TIEE

Teaching Issues and Experiments in Ecology - Volume 22, February 2026

EXPERIMENTS

Invasive plants and their relationship to ecosystem properties: a multi-week authentic research project

Jennifer E. Slate[1] and Pamela Geddes[2]

[1]Department of Biology, Northeastern Illinois University (NEIU), 5500 N. Saint Louis Avenue, Chicago, Illinois 60625

[2]Department of Biology and Environmental Sciences Program, Northeastern Illinois University (NEIU), 5500 N. Saint Louis Avenue, Chicago, Illinois 60625

Corresponding author: Jennifer E. Slate (j-slate@neiu.edu)

Photos taken by General Ecology students at Northeastern Illinois University in early November show the impact of *Rhamnus cathartica* (buckthorn) upon a forested ecosystem. **A.** Buckthorn develops its leaves relatively early in spring and loses its leaves late in the fall. Its dense canopy reduces light reaching the forest floor. **B.** Where buckthorn is absent, the forest floor is open to light and there is a diversity of herbaceous plants.

TIEE

Teaching Issues and Experiments in Ecology - Volume 22, February 2026

ABSTRACT

Students conduct a multi-week field and lab-based research project, over six class periods, to examine ecosystem properties that may be impacted by an invasive plant or promote its spread. We focus on *Rhamnus cathartica* (buckthorn), common in forests of the Upper Midwest, but any plant invader can be chosen and the activity adapted accordingly. Students measure a variety of ecosystem properties, including soil chemistry and biodiversity, at sites with and without the plant invader. They work in teams to develop a research question, collect samples, analyze data, and present results to the class. Each student also conducts a literature search, keeps a field and lab notebook, and writes a paper in scientific format that is revised after peer review. In addition to learning about the ecology of invasive species, students increase their analytical, written, and oral communication skills.

FOUR-DIMENSIONAL ECOLOGY EDUCATION (4DEE) FRAMEWORK

- **Core Ecological Concepts:**
    - Communities
    - Ecosystems

- **Ecology Practices:**
    - Fieldwork
    - Data analysis & interpretation
    - Communicating and applying ecology

- **Human-Environment Interactions:**
    - Human interdependence with the environment

- **Cross-cutting Themes:**
    - Pathways & transformations of matter and energy
    - Systems

INTEGRATION ACROSS 4DEE DIMENSIONS

All dimensions are integrated in this field study. Students investigate how an invasive plant alters forest ecosystems by measuring soil characteristics and biodiversity across sites with varying invasion intensity. Working in small groups, they develop research questions, collect and analyze field and laboratory data, and interpret statistical results to identify ecological patterns. By measuring variables related to nutrient cycling and decomposition, students examine interactions between biotic and abiotic ecosystem components. They communicate results through scientific writing and conference-style oral presentations, connect their findings to the primary literature, and consider implications for local management and restoration efforts.

CLASS TIME

The activity is conducted during six class periods of 2-2.5 hours (total of 12-15 hours). Students work in small groups to 1) develop a research question, 2) collect samples in the field, 3) analyze samples in the lab, 4) interpret data and conduct statistics, 5) give an oral presentation of results, and 6) conduct peer review of classmates' written papers. Instructors can focus on specific parts of this activity (e.g., 1 through 3 only) to make the activity shorter and smaller in scope.

OUTSIDE OF CLASS TIME

About 15 hours outside of class are needed to complete assignments. These tasks include reading and interpreting the primary literature, conducting data analysis, preparing an oral presentation, and writing a paper in standard scientific format (Abstract, Introduction, Methods, Results, Discussion, Acknowledgments, and Literature Cited sections).

STUDENT PRODUCTS

Each of the six class periods has an associated assignment. We provide handouts for all assignments with goals, instructions, and expectations.

- Assignment #1: Primary literature. Students find and read a primary research paper related to their research question. They write answers to guided questions to learn about the type of information included in each section of a primary research paper.
- Assignment #2: Field notebook. As they collect samples and data in the field, students record their data and the procedures used. They also make ecosystem observations that will provide a basis for a study site description in the Methods section of their research paper.
- Assignment #3: Lab notebook. As they process and analyze samples in the lab, students record their data and the procedures used. They will draw upon the lab notebook, along with the field notebook, when they write the Methods and Results sections of their research paper.
- Assignment #4: Data analysis. Students create graphs and conduct statistics (e.g., standard error, t-tests, or other statistical analyses). They summarize the trends in the data and draft a Results section for their research paper.
- Assignment #5: Oral presentation. Students construct slides for an oral presentation and present their research projects to the class. The class period resembles a scientific conference, with a question-and-answer session after each presentation.
- Assignment #6: Research paper. Students write a paper in standard scientific format (Abstract, Introduction, Methods, Results, Discussion, Acknowledgments, and Literature Cited sections). After conducting peer review and receiving feedback from the instructor, they revise their papers.

TIEE

Teaching Issues and Experiments in Ecology - Volume 22, February 2026

SETTING

Field work is conducted at a site impacted by the plant invader and at a relatively unaffected site. Ideally, the sites are in close proximity. We have chosen a local nature preserve that is in the process of removing a common invader in our area, *Rhamnus cathartica* (hereafter buckthorn), but that still contains affected areas. Students identify the invasive plant through leaf or twig morphology, depending upon the season. Soil and leaf litter samples are collected at both sites and brought back to the lab for processing and analysis.

