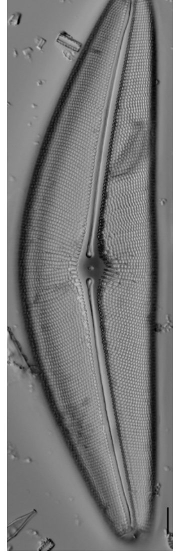
INQUIRY & INVESTIGATION

Investigating Ecological Disturbance in Streams



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Abstract

Teaching students about ecological disturbance provides them with an understanding of a critical factor that shapes the structure and function of biological communities in environmental systems. This article describes four simple experiments and related curriculum that students can use to conduct inquiry around the theme of disturbance in stream ecosystems: insect drift, colonization, life history, and the intermediate disturbance hypothesis. Over five years, our students conducted these experiments 57 times; 79% of the experiments resulted in data that supported students' hypotheses. Our findings show that the experiments can be used as a framework for inquiry-based learning about important ecological processes such as disturbance, dispersal, colonization, and succession. These experiments meet several of the Next Generation Science Standards*, are easily and ethically conducted, and require very little equipment.*

Key Words: *inquiry-based learning; stream insects; stream disturbance; insect drift; intermediate disturbance hypotheses; life history.*

○ Introduction: Ecological Disturbance in Streams

From forest fires to floods, disturbance plays a major role in shaping the diversity of biotic communities. Disturbance is an event that temporarily disrupts and changes an ecosystem or biotic community (White & Pickett, 1985). For the purposes of this article, we differentiate ecological disturbance, which occurs through natural events, from environmental disturbance, which is related to human activities. Ecological disturbance drives biotic community succession, maintains species diversity, and supports ecological function (Hobbs & Huenneke, 1992). Despite its relevance to the study of ecology and environmental science, few of our students understand the importance of ecological disturbance, and many students view disturbance as having only a negative effect on ecosystems.

Disturbance is an important aspect of natural science education and an interesting topic for inquiry. However, in most natural systems, disturbance experiments can be difficult to conduct in the short timeframe required by most educational settings. Moreover, causing a large disturbance may harm organisms and be counterproductive to student learning (Orlans, 1988). Because streams and stream insects rapidly recover from disturbance (Resh et al., 1988), they represent an opportunity for conducting disturbance experiments that can be completed over a couple of days. Furthermore, the main form of disturbance in streams is substrate mobilization (Resh et al., 1988); thus, stream disturbance can be nonlethally simulated by simply moving substrate or removing insects from substrate. The relative ease of simulating disturbance in streams and the fast colonization rates of stream insects make streams ideal ecosystems for education-based experiments focused on ecological disturbance.

Here, we describe four stream experiments and the curriculum that we developed around the theme of ecological disturbance. These experiments are simple to conduct, nonlethal, and aligned with several of the *Next Generation Science Standards* for high school (Table 1). For each experiment, we provide the relevant background information, experimental methods, and examples of typical student results. We also describe the related curriculum and provide recommendations for how to implement the curriculum and experiments.

○ Methodology

Pedagogical Overview & Fieldwork

We developed these experiments so that our students could conduct authentic ecological inquiry on short field trips during which multiple experiments could be conducted simultaneously. All the disturbance experiments described here can be conducted in two field trips but, if necessary, the life history, disturbance, and energy experiments can be completed during a single field trip. Using a guided-inquiry approach, we have implemented the ecological disturbance curriculum and experiments in a range of educational settings from freshman high school to upper-division college courses. For all educational settings, we used the same

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Table 1. Summary of the *Next Generation Science Standards* addressed by the disturbance experiments.

