FEATURE ARTICLE

Collaboration to Cultivate the Practices of Science: Local Ecological Research as a Gateway to Biodiversity Science

JEFFREY GRANT, PATRICK MURPHY, REBECCA S. BARAK, MARLENE HAHN, EMMA LEAVENS, ANDREW L. HIPP

Abstract

High school biology students are provided few classroom opportunities to learn natural history or to see themselves as scientists. This poses a risk to their gaining the basic knowledge needed to play a positive role in the biodiversity crisis. However, science-as-practice in the classroom introduces the opportunity to equip students with knowledge of the natural world while they cultivate the practices and mindsets of science. Collaborations between teachers and local researchers can support students in becoming the scientifically literate citizens society will need to address threats to our environment and biodiversity. In this article, we present a semester-long science-as-practice plant biodiversity unit we have developed as collaborating scientists and educators. The unit entails three components: (1) a strong, even-handed collaboration between teachers and researchers; (2) an open-ended, science-as-practice approach; and (3) a local biotic community, which serves as an empirical study system. The project melds student-guided research with targeted instruction and research mentorship. Through their work, students see themselves as scientists.

Key Words: *student research; experimental design; ecological restoration; botany; AP Biology; scientific process.*

○ Introduction

Humans are changing global ecosystems and eroding biodiversity (La Sorte et al., 2014; Loreau et al., 2022). It is remarkable that in the midst of this biodiversity crisis, standard high school biology classes provide students little training in botany and natural history (Kramer & Havens, 2015) and the important role that they can play in improving local biodiversity through ecological restoration and gardening at their own homes (Lin, Egerer, & Ossola, 2018; Narango, Tallamy, & Shropshire, 2020). In the experience of the AP Biology teachers writing this paper (JG, PM), many biology lessons also do not fully exercise the skills of inquiry, interpretation, and argumentation. These scientific skills, coupled with knowledge of the natural world, will be needed to address ecological challenges.

In an effort to foster curiosity and scientific inquiry about the natural world, four of us—JG and PM as teachers, AH and MH as researchers—formed a scientist–educator team in 2013. Our goal was to mentor students in the practices of plant biodiversity science. From the outset, our work followed what has been described as the Classroom-Research-Mentoring Framework (Cooper & Bolger, 2024). The AP biology teachers (JG, PM) joined a research lab group (AH, MH), where they gained training in specimen-based research and co-developed training materials for the classroom. The researchers (AH, MH) taught scientific practices in the classroom alongside the teachers and mentored students in data-gathering, analysis, and interpretation. All four co-mentored the students through a semester-long independent project.

This initial work focused on plant evolutionary and morphological diversity of a single group of plants—sedges, the genus *Carex*—using museum specimens. Our collaboration entailed two key components: (1) **even-handed collaboration between teachers and researchers**, in which responsibility for teaching and mentoring is shared; and (2) an **open-ended science-as-practice approach**, in which students design their own study and gather novel data to address their questions over the course of a semester-long independent study. Our first three years demonstrated that students could gather research-quality data and that participation in the semester-long unit increased their concept of themselves as scientists. However, students' understanding of plant biodiversity changed relatively little (Hahn et al., 2016).

> *If students don't understand why it is valuable to learn a concept, they are more apt to resist learning it.*

We sought to remedy this by adopting a third project component: (3) a **local biotic community**—the tallgrass prairie—in which to provide training in scientific practices centered on biodiversity science. This article introduces our collaboration between practicing scientists (RSB, MH, EL, AH) and AP Biology teachers (JG, PM). We have implemented the described project in 3 to 5 sections of AP Biology each

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fall semester since 2013 (totaling 65 to 120 students each year). While the approach we present here is situated in the tallgrass prairie, the components of our collaboration and our goals of enabling students to do natural science and increasing their understanding of the natural world are sufficiently flexible to fit many contexts.