COURSE CONTEXT

We conduct this research activity with a 300-level General Ecology course with lecture and laboratory. Students are encouraged to take it as early as possible in the biology major, and it fulfills a writing-intensive course requirement. Students learn to keep a field and lab notebook, create graphs, make presentation slides, and write a research paper. The maximum class size is 24.

INSTITUTION

Northeastern Illinois University is an urban, public and federally designated Hispanic Serving Institution. Our student body of about 5,800 is primarily undergraduate and many attend part time. Although we are a 4-year university, many of our students transfer from community colleges and about 40% are the first in their families to attend college.

TRANSFERABILITY

Because invasive plant species are common in all regions, instructors can easily adapt this activity for any invasive plant species, in any ecosystem. Although our students study a common invasive, terrestrial plant in the Upper Midwest (buckthorn), the activity can be tailored to any area with problematic plant invaders, including aquatic ecosystems. We provide protocols for measuring a variety of biotic and abiotic variables, which instructors can choose from as appropriate for local ecosystems and as resources and time allow. Instructors may also include some or all of the assignments we created. We designed the activity for biology majors, but invasive species are of wide interest and expectations for student work can be adjusted for non-majors and for high schoolers. Many parks, nature preserves, and other natural areas open to the public have invasive plant species and are accessible to those with disabilities.

ACKNOWLEDGEMENTS

We thank Robert Porter, Liza Fischel, and the Chicago Park District for access to sampling sites at the North Park Village Nature Center in Chicago, Illinois. We greatly appreciate Jim Steffen at the Chicago Botanic Garden for providing inspiration for this activity and for helping us brainstorm about variables that students could test. The Biology Department at Northeastern Illinois University and its staff, Kip Conwell, Jennifer Sevilla, and Sara Crow, gave invaluable help by procuring all necessary supplies and equipment. Finally, we thank the many students in our General Ecology classes who participated in this activity over the years and gave feedback.

SYNOPSIS OF THE EXPERIMENT

Principal Ecological Question Addressed
What ecosystem properties are impacted by an invasive plant or promote its spread?

What Happens
Students are introduced to invasive species, their ecological consequences, and the ecosystem properties that promote their spread. Small groups work together to develop a research question, conduct fieldwork, process samples in the lab, statistically analyze data, and give an oral presentation of their results to the class. Finally, each student writes a report in the style of a primary research paper. After receiving feedback in a peer-review activity, students revise their drafts.

Experiment Objectives
A. Investigate the ecosystem properties that may be impacted by an invasive plant or promote its spread.
B. Explore the scientific process by developing a research question, collecting and analyzing data, interpreting results within a framework of the broader scientific literature, and conducting peer review.
C. Use instruments and methods common in ecological research, while keeping detailed and accurate notes in field and lab notebooks.
D. Communicate research findings in standard scientific format by writing a report in the style of a primary research paper and by giving an oral presentation as if at a scientific conference.

Equipment/ Logistics Required

Students may measure a variety of abiotic and biotic characteristics, such as soil properties, plant and invertebrate biodiversity, and microbial function. The class may be divided into small groups that each investigate a different variable, or an instructor may select a subset of variables for analysis by the entire class. We provide step-by-step methodologies for all protocols that include lists of necessary equipment and supplies, as well as suggestions to simplify or expand the protocols.

- **Soil moisture and organic matter:** Moisture and ash-free dry mass are determined by drying soil at 105 ^{o}C and then burning it in a muffle furnace at 550^{o} C. Soil color can also be assessed in the field with a Munsell Color Chart.
- **Nutrients:** Soil nutrients are extracted using a reagent to create a liquid nutrient solution that is analyzed by a spectrophotometer or a portable

colorimeter. If this equipment is not available, then inexpensive soil nutrient kits may be used.

- **pH:** After mixing with water, pH of soil is measured with a pH meter or estimated with pH paper.
- **Leaf litter:** Quantity of leaf litter is determined by collecting leaves within quadrats of a known area and measuring dry mass. Alternatively, students can count leaves in the field. If leaves are identified to species, then students can calculate richness (presence/absence of tree species) and Shannon Diversity Index.
- **Invertebrates:** Macroinvertebrates from soil or leaf litter are identified using a stereomicroscope or magnifying glass. Students can calculate taxa richness (presence/absence of taxa) and Shannon Diversity Index.
- **Microbes:** Microbial functional diversity is assessed using Biolog EcoPlates, which measure the utilization of different carbon substrates by microbes. Students can calculate simple metrics such as % functional diversity, % similarity, and % variation, or perform more complex community-level analyses such as nonmetric multidimensional scaling (NMDS).
- **Herbaceous vegetation and soil temperature:** Students count stems of herbaceous plants within quadrats and measure temperature with a soil thermometer. Dense canopies of invasive plants can reduce light reaching the forest floor, potentially reducing both herbaceous plant growth and soil temperature.

Summary of What is Due

Students search for and read the primary literature, write a report that places their results within the context of that literature, and communicate the results in an oral presentation. They also keep field and lab notebooks, graph their data, and conduct statistics. We provide handouts for each assignment, with goals, instructions, and expectations. Below, we link each assignment with the experiment objectives given above.

Assignment	Objectives assessed
#1. Primary literature	A. Investigate the ecosystem properties that may be impacted by an invasive plant or promote its spread. B (in part). Explore the scientific process by developing a research question.
#2. Field notebook	B (in part). Collect and analyze data.

