administrators and ground's crews. Sites were often located in less desired areas on campus that left plants prone to flooding or growing in poor soil. Due to the hurdles experienced by our participants, such as grounds crews unintentionally mowing plots or heavy trucks snow plowing and dumping loads of snow through them in the wintertime, the faculty did not have much control over the plots. These challenges underscore the decline in both number of participating institutions and stem counts reported in Figs. 2 and 3. Although herbivory was reported by participants, the literature documents the co-evolution between common milkweed and insect herbivory (Agrawal 2005). Therefore, insect herbivory is not necessarily a negative factor when considering the growth of common milkweed.

Common milkweed is considered an "easy" to grow plant with evidence of its volunteer nature as a troublesome weed well documented in the literature (Hartzler and Buhler 2000). However, the process from seed germination to transplant can still be challenging, especially for novices. The unexpected challenges and disturbances encountered meant that this project was often more time-consuming than faculty members had anticipated. Given that common milkweed typical establishes deep roots in the first year, heavy foliage in the second and flowers in the third year, the challenges and disturbances of the plot sites may have impacted the 3-year milkweed growth cycle, the time frame for this project.

Higher education institutions can place enormous demands on faculty members' time (Hebert 2018). Only a select number of our participant institutions participated in every season from fall 2018 to fall 2020. Our data illustrate a lack of participation in the summer seasons, as data collection during the summer was optional. Other reasons could include inaccessibility to plots, minimal to no research student help or lack of time. In addition, the COVID-19 pandemic could have played a role in decreased institutional involvement and lack of undergraduate research assistants, especially in 2020, the last year of the study.

CDE may inspire undergraduate students under the tutelage of faculty to develop independent research projects or curricular modules that can be used in formal classrooms

Our findings reveal that undergraduate participants in this study produced independent research projects centered on data collected at the institution or educational curricula. One of the challenges in undergraduate research experiences is documenting improvement within the next generation of scientists because data are often self-reported by students, fragmented, and does not represent integrated learning with power (Linn et al. 2015). We argue that the MLA CDE provided structure to learn, and practice nuanced scientific skills and that that structure allowed students opportunities to branch out and produce independent research projects and other creative work, such as curricula for elementary and secondary classrooms that align with several of the benchmarks of the Klemow et al. (2019; Table 5) and NGSS (2013; Table 6), findings that address our research question. We assert that the research projects and curricula demonstrate application of and validation of scientific skills learned by undergraduates that go beyond self-reports used to document outcomes in undergraduate research experiences (Linn et al. 2015) and advance our understanding of possible learning benefits of undergraduate research with CDEs. Although undergraduate outcomes are described in recent papers (Colautti et al. 2014), those outcomes relate to assistance in generating scientific data from a project and do not mention ways that said project may have inspired undergraduate involvement to complete their own independent research projects or develop ancillary creative work, like curricula.

Our work goes beyond that of Jensen-Ryan et al. (2020), as some of the undergraduate students who were part of the MLA CDE endeavors were inspired by the project to develop independent research projects and educational initiatives that could be brought into formal K12 classrooms, extending broader implications of the original project. Undergraduate students often have many experiences with data collection and interpretation; however, that communication and presentations of results is often neglected (Linn et al. 2015). In our study, many students were inspired by the CDE to complete independent research projects that they presented at symposia or conferences that demonstrate their capability to navigate the higher sense making skills of the nature of science (Koomen et al. 2021*a*,*b*) and the NGSS (2013) and validate these skills (Linn et al. 2015). Additionally, several students (Billie, Octavia, Kala) translated components of the CDE into secondary (middle and high school) curricula, aligned with national standards (NGSS 2013), another validation of duration of learning and understanding.

