Using the SCIENTIFIC PROCESS to Engage Students With Our CHANGING PLANET

by Daniel L. Preston, Phillip G. Taylor, Nora C. Brown, and John A. Mischler

Have you ever seen a forest that was cut down? Or a new parking lot in an area that used to be a natural space? Or perhaps a stream or pond that became stinky and neon-green with algae due to pollution? These human-caused alterations to the natural world are often called *ecosystem change*, or on a very large scale, *global change* (see Figure 1 for glossary terms in italics). Some of these changes are easy to observe, whereas others are not readily apparent. Such changes—including those caused by deforestation, climate change, invasive species, pollution, and overexploitation of resources—are leading to complex environmental, societal, and economic problems that future generations will need to overcome (Camill 2010). These issues are obviously important to teach, but they can also be challenging to make tangible. How can they be conveyed in our classrooms in an engaging way that is meaningful for students?

We addressed this challenge by designing a collection of science lessons that explore the causes and

FIGURE 1 Glossary of important terms

These terms should be introduced throughout the lessons, should be defined in the students' scientific notebooks, and can be used to evaluate students at the conclusion of the project.

- *Global change*: Changes to the planet's environmental systems, such as nutrient and water cycles, the climate, and ecosystems. Global change is frequently driven by human activities.
- *Nutrient pollution*: Unintended inputs of nutrients, such as nitrogen and phosphorus, into natural areas. Often caused by agricultural fertilizers, human and livestock waste, and by-products of industry.
- *Invasive species*: Species that are introduced from their native range into a new area, where they then have an ecological or economic impact.
- *Ecosystem*: An integrated system of interacting biotic and abiotic components. Ecosystems can range in scale from very small (the water within a tree hole) to very large (an ocean).
- *Biotic factors*: The living components of an ecosystem, including microorganisms, plants, and animals.
- *Abiotic factors*: The nonliving components of an ecosystem, including water, soil, air, and rocks.
- *Microcosm*: A small-scale representation of a larger system. The jars are microcosms of pond ecosystems.
- *Replicate*: The individual experimental unit. Each jar is a replicate in the experiment.
- *Treatment*: A set of replicates within an experiment that undergo the same manipulation.
- *Bottom-up effect*: An effect on an organism or population that is driven by that organism's resource. For example, nutrient availability can control growth of algae.
- *Top-down effect*: An effect on an organism or population that is driven by that organism's consumers. For example, herbivores can control algae growth.
- *Primary production*: The rate at which photosynthetic organisms (plants and algae) produce new biomass.
- *Phytoplankton*: Algae that are suspended in the water column.
- *Periphyton*: Algae that are attached to surfaces, such as the sides of the jars.

consequences of two common forms of environmental change: *nutrient pollution* and *invasive species*. Nutrient pollution from fertilizer and agricultural waste affects about 70% of freshwater ecosystems in the United States, and nonnative invasive species now dominate many aquatic ecosystems, including San Francisco Bay and the Great Lakes (Chislock et al. 2013; Hettinger 2012). In many places, students need only look out the classroom window to see these issues in action.

The core of the lessons involves a long-term (about four to eight weeks) classroom experiment where students create miniature freshwater ecosystems within 1-liter jars. Students use their jars in a replicated experiment that reveals how invasive species and nutrient pollution, both alone and in combination, can lead to striking changes in freshwater ecosystems. The curriculum includes inquiry-based education modules that explicitly address *Next Generation Science Standards* (*NGSS*) for middle school students (see sidebar, p. 40 and NGSS Lead States 2013).

Module 1: Build an ecosystem

What is an *ecosystem*? In the first module of the experiment, students learn about the components of an ecosystem by building a miniature freshwater ecosystem within a 1-liter glass jar. The module emphasizes both the *abiotic factors* (soil, rocks, water, air, and sunlight) and *biotic factors* (microorganisms, plants, animals) that make up ecosystems. Later in the experiment, students will learn how these components are intricately linked and can be influenced by human activities.