Disciplinary Core Idea	Science & Engineering Practices (SEP), Crosscutting Concepts (CCC)	Experimental Activity or Result
LS2.C: Ecosystem Dynamics, Functioning, and Resilience.	SEP: Mathematical and computational thinking. CCC: Scale, proportion, and quantity.	Standardizing rock size, calculating stream flow and drift rates. Identification of sample unit. Scaling up drift energy to kilocalories per day.
LS2.B: Cycles of Matter and Energy Transfer in Ecosystems.	SEP: Mathematical and computational thinking. CCC: Energy, matter, system models, structure, and function.	Estimating drift, biomass, and energy in the stream. Calculating percent r- and K-selected organisms.
LS2.C: Ecosystem Dynamics, Functioning, and Resilience.	SEP: Engaging argument from evidence. CCC: Stability and change.	Using data to test hypothesis. Analyzing potential error. Understanding disturbance and diversity.
LS2.C: Ecosystem Dynamics, Functioning, and Resilience.	SEP: Constructing explanations. CCC: Stability and change.	Interpreting results. Proposing cause and effect. Documenting the intermediate disturbance Hypothesis.
LS4.C: Adaptation ETS1.B: Developing Possible Solutions.	SEP: Using mathematics and computational thinking. CCC: Cause and effect.	Estimating drift and energy in the stream. Explaining cause and effect related to disturbance.
ESS3.C: Human Impacts on Earth Systems. ETS1.B: Developing Possible Solutions.	SEP: Constructing explanations and designing solutions. CCC: Stability and change.	Documenting the effect of flood disturbance on stream insects and algal communities. Documenting the intermediate disturbance hypothesis.

basic approach, but with different requirements for analyzing data and communicating the results. For example, some students analyzed data with a box plot and gave a short presentation about their results, while others conducted a statistical test and communicated their findings through a scientific paper. To facilitate online learning or to shorten the classroom time requirements, we developed online content videos and created virtual disturbance experiments (SWRP, 2020).

Table 2 outlines the timing of the major curricular activities and the related student and teacher roles. Scaffolding for the experiments begins with an introductory unit on stream ecology and stream insects. We then discuss the overarching design of ecological experiments and introduce the overarching topics of stream disturbance, life history and succession, dispersal, and stream energetics. The next major phase of the curriculum is the experiment proposal and approval process. During this phase we work closely with our students to design and propose an experiment using a proposal form that asks students to state their hypothesis, identify independent and dependent variables, create a schematic of the experimental design, and make a graphical prediction of their expected results. Students are not permitted to conduct the experiment without prior approval. During short (1- to 1.5-hour) field trips, students work in groups to install the experiments and then return two to seven days later to remove the experiments. Experimental data sheets, proposal forms, and example data sets are available online (SWRP, 2020).

Field Methods

The basic methodology for the disturbance experiments is based on a similar set of experiments focused on sediment pollution (Edwards & Shroufe, 2016). Our students have conducted the disturbance experiments in five different streams with consistent results; however, it is important to carefully consider the type of streams selected for these experiments. Streams should be shallow enough to wade across, have a moderate flow (0.5–3.0 feet/second), have rocky substrate, and not be severely polluted.

The specifics of each experimental methodology are described below, but some general procedures are followed for all the experiments. To avoid disturbing insects into downstream experiments, the experiments should be installed from upstream to downstream and harvested in the opposite direction. When collecting rocks for use in the experiments, make sure to use rocks from the stream that have sufficient algae growth (rocks with sufficient algae will feel "slimy"). When rocks are removed from the streams, quickly pick up the rock and directly transfer it to a white tub, and then gently rub the rock to dislodge insects. Some of the insects may be very small and hard to see; thus, "poking" debris with a pencil will force the insects to move and make them easier to count. For two of the experiments, both the total number of insects and insect density (e.g., insects/cm^2) on the rock surface area will need to be calculated. The surface area of rocks can be estimated by measuring the two longest axes with a string and applying the following formula (Bergey & Getty, 2006): rock surface area = length × width (π/4).

Table 2. Summary of the main pedagogical activities associated with the disturbance experiments. Videos for all content and experiments are available online (SWRP, 2020).