	C (in part). Use instruments and methods common in ecological research, while keeping detailed and accurate notes in a field notebook.
#3. Lab notebook	B (in part). Collect and analyze data. C (in part). Use instruments and methods common in ecological research, while keeping detailed and accurate notes in a lab notebook.
#4. Data analysis	B (in part). Analyze data with statistical methods and interpret results within a framework of the broader scientific literature. D (in part). Communicate research findings in standard scientific format.
#5. Oral presentation	A. Investigate the ecosystem properties that may be impacted by an invasive plant or promote its spread. D (in part). Give an oral presentation as if at a scientific conference.
#6. Research paper	B (in part). Interpret results within a framework of the broader scientific literature and conduct peer review. D (in part). Communicate research findings in standard scientific format by writing a report in the style of a primary research paper.

DETAILED DESCRIPTION OF THE EXPERIMENT

Introduction

Modern transportation and globalization allow invasive species to spread at unprecedented rates. Invasive species are found outside of their native range due to intentional or unintentional introduction. For example, *Dreissena polymorpha* (zebra mussel) was transported inadvertently in ballast water of ships, but *Rhamnus cathartica* (buckthorn) was brought intentionally as an ornamental plant. To be classified as invasive, a species must cause harm to the environment, the economy, and/or human health (Mack et al. 2000).

Managing the impacts of invasive species is essential for sustaining human livelihoods and halting biodiversity loss (IUCN 2025). Invasive species disrupt the ecological processes that humans and native species rely on by altering species interactions and ecosystem functioning. For example, invasive species that fix nitrogen alter soil chemistry, invasions that displace native pollinators reduce agricultural yields, and highly flammable invasive grasses increase wildfire intensity in forests and shrublands (Charles and Dukes 2008).

Invasive species can become established due to their specific traits or to a lack of enemies (Mack et al. 2000). The enemy-release hypothesis predicts that a lack of predators, pathogens, or competitors in a new environment can allow an invader to thrive. Additionally, invasive species often have traits or attributes that encourage establishment, such as abilities to grow and spread quickly or to reproduce asexually. Adaptations such as flexible diets or resting stages can allow them to withstand a wide variety of environmental conditions. Some invasive plants have chemical defenses, producing allelopathic (toxic) substances that deter predators (Sedio et al. 2020) or inhibit growth of competing plants (Kalisz et al. 2021). Physical defenses, such as the spines on the tail spine of the invasive *Bythotrephes longimanus* (spiny water flea), deter predators (Miehls et al. 2013).

It is increasingly recognized that not all invasive species are exotic or non-native. Native species that spread uncontrollably within their ecosystem can also be characterized as invasive (Valéry et al. 2009). Human activities, such as fire suppression or habitat modification, can allow some native species to become dominant and exert economic and ecological impacts comparable to non-native invasive species (Carey et al. 2012). A well-known example is *Odocoileus virginianus* (white-tailed deer), which due to elimination of most natural predators has become a dominant herbivore. At high densities, deer impact biodiversity of native prairie plants and consequently nutrient cycling by selectively grazing on forb species (Pruszenski and Hernández 2020).

An example of a non-native plant invader is *Rhamnus cathartica* (common buckthorn), introduced to North America in the 1800s as an ornamental shrub. It has become widespread in Upper Midwestern forests and is easily recognized by the ends of its twigs, which have a short thorn that gives the plant its name (Mascaro and Schnitzer 2007). Buckthorn's ability to invade forests is tied to its extended phenology. It has a longer season for photosynthesis than most plants because it develops its leaves relatively early in the spring and loses its leaves in late autumn (Schuster et al. 2020). Its fruits have a laxative effect, increasing seed dispersal by birds. Once dispersed, often near roads (Kurtz and Hansen 2018), buckthorn grows quickly, can tolerate a range of light and water conditions, and is difficult to eradicate because it resprouts from cut stumps. Its germination increases in the presence of European earthworm species that are also invading the Upper Midwest (Roth et al. 2015).

Many ecological consequences of buckthorn invasion are documented (Knight et al. 2007). Buckthorn produces emodin, an allelochemical that inhibits the growth of other plants (Klionsky et al. 2011, Warren II et al. 2017). Invertebrates consume and help decompose buckthorn's nutrient-rich leaves relatively quickly, which may in turn modify nitrogen mineralization rates and soil pH (Heneghan et al. 2002, 2006, 2007). The soil microbial community also differs between sites invaded by buckthorn and sites without buckthorn (Heneghan et al. 2004). This extensive body of research provides an ideal framework to test the relationship between ecosystem characteristics and buckthorn invasion.

In this activity, you will compare ecosystem properties in areas that vary in density of an invasive plant. Variables that you may measure include abiotic factors (e.g., nutrient concentrations or pH) and biotic factors (e.g., biodiversity of other plants or invertebrates). Although we have focused on buckthorn, you may study another problematic invasive plant species in your region. Engaging with a real, local problem connects your learning and the university with the greater community. Many nature preserves, for example, have ongoing programs to eradicate invasive species. Collaboration with land managers on this project can provide the opportunity to contribute to conservation and restoration issues in your local area.

Materials and Methods

Study Site

Field work is conducted at sites invaded by buckthorn (or another chosen invasive plant species) that differ in the level of invasion. For example, a site with extensive invasion may be compared to a site with minimal invasion. Alternatively, a site with extensive invasion could be compared to a restored site in which the invader has been removed or to a control site that has not been invaded by the plant species.