○ The Three Components

(1) Collaboration

Our project starts with collaboration between scientists and teachers. From the beginning, we have emphasized that all partners be involved in the science, teaching, and mentorship. To facilitate this, the teachers (JG, PM) have each spent several weeks with the researchers, working on active research and co-developing teaching ideas and modules. The researchers in turn spend ample time in the classroom co-mentoring with the teachers. Teachers bring expertise in translating and contextualizing knowledge, mentoring students, and recognizing what students need to keep their work progressing. Scientists bring expertise in the practices of science—experimental design, data visualization and analysis, formulating hypotheses—and the local biotic community. The scientists are uniquely able to model enthusiasm for science and empower students by recognizing and treating the students as scientific peers, modeling the connection between practice and understanding (Manz, Lehrer, & Schauble, 2020). Our collaboration required about three to four weeks per year of the scientists' time to establish the collaboration; after the first two years, it has taken about 7 days during the fall semester and about 2 days during the summer for planning. But collaborations may require even less time: if a researcher is willing to spend a field trip working with students to understand a natural area and gather data in it, then a second to discuss students' independent research ideas with them, the collaborating teachers could potentially fill in the rest.

The collaboration does not end with the teachers and scientists. Students start each semester as learners, mentored in the processes of hypothesis generation, data-gathering, analysis, and presentation. Then, they join the teachers and the researchers as collaborators. The teachers and researchers help the students to ask and investigate questions of their own choosing and decide how they will build their studies. The researchers, teachers, and students jointly evaluate the scientific merits of their questions, while the teachers ensure that grades are assigned in keeping with curriculum standards.

(2) Open-Ended Science-as-Practice Approach

We first model and then mentor the students in four NGSS / NSTA Science and Engineering Practices (https://ngss.nsta.org/Practices-Full.aspx):

1. **Asking questions and defining problems.** Our project provides students numerous opportunities to ask precise questions that are testable with their data. We emphasize that good questions move a research program—even a single study—from one stage to the next. Our goal is for students to identify and recognize interesting questions that can be addressed with their data.
2. **Planning and carrying out investigations.** Beginning in a local experimental prairie restoration, we introduce key elements of experimental design, then revisit these repeatedly as students map out their experiments. Our goal is for students to understand the tight connection between hypotheses, experimental design, and data.
3. **Analyzing and interpreting data.** We introduce the practices and tools of data visualization and quantitative reasoning as ways of exploring the narratives embedded in data, and data analysis as a way of assessing the support for hypotheses. Our goal is for students to understand that different hypotheses imply different patterns in their data.
4. **Obtaining, evaluating, and communicating information.** Throughout the semester, we mentor students in contextualizing their research based on others' work. We probe why their question is important, what they did, what they found and expected to find, and what their findings mean. At the end of the semester, they present their work. Our goal is for students to understand that science is a cyclical process that thrives on evolving dialogue. Presenting work is a vehicle to opening the next conversation.

Within these practices, we provide students with ample opportunities to work with real plants, make observations, and grapple with questions about how their actions and their research can improve the human and non-human world. By engaging in these practices with students, they learn these skills as practices rather than lessons.

(3) Local Biotic Community

Tallgrass prairie is one of the most endangered ecosystems in North America: less than 0.01% of the original tallgrass prairie remains intact in Illinois (Iverson, 1988). Yet tallgrass prairie supports high diversity at both landscape and local scales, where average plant species' richness may exceed 17 species in a single 0.25 m^2 plot (Bowles & Jones, 2004). It is also one of our dominant local ecosystems.

In the first two years of our prairie work with students, students collected data in a prairie remnant that is embedded in their neighborhood. In 2017, we shifted our work to a prairie restoration experiment that we (EL, RB, AH) helped design, install, and maintain. The prairie provides many roads to student research and is grounded in our own research, but the empirical system for this work could be a garden plot, a forest preserve, or a weedy field. The key elements are that it be accessible and amenable to study.

○ Lesson Details

Note: Supplemental Materials are available with the online version of this article.

Our semester-long unit involves six or seven face-to-face meetings between the scientists and the students in the field, classroom, and lab. This semester project has been run with up to five sections of twenty eight students for each of the last ten years. The class periods for lectures and labs have ranged from 50 to 80 minutes, as our school has shifted from standard periods to block periods. Logistically, we have found it easy to scale up to five classes (all meeting on the same day) because the prep for each class is the same. The semester is composed of empirical study in the field and lab (Activities 1, 3), experimental design and data analysis (Activities 2, 4), execution of an independent project (5), and presentation of results (6) (Timeline: Supplement 1). In this way, the semester mirrors essentially all aspects of a full scientific study, from literature review to publication.

For each activity below, we identify learning objectives addressed by the activity and timing required for our implementation. For some activities, we suggest potential variants that may help in generalizing the activity to contexts and study systems other than our own. Our goal in outlining this work is not to replicate what we do in other places: it is to share what we have learned through this project about making science concrete and local, in the hopes that others can implement projects that work well in their own local contexts.