Day (Duration)	Major Class or Online Activity	Participant Roles
Day 1 (1.25 hours)	Content lecture or video on stream macroinvertebrates, stream ecology. Practice identifying live or preserved insects.	Student role – Learn relevant content material. Teacher role – Give lecture or show content videos, help with insect identification.
Day 2 (1.25 hours)	Content lecture or video on experimental design for natural science experimentation. Introduction to experiments. Experiment proposal.	Student role – understand experimental design, become familiar with experiments, and work in groups to propose the experiment. Teacher role – Give lecture or show video. Guide experiment proposals.
Day 3 (1–1.5 hours)	Field trip to install experiments.	Student role – Prepare experimental substrate, measure rocks, install experiments. Teacher role – Help with substrate selection, select sites for experiments, demonstrate how to install experiments.
Day 4 (1–1.5 hours)	Field trip to remove experiment.	Student role – Remove experiments and count insects. Teacher role – Help remove experiments if necessary.
Day 5 (1.25 hours)	Content lecture or video on data analysis using the CRAN R statistics program. Data organization and analysis.	Student role – Organize results and analyze data. Teacher role – Give lecture or video on data analysis. Support data analysis.
Days 6–7 (2.5 hours)	Communicating science through a paper or poster. Peer review.	Student role – Work in groups to write and revise a scientific paper or poster describing their experiment. Students peer review each other papers or posters. Teacher role – Facilitate peer review activity and grade at least two drafts of the paper or poster.

The stream insects featured in three of the disturbance experiments are mayflies in the family Baetidae (Figure 1). Baetids are common and present in nearly all streams in the United States, with the exception of the lowlands in the southeastern part of the country (U.S. Environmental Protection Agency, 2006). Baetids represent the classic *r*-selected organism with a fast life cycle, high reproductive rate, and wide dispersal ability. These mayflies' life history characteristics and their ubiquity in streams make them an ideal model organism for studying stream disturbance. Baetids are also easy to identify; they are small, fast swimmers with an unsegmented thorax and two or three cerci (tails). Baetids are often confused with stoneflies, but they can be distinguished from stoneflies by their ability to swim. In contrast to the other experiments, the life history experiment is focused on the response of mayflies, caddisflies, stoneflies, and true flies to disturbance.

To evaluate the reliability of the experiments, we reviewed student work samples since 2015 and were able to document 57 disturbance experiments conducted by our students. We reviewed each poster and used p-value <0.05 or evaluated general trends to determine if the experimental hypothesis was supported by the results.

Figure 1. Small minnow mayfly (Baetidae) and scale view in an ice cube tray. Baetids are easy to identify by their fast swimming and resemblance to minnows.

Insect Drift & Colonization

Downstream dispersal of some insects occurs through a process known as drift. There are two main types of drift. Catastrophic drift occurs through substrate disturbance or from high-flow events that scour insects off substrate. Behavioral drift is an intentional behavior that insects exhibit when they are feeding, avoiding predation, or colonizing open habitat (Brittain & Eikeland, 1988). Baetids are well known as prolific behavioral drifters, intentionally releasing from the substrate in the evening and morning to drift downstream and colonize habitat that may provide better feeding opportunities and predator avoidance (Allan, 1987). Once drift is initiated, baetids and other drifting insects colonize open habitat through a process primarily related to stream velocity (Townsend & Hildrew, 1976). In areas of a stream with higher velocity, there are more insects drifting and thus they are more likely to colonize open habitat. In this experiment, students take 6–10 similar-sized rocks from the streams, remove all organisms from them, and measure their size (Figure 2E). The rocks are then placed back in the stream across a range of velocities (Figure 2A). The rocks are marked with flags so that they can be found at the end of the experiment. Students then measure stream velocity at the different locations where the rocks were placed. These measurements can be accomplished with a cork and stopwatch or, more accurately, with a flow meter. After three to five days, each rock is removed from the stream and placed in a tub where insects are removed from the rocks and counted. In this experiment, the number of insects on the rocks is the dependent variable and the stream velocity is the independent variable. The sample unit is each rock. The hypothesis for this experiment is that stream insect abundance on rocks will be positively correlated with stream velocity. Data can be displayed with a scatter plot and statistically analyzed using linear or polynomial regression models.

Energy in the Drift

Drifting insects are a major food source for fish (Brittain & Eikeland, 1988) and other organisms, yet few students realize the amount of food energy in the drift. Baetids are the primary insects in the drift, and their abundance can be estimated using a small drift net (less than one square foot) or some other secured small net to collect drifting insects (Figure 2B). The drift net is placed in the stream (Figure 2B) for an hour, and then students count the number of baetids captured in the net. In some cases, there may be too many baetids in a sample to count, in which case a subsampling procedure is used to quickly estimate the total number of baetids in the net (Edwards, 2016). After counting, insects should be immediately returned to the stream. In general, more insects will be captured in the morning and evening than in the middle of the day.