Overview of Data Collection and Analysis Methods

Class period #1: Learn about invasive species and experimental design. Your instructor will introduce the problem of invasive species and discuss ecosystem characteristics that may be impacted by an invasive plant or promote its spread. You will develop a research question and determine which ecosystem variables to measure. The instructor will provide guidance as to equipment and/or logistic limitations. **Assignment #1** is to find and evaluate published research relevant to your research question.

Class period #2: Conduct fieldwork. You will travel to the field sites, each of which has different levels of invasion by the plant invader, to collect data and/or samples to bring back to the lab for analysis. **Assignment #2**, which is to describe the equipment and methods used at the field sites and to record ecological observations and data obtained, will be completed while conducting fieldwork.

Class period #3: Analyze samples in the lab. Following protocols provided by your instructor, you will analyze the samples that were collected in the field. A wide range of variables may be measured, such as soil characteristics (e.g., soil nutrients, pH, or organic content) or biodiversity (e.g., taxonomic diversity of invertebrates or functional diversity of microbes). While analyzing your samples, you will complete **Assignment #3**, which is to describe the methodology used in the lab and to record results in your lab notebook.

Class period #4: Interpret your data. The instructor will provide guidance on how to create graphs and calculate statistics. Depending upon your data, you may make bar graphs or scatterplots. Statistical tests can be descriptive (e.g., mean and standard deviation) and inferential (e.g., t-test, correlation, or regression). **Assignment #4** is to draft a Results section in the style of a primary research paper that includes graphs or tables, statistical analyses, and a written summary that describes the trends in your data.

Class period #5: Present results to the class in an oral presentation. With your group, you will prepare and give an oral presentation to explain your research project and its results. By listening to your classmates' presentations, you will also learn how your results relate to those obtained by others. The goal is to obtain a broad understanding of how the plant invader may impact or be related to multiple aspects of the ecosystem. **Assignment #5** provides a framework for creating presentation slides and expectations for giving an effective presentation.

Class period #6: Conduct peer review of classmates' research papers. Following guidelines provided by your instructor, you will comment on the drafts of classmates' research papers. The goal is to provide helpful feedback that will enable your classmates to improve their papers as they revise and rewrite. You will also benefit by receiving constructive criticism on your own paper. This exercise simulates the peer review process that occurs before a primary research paper is published. **Assignment #6** provides instructions for what is expected in your research paper and guidance on how to conduct an effective peer review.

Questions for Further Thought and Discussion:

1. What information can you find in the literature about the chronology or timeline of this invasive species' spread?
2. Why has this species been successful at invading? Are there particular characteristics of the species that make it a successful invader?
3. How does this invader affect humans (e.g., economic activity, recreation, or health)? Are any of these effects known in areas where you live?
4. Have any control strategies been tried, and if so has there been success? If control has not been attempted or if attempts have failed, what do you think could be good options for managing this invasive plant, and why?
5. What are some of the most important ecological effects of this invasion? Describe any known effects of this species on other species or on ecosystem properties.

6. Given the observational study you conducted, can you conclude that the invasive species is causing the changes in the ecosystem properties you measured? Could it be the other way around, with particular ecosystem properties promoting its spread?
7. Discuss the difference between causation and correlation. Could the abundance or biomass of the plant invader simply be correlated with your results because an unknown factor is influencing both? Design experiments to test for causation. For example, how could you determine if it is the invasive species that is causing the environment to change? Or, could you test if particular environmental conditions are driving the plant invader to grow and spread?

References

Boettcher, T. J., S. Gautam, and J. Cook. 2023. The impact of invasive buckthorn on ecosystem services and its potential for bioenergy production: a review. Journal of Sustainable Forestry 42: 218-240.

Carey, M. P., B. L. Sanderson, K. A. Barnas, and J. D. Olden. 2012. Native invaders – challenges for science, management, policy, and society. Frontiers in Ecology and the Environment 10: 373–381.

Charles, H. and J. S. Dukes. 2008. Impacts of invasive species on ecosystem services. In Nentwig, W. (ed.) Biological Invasions. Ecological Studies (Analysis and Synthesis), Vol. 193. Springer: Berlin.

Dolinski, L. F., T. L. Bal, C. R. Webster, and S. C. Resh. 2024. Assessing the utility of a native pathogenic fungus as a biocontrol alternative to herbicide on invasive buckthorns in forests of Upper Michigan. Natural Areas Journal 44: 57–64.

Heneghan, L., C. Clay, and C. Brundage. 2002. Rapid decomposition of buckthorn litter may change soil nutrient levels. Ecological Restoration 20: 108–111.

Heneghan, L., F. Fatemi, L. Umek, K. Grady, K. Fagen, and M. Workman. 2006. The invasive shrub European buckthorn (*Rhamnus cathartica*, L.) alters soil properties in Midwestern U.S. woodlands. Applied Soil Ecology 32: 142–148.

Heneghan, L., C. Rauschenberg, F. Fatemi, and M. Workman. 2004. European buckthorn (*Rhamnus cathartica*) and its effects on some ecosystem properties in an urban woodland. Ecological Restoration 22: 275–280.

Heneghan, L., J. Steffen, and K. Fagen. 2007. Interactions of an introduced shrub and introduced earthworms in an Illinois urban woodland: Impact on leaf litter decomposition. Pedobiologia 50: 543–551.

Hofmann, A. H. 2020. Scientific Writing and Communication, Fourth Edition. Oxford University Press: New York.