The core of this module is the construction of the small-scale pond ecosystems, or *microcosms*. Microcosms are small-scale representations of larger systems and are often used in ecological experiments. It works well to assign two students to a single jar (16 jars for a class of 32 students). The pond microcosms are constructed with a gravel base, a layer of real pond mud, and dechlorinated tap water (see Figures 2 and 3 for instructions to set up the jars, a materials list, and safety instructions for working with field-sourced pond materials).

As with many in-class scientific investigations, it is

FIGURE 2 Materials (and sources)

These materials are essential to complete the project and can be purchased for a class of 32 students for around $100.

- 16 one-liter glass canning jars (hardware or grocery store)
- Gravel (about 5 lbs for one class; hardware or aquarium store)
- Pond mud (local lake, pond, or wetland) (an unpolluted location chosen by the teacher that meets the general standards provided in this article)
- Two 5-gallon buckets for mud and for dechlorinating tap water (hardware store)
- Water dechlorinator (aquarium store)
- Small bottle of general-purpose liquid plant fertilizer (hardware store)
- Aquatic snails, three per jar (aquarium store)
- Data notebooks
- Clear plastic grids (science supply store)
- Phytoplankton color scale (homemade)
- Small eyedropper/pipette for administering fertilizer

Optional items. These materials are useful for a variety of extensions that are mentioned in the text but are not essential to complete the project in its most basic form.

- Petri dishes for counting aquatic organisms under the microscope
- Turkey baster
- Nitrate test kit (one per class)
- Phosphate test kit (one per class)
- Dissolved oxygen test kit (one per class)
- Invertebrate ID guide (can also be found online or in a library)
- Fluorescent light fixture
- Magnifying glasses/hand lenses
- Microscopes and slides
- Thermometer (one per class)

FIGURE 3 Pond microcosm construction instructions

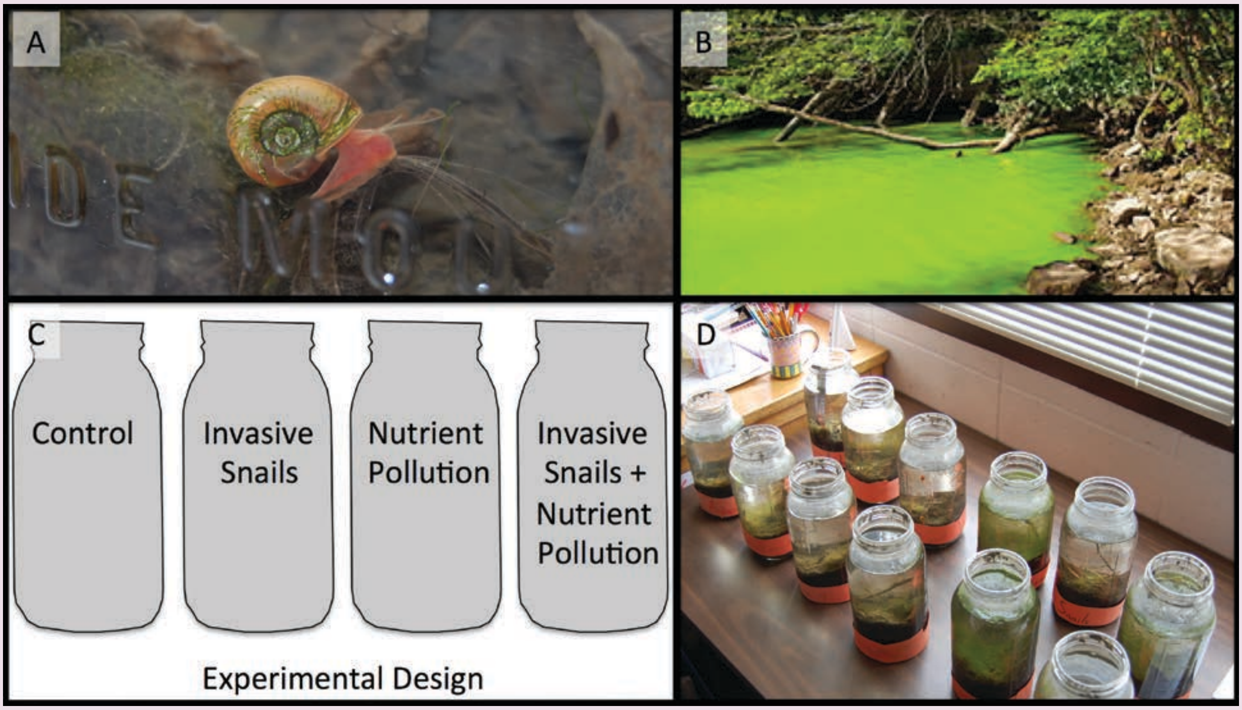
Steps 1–7 correspond to Module 1. Step 8 occurs in Module 2. The jars are to be set up by students with the help of the teacher at several steps. Safety note: Students must wear indirectly vented chem splash goggles and gloves during construction and work with the jars.