Activity 1: Introducing Prairies & Ecological Experimentation

The semester begins with a late August visit to our field experiment at The Morton Arboretum, which is designed to test how plant diversity affects ecological restoration outcomes (Hipp et al., 2018). Students read a handout (Supplement 2) before they arrive that introduces the experiment and gives them a structure for their data collecting. While the experiment connects closely to our shared interests, values, and current research, the scientific benefit to the students could be achieved with a visit to essentially any field or garden experiment, or even a forest plot where the students gather data. The goals of this activity are to introduce students to a local biotic community, get them thinking about questions regarding local ecology, and illustrate how experiments are designed to address specific questions.

In most years, students measure plant height as a proxy for productivity. We ensure that students work in groups and train them in collecting data. As they are collecting, the teachers, several research interns, and the researchers circulate among the student groups, checking in, asking questions, and ensuring that data are collected accurately. As students complete their work gradually and at different times, we encourage them to take the extra time to make auxiliary observations, take photos of the experimental prairie, or ask questions about the experiment. Many of their post-data-collection observations inform questions they choose to investigate in their independent work.

Learning objectives: (1) understand the study system and its history, (2) examine experimental design in the field, and (3) learn to gather data. **Potential variants:** collect data on plant diversity in a nearby old field, wood lot, or garden, and focus experimental design discussion on how to sample vegetation; or work with local researchers to identify an ecological or agricultural experiment in which data could be gathered safely, and build in time to learn how that experiment is laid out to address the questions. **Time / place:** ½-day field trip; in our project, all students arrive together in 1–2 school buses, and the researchers bring together interns to help support interpretation and data collection.

Activity 2: Data Analysis & Connections

Prior to the second activity, students enter their data into a shared spreadsheet (we use Google Sheets, but any other shared data platform would work; Supplement 3). Once data are entered, they are shared with the scientists and students. The scientists graph the data, as do the students. As our experiment has plots that are paired in two different experimental blocks, one on the east half and one on the west half of the experiment, we pose a simple question: are plants taller in the east or the west block? We encourage the students to represent the data however they like at this point, with the goal being to clearly visualize the answer to just the one question. It also primes them for a discussion about how data representation mirrors the questions we are asking.

In class, a few groups share their representation, then one of the collaborating researchers walks through how they chose to visualize the data. To ease with interpretation, we emphasize two basic types of quantities that underlie almost all hypotheses the students propose and the statistical methods needed to assess those hypotheses: differences among groups of individuals and correlations between different measurements. We introduce and demonstrate three sets of statistical tools: Student's *t*-test and ANOVA to test for differences, with boxplots and histograms to visualize differences; Pearson's product moment to test for correlation, with scatter plots to visualize correlation; and confidence intervals and *p*-values as ways of assessing the biological and statistical significance of results. We provide worked examples after the students have worked through the data themselves, including an explanation of the statistical approaches and code that students can use to graph data themselves if they are inclined to move beyond spreadsheets (Supplement 4). The particular statistical level and approaches needed will differ from lab group to lab group depending on their independent project, so this lecture simply introduces possible ways of approaching data. As students need to implement these or other statistics in their research, they work in small groups with their teachers to do so, in consultation with the scientists as needed. **Learning objectives:** (1) gain experience manipulating and analyzing tabular data; (2) appreciate the increased accuracy and precision that comes from sharing data, and the responsibility of all participants to generate data that all can use with trust; and (3) understand that different questions and data types demand different kinds of statistics and data visualizations. **Potential variants:** It is not important that students master statistical methods for this project, but that they understand that data visualizations and statistics (like the examples provided in Supplement 4) help make interpreting data easier. They connect patterns in the data to the hypotheses we want to test. **Time:** one class period

Activity 3: Quantifying Diversity & Function

In this activity students quantify seed morphology and diversity and learn about the biology of seed germination (Supplement 5). We purchase seeds of 35 different native prairie species. Each lab group is given seeds of three or four species to measure and grow in the classroom. For each seed, students record mass, shape, and time from planting to germination. We ask students to suggest hypotheses about how differences among seeds of different species might influence dispersal, competitive ability, or germination. We use this opportunity to guide students in dialogue about what questions their data are well suited to address, either with or without additional data collecting. Lab groups from all sections of AP Biology share their data using Google Drive. These shared data can be used as raw data for testing hypotheses or to help students identify species for further experiments. **Learning objectives:** (1) understand that biologically significant traits vary within and among species, and (2) reinforce the power of and responsibilities demanded by group science. **Time:** two class periods