International Union for the Conservation of Nature (IUCN). 2025. Invasive alien species. Accessed 29 Oct 2025. https://iucn.org/our-work/topic/invasive-alien-species

Kalisz, S., S. N. Kivlin, and L. Bialic-Murphy. 2021. Allelopathy is pervasive in invasive plants. Biological Invasions 23: 367–371.

Klionsky, S. M., K. L. Amatangelo, and D. M. Waller. 2011. Above- and belowground impacts of European buckthorn (*Rhamnus cathartica*) on four native forbs. Restoration Ecology 19: 728–737.

Knight, K. S., J. S. Kurylo, A. G. Endress, J. R. Stewart, and P. B. Reich. 2007. Ecology and ecosystem impacts of common buckthorn (*Rhamnus cathartica*): a review. Biological Invasions 9: 925–937.

Kurtz, C. M. and M. H. Hansen. 2018. An assessment of common buckthorn in northern U.S. forests. Res. Note NRS-250. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. https://doi.org/10.2737/NRS-RN-250

Mack, R. N., D. Simberloff, W. M. Lonsdale, H. Evans, M. Clout, and F. Bazzaz. 2000. Biotic invasions: causes, epidemiology, global consequences, and control. Ecological Applications 10: 689–710.

Mascaro, J. and S. A. Schnitzer. 2007. *Rhamnus cathartica* L. (common buckthorn) as an ecosystem dominant in southern Wisconsin forests. Northeastern Naturalist 14: 387–402.

McMillan, V. E. 2017. Writing Papers in the Biological Sciences, Sixth Edition. Bedford/St. Martin's: Boston.

Miehls, A. L. J., A. G. McAdam, P. E. Bourdeau, and S. D. Peacor. 2013. Plastic response to a proxy cue of predation risk when direct cues are unreliable. Ecology 94: 2237–2248.

Pruszenski, J. M. and D. L. Hernández. 2020. White-tailed deer in tallgrass prairie: novel densities of a native herbivore in managed ecosystems. Natural Areas Journal 40: 101–110.

Roth, A. M., T. J. S. Whitfeld, A. G. Lodge, N. Eisenhauer, L. E. Frelich, and P. B. Reich. 2015. Invasive earthworms interact with abiotic conditions to influence the invasion of common buckthorn (*Rhamnus cathartica*). Oecologia 178: 219–230.

Schuster, M. J., P. D. Wragg, L. J. Williams, E. E. Butler, A. Stefanski, and P. B. Reich. 2020. Phenology matters: Extended spring and autumn canopy cover increases biotic resistance of forests to invasion by common buckthorn

(*Rhamnus cathartica*). Forest Ecology and Management 464, Article No. 118067 https://doi.org/10.1016/j.foreco.2020.118067.

Sedio, B. E., J. L. Devaney, J. Pullen, G. G. Parker, S. J. Wright, and J. D. Parker. 2020. Chemical novelty facilitates herbivore resistance and biological invasions in some introduced plant species. Ecology and Evolution 10: 8770–8792.

Valéry, L., F. Hervé, J.-C. Lefeuvre, and D. Simberloff. 2009. Invasive species can also be native. Trends in Ecology and Evolution 24: 585.

Warren II, R. J., A. Labatore, and M. Candeias. 2017. Allelopathic invasive tree (*Rhamnus cathartica*) alters native plant communities. Plant Ecology 218: 1233–1241.

Tools for Assessment of Student Learning Outcomes:
The assignments for this activity provide a framework for conducting authentic scientific research. In Assignment #1, you will conduct a literature search to discover prior research related to your project. You will also become familiar with the format of a scientific paper by analyzing the content in each of its sections. In Assignments #2 and #3, you will write field and lab notebook entries in which you describe the study sites, note the methodologies used to conduct the experiment, and record data. Assignment #4 guides you through the drafting of the Results section for your research paper, which will include graphical presentation of data, statistical analyses, and a written summary of trends shown by your data. In Assignment #5, you will present your research project to the class, in an oral presentation modeled after a scientific conference. Assignment #6 is to write a research paper in standard scientific format, with Abstract, Introduction, Results, Methods, Discussion, Acknowledgments, and Literature Cited sections. Before researchers can publish in a peer-reviewed journal, they must undergo a review process in which their paper is evaluated by experts in the same field. Similarly, you will revise the research paper that you write after receiving feedback and suggestions from classmates and your instructor.

NOTES TO FACULTY

Challenges to Anticipate and Solve
Selecting field sites: Field sites must vary in density or biomass of the invasive plant. We suggest contacting local park districts or nature preserves to learn of restoration efforts. Restored and unrestored areas (e.g., burned vs. unburned areas or chemically treated vs. non-treated areas) may be compared.

Obtaining permits: Collecting plant, invertebrate, or soil samples often requires permits from state or local governmental agencies, such as the Department of

Natural Resources or park districts. The permitting process may take weeks to months, so applications should be submitted as early as possible.

Group work: To encourage students to contribute fully during group work, they fill out a "colleague evaluation form" in which they rate themselves and each other on a scale of 1-10 with respect to cooperation and input on data collection, analysis, and presentation of results. For work completed as a group (e.g., preparation of presentation slides), everyone receives the same grade if all have pulled their own weight. We let students know from the beginning about the colleague evaluation form and make our expectations clear. Since much of the work is done during class, the instructor can also see how students are working together and intervene by talking with students individually about their contributions when needed. In our experience, the colleague evaluation form has been an effective motivator, and most students rate their groupmates highly.