1. Using a shovel, collect one bucket full of pond mud per class. To keep the organisms alive, do not store the mud in the bucket for more than 24 hrs. before use. Select a location that is unpolluted to collect the mud.
2. Distribute jars and have students add a 3 cm layer of gravel to the bottom of each jar.
3. Mix the pond mud thoroughly in the bucket to an even consistency. To minimize the mess, mud is best added by the teacher while students hold the jar. Add a 10 cm layer of mud to each jar. Have students clean off the outside of the jar to remove mud.
4. Add dechlorinator to two buckets of tap water. Wait 10 minutes and then have students add the water to each jar. Have students fill the jars to near the top and leave the jars uncovered. The water in the jars will clear within 48 hrs. if left undisturbed.
5. Have students construct a label for their jar with their group name and later add the treatment to the label.
6. Have students place the jars in a sunny window or underneath bright fluorescent lights if natural light is unavailable. Have a designated space for each class to keep their jars.
7. Let the jars settle and become established for several days to a week. In the event that mold forms within a jar or a jar develops an unpleasant odor, the jar in question should be disposed of by the teacher. High light generally prevents these problems, as light supports photosynthesis that adds oxygen to the water, promoting a "healthy" environment within the jar. Low-oxygen conditions, due to either lack of photosynthesis or poor gas exchange into the water (jars must be left uncovered without lids), are the most common cause of organisms dying within the jars.
8. Randomly assign each jar to one of the four treatments (see Figure 4). Students should add their specific treatment to their jar label. Using an eyedropper, the teacher should add 0.5 mL of liquid fertilizer to the nutrient treatment jars while students are present and able to watch. Students should add three adult snails to the snail treatment jars. Add both nutrients and snails to the combined treatment jars.
9. Top off the jars with dechlorinated water as necessary to keep the water level near the top. This should be done by students. The teacher should add another 0.5 mL of fertilizer in about three weeks to each of the nutrient-pollution treatment jars.
10. Disposal of jars at the end of the project: The microcosms must not be dumped into local water bodies, as this has potential to spread nonnative species (and this must be emphasized to students). It is best to ensure that everything in the jars is killed at the end of the experiment. One way to do this is to dump the jars into a compost area or into a garden where the contents will become fertilizer (again, only if there is no chance the material can make its way into a water body). If this is not possible, the water can be poured onto a grassy area away from water bodies and the solid material can be sealed in a trash bag and discarded.

recommended that students wear protective indirectly vented chemical splash goggles and gloves, both to maintain safety standards and to train students to be in the habit of wearing personal protective equipment when in a classroom laboratory setting. The pond mud should only be collected from an unpolluted lake, pond, or wetland that has not been affected by agricultural runoff or past/present industrial waste. Public

FIGURE 4 Invasive species

Invasive species, including some freshwater snails, are organisms that are introduced by humans to areas outside their native range where they then have an ecological or economic impact (A). Nutrient pollution in aquatic ecosystems can be the result of excess agricultural fertilizers or livestock waste entering natural water bodies. Nutrient pollution can lead to blooms of algae and can strongly alter aquatic ecosystems (B). The design for the classroom experiment involves four treatments that evaluate the individual and combined effects of invasive snails and nutrient pollution (C). The established pond ecosystems are set up on a table in the classroom where they will receive strong light (D).