To estimate the number of baetids in the total stream drift, students will need to measure the stream profile, calculate flow, and make assumptions about the distribution of insect drift through the stream channel. With this information, students can estimate the total number of baetids in the drift per hour for that cross section of the stream and then convert that value to calories. This requires that students know the mass of a baetid, which can be estimated by measuring the mean length of the specimens. Students estimate the mean length of 10–20 baetids and use an empirical model to calculate the mean mass as follows (Benke et al., 1999): baetid dry mass (mg) = length (mm)$^{2.875} \times 0.0053$.

Using published caloric values of baetids (Cumminns & Wuycheck, 1971), students estimate the total calories of insects in the stream cross section. We ask our students to convert this value to their favorite food and estimate the daily and annual number of servings in the drift. The sample unit in this experiment is kilocalories per day.

Caution should be taken when conducting this experiment, because drift nets can harm or kill insects if they are not checked frequently enough. It is not necessary to leave the drift net in the stream more than an hour, and low numbers of insects captured can still be used to estimate energy.

Life History & Disturbance

Disturbance in streams is primarily associated with high-flow flood events that mobilize and turn over rocks on the stream bottom. When streambed mobilization occurs, insects detach from the

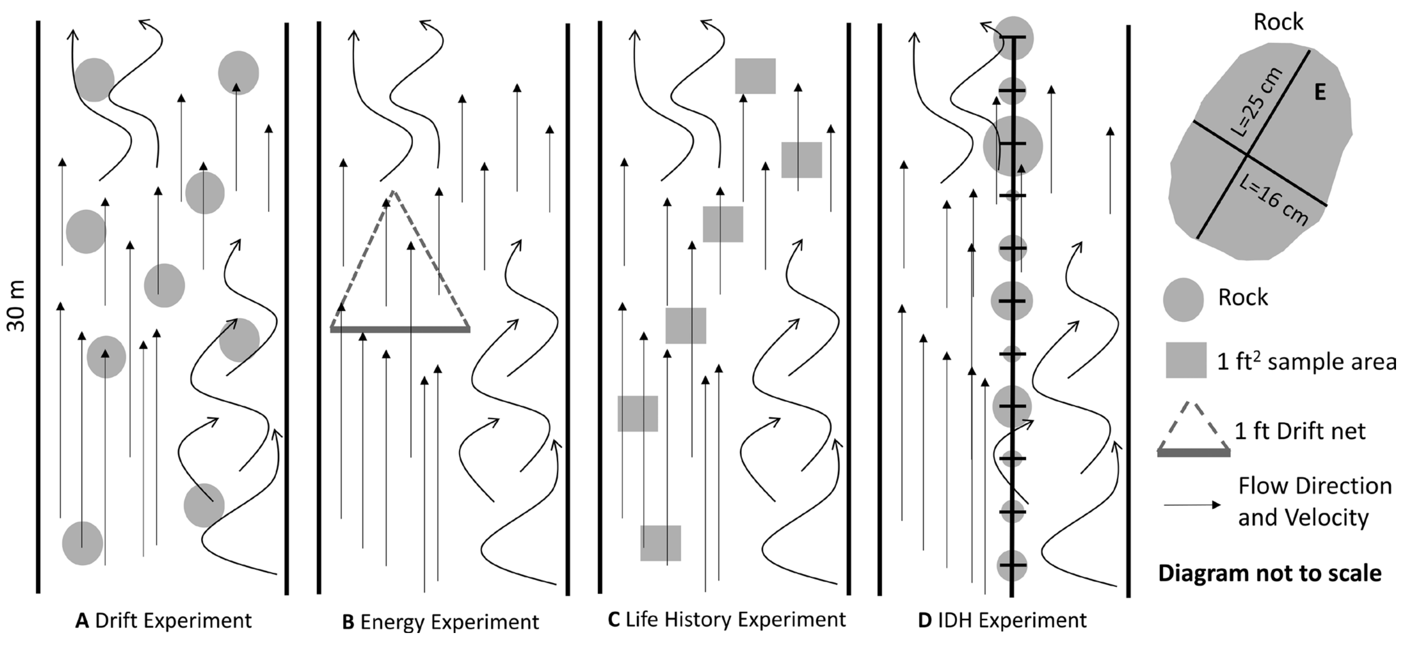

Figure 2. (**A–D**) Setup for each disturbance experiment in relation to flow variability in a 30 m reach of stream. For experiments in which rock size is measured, a string is wrapped around the two longest axes to estimate rock surface area (**E**). Diagram not to scale.