Comments on Introducing the Experiment to Your Students:

We begin the discussion of invasive species by describing a well-known example (e.g., zebra mussels) and students learn that characteristics such as high fecundity or broad environmental tolerance can allow certain species to invade new environments. We then introduce buckthorn, an invasive plant of local concern. We present possible ecosystem variables that could promote its spread and discuss its potential abiotic and biotic effects. Students brainstorm together to develop research questions that they could investigate. Due to time and equipment limitations, not all of students' ideas are feasible. When necessary, we help students relate their interests to what is possible with the resources available. We explain that research is an iterative process in which exploring smaller, more focused questions is often a necessary and valuable first step.

Comments on the Data Collection and Analysis Methods:

Experimental design: Most students lack prior research experience and benefit from a discussion about experimental design. They should consider factors that may affect the ability to obtain accurate and precise measurements. For example, if they will measure soil nitrate, then they need to decide the depth at which to obtain the soil samples and determine how to consistently collect to that depth across sites.

Organism identification: We do this activity with students who have little to no experience with taxonomic identification and provide examples of simple keys in the experimental protocols. Students can quickly learn to identify invertebrates to order and leaves to genus. For students who want to go further, additional identification guides are available in the classroom. We also encourage students to make their own taxonomic categories based on morphological characteristics for organisms such as mites (e.g., round vs. flat body shape or long vs. short legs). This helps them develop observational skills and an eye for distinguishing features.

Level of statistical analyses: Depending upon the course level and available time, students may focus on descriptive statistics (e.g., mean, range, standard deviation, and standard error), simple inferential statistics (e.g., t-test, correlation, or regression), or more advanced statistics of the instructor's choice. Many of our students have little to no prior experience with statistical analysis, so we introduce the concept of a null hypothesis and explain how to interpret p-values.

Statistics and graphing platforms: The choice of software depends on both instructor and student familiarity. Excel and Google Sheets can perform many statistical tests (e.g., regression, t-test, and ANOVA) and generate graphs (e.g., scatterplot and bar graphs). We have also used R, but it is best if students have prior familiarity due to the learning curve. Regardless of the platform, we encourage students to be self-sufficient by searching for step-by-step tutorials online. We also ask them to critically evaluate all computer-generated output. For example, Excel's built-in "standard error" function will give incorrect error bars on a bar graph, so students should find a tutorial that shows how to customize a graph by manually entering the standard error values.

Drawing conclusions: We emphasize that original research may yield unexpected conclusions and that students should not become disappointed or assume error if a variable they measure is not significantly related to the invasive species. In addition, instructors can use Question 7 in Questions for Further Thought and Discussion to help students understand that a significant result may demonstrate correlation rather than causation.

Comments on Questions for Further Thought:

1. What information can you find in the literature about the chronology or timeline of this invasive species' spread?

• For Question 1, we encourage students to include not just primary literature but also grey literature in their search for information. For example, the USDA has research notes on buckthorn and other invasive species (e.g., Kurtz and Hansen 2018). Instructors may also steer students toward informative internet resources such as the National Phenology Network (https://www.usanpn.org/).

2. Why has this species been successful at invading? Are there particular characteristics of the species that make it a successful invader?

• Question 2 prompts students to think about specific characteristics (e.g., rapid development, high reproductive rate, clonal/asexual reproduction, production of allelochemicals, or broad environmental tolerance) that may make the species a successful invader. Buckthorn has many such characteristics, including seedling survival in bare soil, high photosynthetic rates, and suspected unpalatability to herbivores (Knight et al. 2007). These characteristics can give an ability to colonize disturbed environments, outcompete other plants, and avoid predation.

3. How does this invader affect humans (e.g., economic activity, recreation, or health)? Are any of these effects known in areas where you live?

• For Question 3, we encourage instructors to discuss the benefit of ecosystem services to human society and to explain how invasive species can alter and disrupt those services. Ecosystem services can be provisioning (e.g., food), regulating (e.g. erosion control), cultural (e.g. recreation), or supporting (e.g., nutrient cycling). Ecosystem services disrupted by buckthorn include carbon storage, soil retention, nutrient cycling, food and refugia for animals, and activities such as hiking or bird-watching (Boettcher et al. 2023).

4. Have any control strategies been tried, and if so has there been success? If control has not been attempted or if attempts have failed, what do you think could be good options for managing this invasive plant, and why?

• Question 4 allows students to research both attempted and potential control strategies. If control has not been attempted or has been unsuccessful, students can think about traits of the invasive plant that may be targeted, or research the native habitat of the invader to identify potential predators. For example, the pathogenic fungus *Chondrostereum purpureum* is being investigated as a biological control for buckthorn (Dolinski et al. 2024).

5. What are some of the most important ecological effects of this invasion? Describe any known effects of this species on other species or on ecosystem properties.

• Question 5 guides students to think about how the invading species affects both biotic and abiotic factors, at the community and ecosystem levels. For example, the leaf litter of buckthorn is colonized quickly by arthropods due to its high nitrogen content. Buckthorn's leaf litter thus decomposes more quickly than that of native trees, which may contribute to high concentrations of total nitrogen in soil in buckthorn-invaded areas. Buckthorn-invaded and uninvaded areas also have distinct soil microbial communities (Heneghan et al. 2002, 2004, 2006, 2007).

6. Given the observational study you conducted, can you conclude that the invasive species is causing the changes in the ecosystem properties you measured? Could it be the other way around, with particular ecosystem properties promoting its spread?