lands, such as state parks and wildlife reserves, can be a good place to collect this material. Contact the land managers ahead of time to receive permission and ask about the history of the water bodies on the property, and specifically the likelihood of pollution. It is best to collect mud from an ecosystem that is rich in plants and animals, as this material will harbor a diversity of microbes, algae, and aquatic invertebrates that will soon be apparent in the jars and will contribute to the results seen in the experiment. While many of these organisms are harmless to people and are natural components of aquatic ecosystems, whenever materials are collected from an untested water source, students must always wash their hands for 20 seconds with soap and water after working with the jars, and all working surfaces must be disinfected.

Students should label the jars with identifying information and place them on a windowsill with bright sunlight or beneath strong artificial fluorescent lighting. Strong light will accelerate the development of the organisms in the jars and make the differences between treatments most obvious. The water temperature of the jars should ideally be kept below about 30°C (86°F). The jars should be open to the air on top, without lids on, to allow the passage of carbon dioxide and oxygen into the water. At the end of the experiment, jars must be disposed of in a responsible manner (see Figure 3 for suggestions).

From the setup of the jars onward, students should use a dedicated scientific notebook to record hypotheses, observations, and data, which can serve as means of evaluation. In their notebook, have students list the steps used to construct their jars. After setting up the jars, students can be asked the following question:

FIGURE 5 Response variables and measurement instructions for Module 3

Response variables	Measurement instructions
Periphyton (attached algae)	Hold the 10 cm grid against a side of the jar and estimate the percent algae cover within each cell. Have both students per group take the same measurement and use the average.
Phytoplankton (suspended algae)	Hold a homemade color scale, ranging from clear to dark green on a scale of 1 to 10 against the jar. Estimate the number that corresponds to the jar's water color. If the walls of the jar are covered in algae, transfer some water to a clean jar to estimate the water color.
Snail reproduction	Count the number of total snail egg masses on all sides of the jar and the number of individual eggs per mass. If present, count the number of baby snails on the jar walls.
Invertebrate diversity	Using the turkey baster, have students collect a sample of water from near the bottom of each jar. Squirt this water into a petri dish and identify the number of different invertebrates that are observed. Identify the invertebrates; use a low-power microscope if desired.
Dissolved oxygen, nitrate, and phosphate concentrations	Follow the instructions for storage, use, and disposal that are provided with these individual test kits. Ensure that test kits do not contain toxic chemicals. Students should be supervised and must wear gloves and indirectly vented chemical splash goggles when working with test kits.

"Describe the parts of an ecosystem. What are the abiotic components and the biotic components of a wetland ecosystem?" An effective extension to this module can include a visit to a local freshwater habitat where students can identify the components of an ecosystem during a scavenger hunt. The module also provides an ideal opportunity to incorporate lessons on many aspects of ecosystem structure and function, including water and nutrient cycles, food webs, and energy flow.