Activity 4: Designing an Experiment

In a classroom visit, the scientists provide a more detailed introduction to the experiment that the students visited and collected data from in Activity 1. Through a presentation (Supplement 6) and subsequent discussion, we reinforce the data analysis principles presented in Activity 2 and experimental design elements introduced in Activities 1 and 2 (replication, randomization, blocking). We follow this with a whiteboard discussion of experimental design, illustrating how experiments are designed to address hypotheses. **Learning objectives:** bring together students' understanding of the connections between hypotheses, experimental design, and data analysis, so that they have all elements in mind as they design their independent projects. **Time:** one class period plus homework time to plan experiments

Activity 5: Executing a Small-Team Independent Project

The core activity of the semester is for student lab groups to design their own observational or experimental study. While their studies are too small to generate publications, students address questions that in many cases are at the boundaries of scientific understanding: students have, for example, asked how evolutionary history affects competitive interactions between species and how community diversity affects growth rates. Other questions are strongly applied: some student projects have included studies of road salt or topsoil quality effects on plants and several have addressed propagation questions that would be of direct relevance to establishing a small prairie. While their studies are all related in some way to the empirical system—tallgrass prairie and its plants—students are encouraged to follow their passion and find interesting questions. The activity has several key components:

- **Selecting a question and relating it to gatherable data.** We work with students at this stage to identify questions that are interesting to them, relevant to the system they are studying, and addressable with data that they can gather in the lab or field. Students fill out a checkpoint (Supplement 7) that articulates their questions, hypotheses, and experimental ideas. These are then reviewed in class with teachers and the collaborating scientists. During this time, we engage the students in dialogue about what data they need to test their ideas and how the questions relate to the biology of the system.
- **Planning.** Once they have a question and a general setup in mind, students plan their experiments and review their plans with both their teachers and the collaborating scientists. They prepare for a review of their plan with a second checkpoint (Supplement 8). At this stage, we reinforce elements of experimental design (blocking, randomizing, replication) as needed and work closely with the students to ensure that the project they are planning is feasible and that the data have a potential to address their question.
- **Setup and execution of study.** Students have class time, space, and materials needed to set up a wide range of tiny greenhouse experiments within our classroom (in flats, under fluorescent lights), as well as a range of seeds to choose from. This section of the work is mostly conducted independently, with support during check-ins with the teachers.
- **Midcourse reviews.** Soon after setup, then again two weeks to a month later, the students meet with the collaborating scientists to review their progress and make mid-course corrections. It is not unusual to reset some experiments in the first check-in or to adjust things even at the second. The check-ins are designed to help students optimize their project within the constraints of space, resources, and time.

Learning Objectives: (1) integrate what students have learned about experimental design, data collection, data analysis, and graphical representation of data; (2) gain mentorship from their teachers and collaborating scientists at nearly every step of the project. **Time:** 5-6 class periods, homework time, and 5–10 minutes per class period to check experiment progress

Activity 6: Interpreting and Communicating Outcomes

The capstone event for the semester is a poster presentation, in which the students present their project to the scientists, their teachers, and outside teachers and administrators. The setup is like a poster session at a conference or science fair. Students structure their poster much like a scientific paper, with introduction, methods, results, and discussion or conclusions. They are evaluated based on a clear rubric (Supplement 9) on the quality of their poster, their explanation of their project, and a peer evaluation (Supplement 10). For the research itself, students are evaluated on connection of their work to past research, execution of the experiment, and interpretation of their results.

The poster day is a highlight of the semester. Teachers, secretaries, and administrators from across the school help evaluate student presentations over the course of each class period. Evaluators move around between lab stations—each set up with a poster—listen to project discussions, and ask questions. Presentations are limited to seven to ten minutes with two to three minutes for questions and answers. Scores from volunteer evaluators (Supplement 11) are averaged for a final grade for the group on one day and peer evaluations are completed the next day.