• Question 6 encourages students to think critically about the direction of cause-and-effect. Observed patterns could be the result of the invasive species altering the environment. Or, the ecosystem characteristics measured could be facilitating the growth of the plant invader. For example, elevated soil moisture in buckthorn-dominated soils could result from reduced evaporation under buckthorn's dense canopy or be due to a preference for growing in wetter soils (Heneghan et al. 2004). Alternatively, the relationship between buckthorn and soil moisture may simply be a correlation, with an unknown third factor influencing both variables (see Question 7).

7. Discuss the difference between causation and correlation. Could the abundance or biomass of the plant invader simply be correlated with your results because an unknown factor is influencing both? Design experiments to test for causation. For example, how could you determine if it is the invasive species that is causing the environment to change? Or, could you test if particular environmental conditions are driving the plant invader to grow and spread?

• Question 7 helps students understand that this activity may provide an example of correlation rather than causation. The concept of correlation versus causation is confusing to students and requires multiple discussions. A relatable example to start with is a day at the beach, with a hot sun that drives people to eat more ice cream and also get sunburned. While eating ice cream and getting sunburned are positively correlated, one doesn't cause the other. Once students understand this distinction, they can think of experiments to test for causation (e.g., is buckthorn responsible for higher soil nitrogen?) that include controls. Designing experiments also provides an opportunity for peers to discuss and compare ideas.

Comments on the Assessment of Student Learning Outcomes:

Parts of some assignments may be done as group activities or discussions during class, rather than given as homework. Below, we discuss these options and common challenges.

Assignment #1: Primary literature. *Part 1*: To help students navigate databases and refine their search strategies, we partner with university librarians when possible, for in-class tutorials. They introduce databases useful for students' projects and instruct on how to develop effective search terms. *Part 2*: Instead of doing as homework, students may analyze the parts of a scientific paper together in class. This shows them that scientific papers are meant to be discussed and learning is enhanced through collaborative analysis. Discussing a paper during class works best if instructors choose a relatively short, accessible paper. To ensure that students have read the paper beforehand, they can be required to annotate the paper either by writing notes on paper copies (summarizing the purpose and main point of each paragraph in the paper's margins) or through a social annotation platform such as Perusall (https://www.perusall.com/). During class, students can work in small groups to discuss each section of the paper using the questions provided in Assignment #1 as a guide, or each group can be responsible for presenting one section of the paper to the class.

Assignment #2: Field notebook. Students may have little experience viewing the outdoors from an ecological lens. Thus, we suggest ecosystem characteristics to notice (e.g., soil color and texture, growth forms of dominant plants, and evidence of animals or species interactions). So that fieldwork goes smoothly, students can prepare by writing out their plans for collecting samples or data beforehand. This is especially important if each student group has a different research question or if an instructor is managing a large class. Students can also divide tasks among their group (e.g., one student labels sample bags, another collects samples, a third records notes in the field notebook, and a fourth checks everyone's work). *Part 5*: Concluding with a group discussion to reflect on their experience before leaving field sites is a great way to wrap up fieldwork.

Assignment #3: Lab notebook. It is beneficial for students to take notes when conducting lab work, even if following written protocols. Describing what they are doing (and the purpose of each task) in their own words builds understanding. Students should be reminded to be thorough, such as to note the equipment used and names of taxonomic keys. Because a lab notebook provides a written record for someone who may continue the research later, data should be recorded logically (e.g., in table format). Any graphs and statistical output generated by the computer while doing Assignment #4 can later be printed, pasted into the lab notebook, and appropriately annotated. To support individual understanding of their data, we require each student to complete an individual lab notebook entry, and we check progress during class.

Assignment #4: Data analysis. *Part 1*: Reviewing a published results section may be done as a small group activity, with the instructor choosing a paper and assigning one graph to each group to analyze and then present to the class. *Parts 2 and 3:* We find it helpful for students to work in groups to analyze their data during class, because those who are more adept with using software to make graphs and conduct statistics can help their classmates. When creating graphs, common problems include labeling axes, including units, and properly inputting error bars. Students also often need feedback on null hypotheses and interpretation of p-values. *Part 4:* As students draft a Results section, we encourage them to also think about how they will also present these results in their oral presentations.

Assignment #5: Oral presentation. Before students prepare presentation slides, we explain how the format of an oral presentation differs from that of a research paper. For example, a presentation slide should have brief text rather than paragraphs, and graphs may have titles instead of figure captions. When grading group presentations, we give a single score based upon quality of slides and points to individuals for maintaining eye contact and for speaking at an appropriate pace and tone. Each presentation is followed by questions from the class. If students are hesitant to ask questions, then we allow time for students to work in small groups to develop questions. This is an excellent time for each group to consider how their findings may connect with those of others. For example, if one group examined microbial diversity and another measured soil moisture, students could discuss if their data suggest a relationship.