Module 2: Global change and experimental design

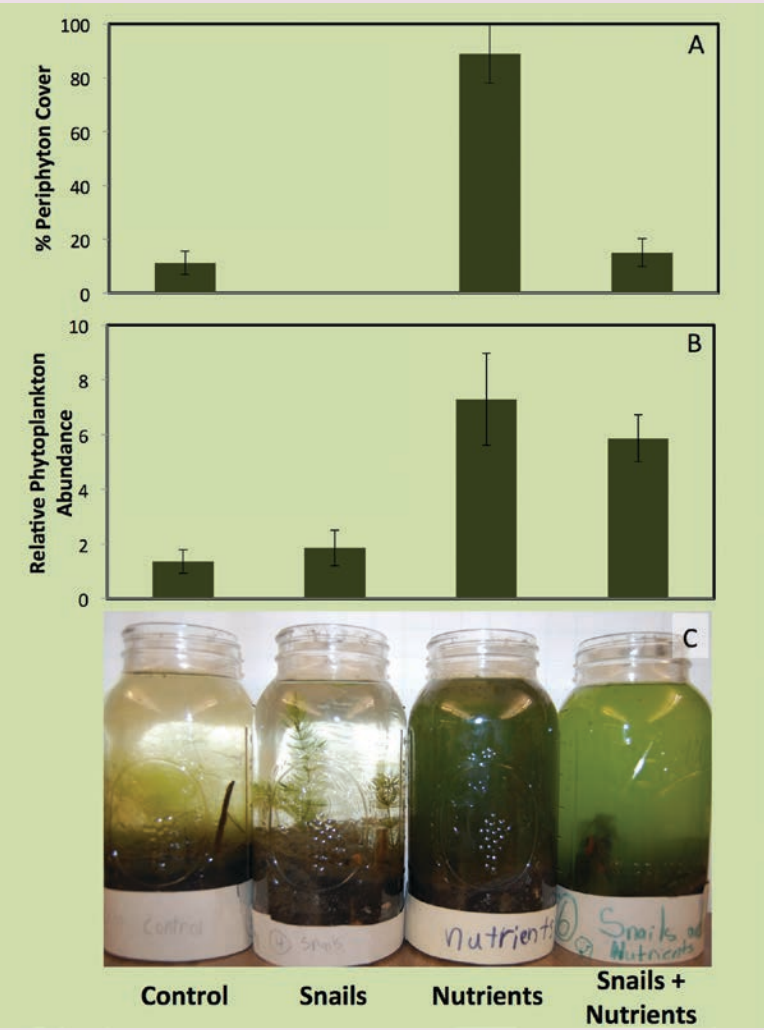
In the second module, students learn about nutrient pollution and invasive species and establish the experiment (Figure 4; also see Chislock et al. 2013 and Hettinger 2012). The four *treatments* within the experiment include (1) control jars with only the native pond community, (2) jars that have fertilizer added, (3) jars that have invasive snails added, and (4) jars that have both fertilizer and invasive snails added (see Figure 3 for instructions on establishing treatments and Figure 4 for images of the treatments). Students should be asked as a class, or in small groups, to come up with these treatments on their own. It is effective to ask students, "How can we use our microcosms to understand the effects of snails and nutrient pollution on aquatic ecosystems?" A guided discussion should lead them to the four treatments.

At the beginning of this module, students should be asked to make detailed hypotheses, as well as their underlying rationale for how the pond ecosystems will change as a result of adding snails or fertilizer. Relevant background information that will help students inform their hypotheses should include: the ecological roles of snails as herbivores and the effects of nutrients on primary production (i.e., the growth of plants and algae). Students can be tasked with finding this information or it can be provided to them through a discussion format. Good questions to lead this discussion include "What direct and indirect effects might fertilizer have within the pond ecosystems?" and "What effects might snails have on various components of the pond ecosystems?" The fertilizer will directly affect the algae in the microcosms, while it will indirectly affect things that feed on the algae, such as the snails.

The experiment has two independent variables—the presence of fertilizer (yes or no) and the presence of invasive snails (yes or no). All other variables are held constant between the jars, providing a good opportunity to discuss independent variables, response variables, controlled variables, and replication. The treatments

FIGURE 6 **Data collected by students and an image of the changes in the pond ecosystems due to the treatments**

The *x*-axis for the graphs corresponds to the image at bottom. The top figure shows differences in attached algae (periphyton) between treatments (A). The middle figure shows differences in suspended algae (phytoplankton) (B). The bottom image depicts representative jars from the four treatments at the conclusion of the experiment (about six weeks).



all have three to five *replicate* jars, depending on the number of students in the class. This is a good time to ask, "Why not use a single jar per treatment in our experiment?" We have also run the experiment in multiple classrooms at once, which allows for a larger dataset if classes share data, as well as comparisons of treatment effects between classes.

After determining which treatments should be used and formulating hypotheses, the experiment can be initiated by adding the liquid plant fertilizer and snails to the designated jars (see Figure 3 for additional instructions). The teacher should be the one to add the liquid plant fertilizer to jars. Snails can be purchased from an aquarium store and most species of snail should work well. Snails that reproduce rapidly, such as pond snails (*Physa* spp.) or ramshorn snails (*Helisoma* spp.) are best. Although these snails are native to North America, they can be used to simulate the effects of an invasive snail because they are easy to obtain and live well inside the jars.