Learning objectives: (1) gain experience presenting, discussing, defending, and admitting the limitations of their work; (2) engage in scientific dialogue, with researchers who have a strong interest in similar questions; (3) get a taste for the scientific life. **Time:** one to two class periods to prepare poster; one period for presentations

○ Conclusion: After the Semester Is Done

The heart of our project is what makes it most valuable to all participants, ourselves included: we enter into a collaboration with the students. As researchers and teachers, we are surprised and delighted at what students come up with each semester. Most students in our AP Biology classes are seniors, yet few of them have been involved in scientific research. Most have never designed their own experiments. Almost all are accustomed to knowing the right answer most of the time. Independent research can be frustrating for them, as they find that there is no script or standardized lab manual for real science. They learn through this work to trust themselves in formulating interesting hypotheses, designing experiments, and interpreting and communicating their results. They learn through direct experience that no one, not even the researchers, knows what the outcome of a real experiment will be. Together, the researchers and teachers invite the students into the scientific community through teaching, mentorship, and encouragement.

The process we present here could be adapted to many local ecosystems. We consider knowledge of local ecosystems paired with scientific skills invaluable in helping students to make a positive impact on biodiversity. Moreover, using the context of their own natural habitat provides a bridge to biological concepts that show up elsewhere in the biology semester. For example, many students get lost in the vocabulary of cellular energetics. Tying dynamics at the level of plant cells back to growth and competition in the tallgrass prairie community has helped students see how biological processes cut across scales of biological organization. Photorespiration makes sense to our students in a new way when we are able to point to the plants they are growing in the classroom and also look at those growing outside their school and homes. If students don't understand why it is valuable to learn a concept, they are more apt to resist learning it.

We encourage teachers interested in this approach to seek out research collaborators. Consider local universities, community colleges, forest preserves, industry, extension offices, and nonprofit research institutes. It may take a while to find someone you can work with, but the benefits of long-term collaboration are great. Every year, we change how we teach, learning from one another as teachers and researchers and honing our ability to engage in productive science dialogue with the students (Enderle et al., 2023). The benefits accrue year after year: whatever career path they choose going forward from our class, students come away having practiced being scientists all semester (Figure 2). Students gain competence supporting statements with evidence and learn that it is okay not to find the answer they expected to find. They learn what it means to conduct research on an untamed system. In the process, they gain habits of open-ended inquiry and critical thinking that will continue to grow into life-long skills even after they leave the classroom.

NGSS - HS - LS2-6

Disciplinary Core Ideas: (LS2.A, LS2.B, LS2.C, LS2.D, LS4.D, ETS1.B)

Cross cutting concepts (cause and effect, stability and change, systems and system models)

Science and engineering practices: (Asking questions, Engage in argument through evidence, Obtaining evaluating and communicating information, Constructing explanations, Analyzing and interpreting data, Planning and carrying out investigations)

Figure 1. NGSS connections.

In addition to the primary goals of the project, we consistently see three auxiliary outcomes of our collaboration:

- **Caring for the land.** In the spring of 2020, the high school planted a small experimental prairie on nearby municipal land (with the help of a grant from the Illinois Department of Natural Resources). This provides students a home for the plants they grow in class and a sense of care for the land. Almost all the students love to take care of their plants, and many help tend the school prairie.
- **Practical experience.** We receive twenty or more emails a year from undergraduate students who took AP Biology with this semester-long research project as part of their curriculum. The students continually express thanks for their experience, which sets them apart from their peers both for opportunities to work in various labs and their own college course work. "I know how to set up my own experiments and conduct data analysis way better than any of my friends." "I got a job working in the lab over the summer because of the experience I had with the prairie project!"
- **Enthusiasm for the natural world.** In the year-end AP Biology course survey, many students call out the first semester research project. "I really enjoyed working with Dr. Hipp and being able to grow our own plants." "I notice prairie plants so much more around the neighborhood because of this class." "I really enjoyed the field trip to the Morton Arboretum and venturing through the prairies in our neighborhood."

Figure 2. Auxiliary outcomes.

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JEFFREY GRANT (jgrant@csd99.org) and PATRICK MURPHY (pmurphy@csd99.org) are both educators at Downers Grove North High School in Downers Grove, Illinois. REBECCA S. BARAK (rbarak@chicagobotanic.org) is a conservation scientist at Chicago Botanic Garden in Glencoe, Illinois. MARLENE HAHN (mhahn@mortonarb.org) is a plant systematics program manager, EMMA LEAVENS (eleavens@mortonarb.org) is a research coordinator, and ANDREW L. HIPP (ahipp@mortonarb.org) is a senior research scientist at The Morton Arboretum in Lisle, Illinois.