substrate and drift downstream (Gibbins et al., 2007). When the flood subsides, insects begin recolonizing the open habitat by drifting in from upstream. Life history traits can be generally categorized as either *r*- or *K*-selected: *r*-selected insects are highly mobile drifters and early colonizers of open substrate, while *K*-selected insects are late colonizers and typically associated with stable environments.

In this experiment, students disturb the substrate and then observe the initial stages of succession by documenting the quick colonization of *r*-selected insects. Students disturb one square foot of the stream bottom and use a D-net to capture insects leaving the area (Figure 2C). Students place the insects in a tub and then categorize them as either *r*- or *K*-selected. This sample is considered the pre-disturbance community. Four to 24 hours later, students resample the same locations and count the number of mayflies, stoneflies, caddisflies, and true flies. This sample is considered the post-disturbance sample. The most common *r*-selected insects in a stream are baetids, but other common *r*-selected insects include black flies (Simuliidae) and midges (Chironomidae). Stoneflies, caddisflies, and mayflies (other than Baetidae) are generally *K*-selected (Poff et al., 2006). Using percentages of *r*- and *K*-selected, students compare the pre- and post-disturbance communities. The dependent variables in this experiment are the percentages of *r*-selected and *K*-selected insects, while the independent variable is pre- and post-disturbance. The sample unit is each one square foot of substrate. The hypothesis of this experiment is that the percentage of *r*-selected insects will increase in the post-disturbance samples. Data from this experiment can be displayed using box plots and statistically analyzed with a *t*-test comparing the pre/post percentages of *r*-adapted.

Intermediate Disturbance Hypothesis

The intermediate disturbance hypothesis (IDH) describes the relationship between disturbance regimes and biodiversity. Initially documented in coral reefs with hurricane disturbance (Connell, 1978), the IDH predicts that the highest levels of biodiversity are maintained at moderate levels of disturbance. The relationship between biodiversity and moderate levels of disturbance is a critically important aspect of ecology and environmental science that few students fully understand. In streams, the major form of disturbance is substrate movement due to high-flow events. This process is one of the primary controls of algal succession and diversity in streams (McCormick, 1996). Diatoms are single-celled algae with silica cell walls that grow on the surface of rocks and other submerged substrate in streams (Stevenson et al., 2010). Early-successional stages of diatoms dominate small rocks that frequently roll over, while late-successional stages of diatoms dominate large rocks that rarely move. Thus, according to the IDH, the highest diversity of diatoms should be found on the medium-sized rocks that experience moderate levels of disturbance (McCormick, 1996).

In this experiment, insect abundance serves as a proxy for diatom diversity because diatoms cannot be identified and counted in the field. This approach requires the assumption that more diatom diversity presents more feeding opportunities and thus more insect abundance. This may not be the case in streams that are polluted or experiencing algae blooms. To explore this assumption, we sampled diatoms from 11 rocks and correlated diatom richness with a small range of rock sizes.

To conduct this experiment, students collect 20–40 rocks from the stream (Figure 2D), place each rock in a white tub, remove and count the insects, and then measure the rock to estimate surface area (Figure 2E). In this experiment, the independent variable is rock size, while the dependent variables are insect counts. The sample unit is each rock. The hypothesis is that the medium-sized rocks will have the highest insect abundance, which can be statistically evaluated using R^2 and *p*-value.