Module 3: Data collection, analysis, and interpretation

At first, the jars will look very similar across the four treatments, but as time passes they will begin to diverge in significant ways. This is a great time to implement a variety of extension lessons (see extensions section below). We recommend collecting data weekly during the establishment phase, although it is also feasible to collect the data at the end of the experiment if time is limited (four to eight weeks after establishing treatments, depending largely on light levels and water temperatures).

Students can measure several response variables, including algal growth, invertebrate diversity, nutrient concentrations, dissolved oxygen levels, water temperature, and snail reproduction (see Figure 5 for instructions on measuring response variables). Students should record their data in a standard-

Connecting to the ***Next Generation Science Standards*** (NGSS Lead States 2013)

Standard MS-LS2 Ecosystems: Interactions, Energy, and Dynamics *www.nextgenscience.org/msls2-ecosystems-interactions-energy-dynamics*		
Performance Expectations The materials/lessons/activities outlined in this article are just one step toward reaching the performance expectations listed below. MS-LS2-1. Analyze and interpret data to provide evidence for the effects of resource availability on organisms and populations of organisms in an ecosystem. MS-LS2-2. Construct an explanation that predicts patterns of interactions among organisms across multiple ecosystems.		
Dimension	***NGSS* code/citation**	**Matching student task/ question taken directly from the activity**
Science and Engineering Practices	Analyzing and Interpreting Data	Students conduct an experiment, collect data, and evaluate hypotheses.
	Constructing Explanations and Designing Solutions	Students draft a plan that outlines the effect of nutrient pollution and invasive species in their experiment and how these factors may be impacting a natural wetland.
Disciplinary Core Ideas	LS2.A. Interdependent Relationships in Ecosystems • Organisms, and populations of organisms, are dependent on their environmental interactions both with other living things and with nonliving factors.	Students build a miniature ecosystem within a jar and then observe the relationships between nutrient availability, primary production, and herbivory.
	LS2.C. Ecosystem Dynamics, Functioning, and Resilience • Ecosystems are dynamic in nature; their characteristics can vary over time. Disruptions to any physical or biological component of an ecosystem can lead to shifts in all its populations.	How might the impacts of invasive species on different tropic levels influence the outcomes within the jars?
Crosscutting Concepts	Cause and Effect	Discuss what factors control plant and algae growth.
	Patterns	Students gather data, create tables, and look for patterns to use as evidence in explanations.

ized manner within their designated scientific notebook. Showing students example tables that include the date of the measurement and headers indicating the particular response variables is useful. One of the primary response variables is the growth of algae within the jars. This includes algal growth on attached surfaces such as the jar walls (*periphyton*) and suspended algae growing in the water (*phytoplankton*). The attached algae can be measured with a simple clear plastic grid measuring 10 × 10 cm, with cells of 1 cm^2 (see Figures 2 and 5). Students in the same group can make the same measure independently on the same jar, allowing for a discussion of measurement error and sample size. Students can use the average values from multiple measurements as the final data. Suspended algae in the water column is quantified most easily using a simple homemade color scale, ranging from 1 to 10, with 1 being crystal clear water and 10 being a dark, pea-soup green color (Figure 5; see Figure 6 for an example of the colors the jars can become). This color scale can be made easily by students on paper with markers or colored pencils.

Also, many of the snails that are added to the jars will quickly lay eggs, which will hatch into baby snails. In the jars with added fertilizer, students should predict that increased algal growth will lead the snails to reproduce more rapidly and lay more eggs. Snail reproduction can be quantified by counting the total number of egg masses that are visible on the walls of the jars and by counting the number of eggs within each mass (Figure 5). If the eggs hatch into baby snails during the experiment, the number of young snails on the walls of the jars can also be counted.