Assignment #6: Research paper. The research paper is the most complex assignment and the one for which we spend the most instructional time. We focus less on grammar and more on high-order writing skills, such as paragraph structure and clarity of explanations. For the Introduction, we emphasize the “inverted triangle” format: broader topics lead to narrower topics, with specific research objectives at the introduction’s end. In the Methods section, students tend to include unnecessary detail (e.g., “then we put samples in the sampling bag and labeled the bags with a Sharpie indicating each replicate number”). Thus, we show them examples of Methods sections from the primary literature so that they can emulate a more concise writing style. For the Results section, we encourage students to imagine that they are describing the main gist of the data while pointing to a graph. The goal is to summarize trends in the data rather than to simply list data points. We stress to students that the Discussion is the section scrutinized most carefully by readers and the section that they will spend the most time writing. Common problems include 1) restating the results without discussing their meaning, 2) lack of depth when comparing or contrasting results to the scientific literature, and 3) poor organizational structure (e.g., one full, continuous paragraph rather than multiple paragraphs that each have a topic sentence). Despite these challenges, we find that after students receive feedback from peers and from the instructor that they are able to make substantial improvements to their drafts. *Note*: Instructors may assign the research paper as an individual or group assignment. If written as a group, each student should read and provide feedback on parts written by others. Students submit initial drafts, their groupmates’ comments, and revisions that reflect group collaboration.

Comments on Formative Evaluation of this Experiment:

Class discussions provide opportunities to gauge students’ understanding and to increase their depth of knowledge. Receiving feedback on a draft allows students the chance to make revisions before submitting a paper for a final grade. Below, we elaborate upon these formative assessment strategies.

Class discussions:

Addressing misconceptions: During the first class period, we ask students to share assumptions about invasive species. Some think that all non-native or exotic species are invasive, but that label is only given when a species' spread causes ecological or economic harm and it can also apply to native species that spread uncontrollably. Another misconception is that invasive species are only spread by humans. Even though an invasive species may have initially arrived through anthropogenic activity, it can continue to spread by natural means (e.g., buckthorn seeds are dispersed by birds). We also address local controversies, such as opposition by well-meaning community members to buckthorn removal from forest preserves due to a concern about cutting down trees. In fact, buckthorn removal allows seedlings of oaks and other native trees to germinate.

Enhancing student understanding: In the question-and-answer period after student presentations, instructors can ask students to articulate scientifically valid rationales. Asking why results may or may not have been expected encourages students to take into consideration material learned in lecture and through literature searches. For example, students may incorrectly assume that higher concentrations of soil nitrogen are always due to nitrogen fixation. An alternative explanation is that nitrogen-rich leaves from an invasive plant attract decomposers, which mineralize nitrogen rapidly into the soil. Because of the opportunity to improve understanding, we schedule oral presentations before research papers are due.

Research paper feedback:

Peer review: In Assignment #6, we provide questions to guide peer review. Students like to help one another and we find that they approach peer review thoughtfully. We emphasize the benefit of receiving feedback so that they don't take comments personally. Peer review can be conducted anonymously or in small groups and is most effective when feedback is honest but given with good intentions. 1) Anonymous: students submit printed copies of papers, without names, on which a classmate anonymously writes comments. This approach works best when students who wrote strong papers provide comments on a weaker paper and when students who wrote weaker papers have the opportunity to review a stronger paper. 2) Small groups: students trade papers in small groups and after writing comments discuss strengths and weaknesses. This can also be done virtually; students post papers in a Google Drive folder and use the Google Doc comment feature to provide feedback.

Instructor feedback: We have found the traditional approach of commenting on final submissions to be ineffective. Instead, we comment on drafts and students use our feedback to make revisions. To make the job of providing feedback more efficient, we recommend that peer review occurs first. Then, instructors can reinforce or add to peers' comments. So that we receive thorough drafts to comment upon, we grade drafts on completeness. Drafts that contain all required elements (e.g., see checklists for research papers in McMillan 2017 and Hofmann 2020) receive full credit. Final drafts are then graded on quality, which motivates students to improve their drafts. Because we have already given feedback on drafts, we do not add comments to final papers. Instead, use the grading rubric (see Assignment #6) to record points obtained for each part of the final submission.

Comments on Translating the Activity to Other Institutional Scales or Locations:

Ubiquity of invasive plants: Instructors can apply this activity to a problematic invasive plant in any region (e.g., Chinese tallow tree, *Sapium sebiferum*, in the southern U.S.). The protocols we provide can also be adapted for aquatic ecosystems (e.g., nutrient concentrations can be measured in water) and so instructors may consider investigating aquatic species (e.g., water hyacinth, *Eichhornia crassipes*, a widespread invasive plant in lakes and ponds).

Variety of ecosystem attributes to measure: Depending upon expertise or availability of resources and equipment, instructors may choose from the protocols we provide, or add their own. A literature search on the effects of the chosen invasive plant may suggest additional ecosystem attributes to measure and students' ideas can be accommodated when possible. If lab work is not possible due to space or time constraints, then we recommend variables that can be measured in the field. Examples include the number and types of leaves in a quadrat (leaf litter composition and identification to genus), incident light, counts of herbaceous stems, and soil temperature and color.

Modular assignment design: Instructors can use all or just a few of the assignments, as appropriate for class size, time, and educational level. For example, the activity's length or scope can be reduced by focusing primarily on data collection (fieldwork and/or lab work) and analysis (Assignments #2–4). Or, instructors may wish for students to do either the oral presentation (Assignment #5) or the written paper (Assignment #6) rather than both. The research paper can also be shortened, such as to require only the objectives, methods, results, and data explanation (see these criteria in the Assignment #6 grading rubric).

Student Collected Data from this Experiment

Students in the General Ecology class at Northeastern Illinois University collected samples and data at forested sites with high and low buckthorn density in the greater Chicago, Illinois area. Data are provided for the following variables: soil nutrients (NO_3, NH_4, and PO_4), soil pH, % soil organic matter, leaf litter mass, leaf litter biodiversity, invertebrate biodiversity, microbial functional diversity, herbaceous stem density, and soil temperature.