Conclusion and implications

Despite promising results from this study regarding the opportunities afforded both higher education faculty and their undergraduate students with a CDE, there are some limitations of our work. First, our faculty participant group was small (10). Our undergraduate student participants group was small (8), too. Faculty may have been biased in inviting only student participants who successfully completed creative projects. Future CDE studies will benefit from larger numbers of faculty and undergraduate participants. Many of our higher education faculty had lost contact information with their former undergraduates after graduation. We encourage faculty mentors to solicit contact information from their undergraduate researchers and to store said information, systematically, in institution archives where privacy and confidentiality are assured.

Broader ecological educational implications of our outcomes in using CDEs for higher education faculty and their undergraduate students include: (1) mitigating challenges with more comprehensive model studies to try to estimate the sample size and redundancy likely to produce robust data; (2) recommendation to faculty members involved in CDEs to proactively inform participants about potential challenges and provide them with guidance on how to mitigate said challenges; (3) encourage the use of educational network to understand institutional use of the CDE project with undergraduates; and (4) the benefit that CDEs might offer educators with alignment with the Klemow et al. (2019) and NGSS benchmarks (2013).

Proactively acknowledging that there may be unforeseen challenges of a plant-based distributed CDE ought to be part of startup materials and workshops. We did pilot studies, including 2 years at one of the co-principal investigator's institutions and one distributed pilot study prior to starting the full MLA study. With a 3-year experimental commitment, that was not enough, especially with factors like chance (herbivory and snow plowing) for ecological field studies. We built in some redundancy in case of loss, but not enough. In retrospect, the project would have benefited from a deeper review of comparable studies in the literature, applying what we learned in the pilot studies to run some models to try to estimate the sample size and redundancy that would be likely to produce more robust data and included some contingency plans.

Additionally, our project participants may have experienced greater success if we outlined some of the challenges, they might face with a plant-based field experiment that involve seed germination, transplant, critters eating plants, or problems on site. Proactive measures that offered insight to participants as they were setting up might have created greater success in stem retention, especially when thinking about developing their plots and the need to coordinate with campus facilities, administration, etc.

This project relied on the EREN network for recruiting efforts where institutions reported their data into the MLA database and the PI team responded to challenges and questions of participating faculty as needed. We did not disseminate or share together the ways that we used the project within our courses and teaching, how we engaged our undergraduate students in the project or how the project inspired undergraduates to develop and create their own work. We advocate for using a network like EREN to disseminate project applications to increase synergy and further outcomes of projects like this one.

Finally, our results also illustrate alignment with both benchmarks from the Klemow et al. (2019) and NGSS (Table 6) with CDEs. Our 4DEE rubric (Table 5) found appropriate and sufficient alignment of evidence in learning for some of the 4DEE benchmarks in undergraduate student projects. The terms appropriate and sufficient are well established in the literature (McNeill and Krajcik 2012) as evaluative phrases of student learning. Thus, our 4DEE rubric, with further enhancements into other ecological domains, is a promising assessment tool in ecological education.

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Conflict of interest

None of the authors have a conflict of interest with respect to the contents of this article.

Open research statement

In compliance with the Open Research statement of the Bulletin for Ecological Society of America all data (for Figs. 2 and 3) can be accessed at: https://doi.org/10.6084/m9.figshare.22102670.v1. Coordinated distributed experiments in higher education: A low barrier to entry and potential for student projects.xlsx.

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Supporting Information

Additional supporting information may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/bes2.2101/suppinfo

Appendix S1. CDE participants with Pseudonyms.

Appendix S2. MLA overview of data analysis (Lesson 5).

Appendix S3. Got Milkweed? Curriculum development for studying local adaptation in *Asclepias syriaca*, by Octavia and Emery.

Appendix S4. Geographic variation in milkweed tolerance against herbivory by Jasmine and Emery.

Appendix S5. Investigating local adaptation in milkweed: Expanding curriculum involving authentic science, by Billie and Emery, Biology & Education Departments.

Appendix S6. Abbreviated undergraduate research project figures: Preliminary results of a common garden experiment with *Asclepias syriaca* (common milkweed) by Jade, Havana & Kala, Department of Biological Sciences at State University.