Once data have been collected for the desired response variables, students should combine all the class data into larger tables on the chalkboard, on an overhead projector, or with an Excel spreadsheet. Each student should generate a table with the data from the entire class within his or her notebook. This data table should include the group and treatment each jar belongs to and the relevant response variables that have been measured. At this point, there is a huge amount of flexibility in what students can do with their data. Students can calculate the mean and variance in each response (such as standard deviation or standard error) with a simple bar chart or box-and-whisker plot (one bar for each treatment; see Figure 6). There are also opportunities to construct scatterplots and line graphs to demonstrate correlations (e.g., snail reproduction and algal growth). These data visualization exercises can incorporate several math and graphing standards, which can be tailored easily to the grade level.

Some patterns in the data will be quite strong. For instance, the fertilizer and snail treatments should influence growth of algae in striking ways. Fertilizer increases growth of both attached and suspended algae, whereas snails reduce the amount of attached algae through grazing (see Figure 6 for student-collected data showing these patterns). These results can lead to a rich discussion of what factors control growth of plants and algae, or *primary production*, within real ecosystems. Discussion questions can include:

- Within the microcosms, are *bottom-up effects*, such as resource availability, or *top-down effects*, such as grazing by herbivores, more important in controlling primary production?
- How might the impacts of invasive species on different trophic levels influence the outcomes within the jars?
- Do the effects observed in the jars mean the exact same things will happen in natural ecosystems? Why or why not?
- Once the patterns have been discussed, the lesson can shift toward evaluating the results with regard to the initial hypotheses that were developed by the class. Which of our initial hypotheses were supported? Which were not?

Extensions: Adaptation, food webs, energy flow, and more

There is considerable flexibility in how the jars are used to convey science standards throughout the experiment. We have developed lessons related to food webs and energy flow, as well as form, function, and adaptation in animals. In our food-web lesson, we ask each student to choose a living organism from within the jars; these should include algae, plants, and invertebrates. Students are tasked with identifying their individual organisms, researching what it eats and who eats it, and other aspects of its natural history. Students then create a drawing and informational document on their organism, which is attached to the wall of the classroom with arrows connecting it to other organisms within the aquatic food web. In this way, students can visualize how all of the organisms are related through trophic links in the food web. A similar activity can be used to create a biomass pyramid, where organisms are arranged into trophic levels and topics such as primary production, secondary production, and energy flow are highlighted.

Another fun extension is to use the final outcome of the experiment to design a management plan for a local wetland that is being affected by invasive snails and nutrient pollution. Have students work in groups to draft a plan to give to legislators that outlines the effects of nutrient pollution and invasive species in their experiment and how these factors may be affecting the natural wetland. Are the effects worth worrying about? If so, what management strategies can be used to ameliorate negative consequences of nutrient pollution and invasive snails? What are the pros and cons of different management strategies?

Assessment

The scientific notebooks can provide a useful means for assessing what each student has done throughout the experiment. Encourage them to take periodic observations of their pond ecosystems and to organize their notebooks with the date of each entry and a clear representation of what they did and what data they collected. Students can also use their experimental data to craft scientific reports that can be used as mock scientific publications that include an abstract, introduction, methods, results, and discussion sections. These reports easily allow the instructor to evaluate what students have learned throughout the experiment. With regard to human impacts on the environment, students should be able to explain what an invasive species is and how humans have moved invasive species around the globe. They should also understand the basic concepts underlying nutrient pollution, including its causes and consequences for aquatic ecosystems.

Conclusion

We have found this investigation effectively engages students, in part because the organisms within the pond ecosystems have inherent appeal, and because the changes that occur owing to nutrient pollution and invasive snails are striking and readily apparent, making complex concepts easy to observe and quantify. Moreover, most students show a high level of personal investment and curiosity in the development of their own freshwater ecosystem, which accelerates learning. Although many global-change issues can be challenging to convey in a meaningful way, the fun factor of this experiment is a big plus in keeping the attention of students while also fostering awareness about important environmental issues and conveying core science concepts. ■

Additional information

Additional information about these lessons/modules, including tips, lesson plans, worksheets, and other resources is available by contacting the authors.

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