○ Results

Insect Drift & Colonization

We have conducted the drift and colonization experiment 15 times with our students, and nine of those experiments resulted in data that supported the hypothesis that insect colonization of rocks would be positively correlated with velocity. Here, we include two student-collected data sets to illustrate representative results (Figure 3A, B). The first data set was collected by high school students and illustrates a positive linear relationship (R^2 = 0.80) between insect counts and stream velocity. The second data set was collected by college students and shows a nonlinear (second-order polynomial)

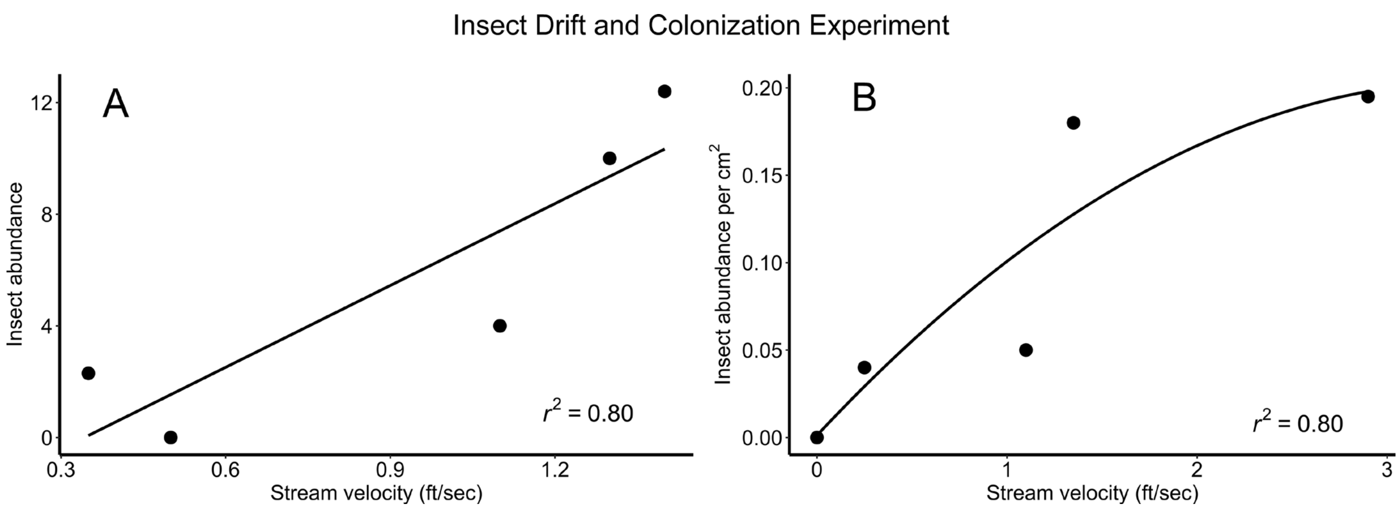

Figure 3. Example student results from the drift and colonization experiment. (**A**) Linear and (**B**) polynomial models for two different colonization experiments from different streams. Insect abundance was expressed as counts per rock (A) or as a density per square centimeter of rock (B).

relationship between insect density (abundance/cm^2) and stream velocity (R^2 = 0.80).

Energy in the Drift

Our students have conducted this experiment four times, resulting in estimates of 65,000–500,000 baetids in the drift each day. This estimate is based on a relatively small number (25–200) of baetids captured in the drift net. Using a mean baetid length of 5.5 mm, our students estimated that 3–356 g of baetids are drifting by a point in the stream every day. Using 5750 calories per gram of baetids, our students estimated 300–2000 kilocalories of energy in the drift per day, which represents about four slices to nearly 1.5 loaves of bread. The total energy in a stream system can be estimated by multiplying this value with the total length of the stream in feet.

Life History & Disturbance

We have conducted the life history experiment 21 times with our students, and 17 of those experiments resulted in data that supported the hypothesis that *r*-selected insects will increase after disturbance. Here, we include a student-collected data set to illustrate the range of typical results (Figure 4A, B). Figure 4A shows an increase in the percentage of *r*-selected insects from 57% in the pre-disturbance insect community to 81% in the post-disturbance community ($p < 0.05$). *K*-selected insects showed the opposite pattern, decreasing from 43% to 19% in the post-disturbance community ($p > 0.05$). Figure 4B shows weaker results, but a similar pattern is evident.

Intermediate Disturbance Hypothesis

Our students have conducted the IDH experiment 16 times, with 14 of those experiments resulting in data that supported the hypothesis. Typical results show that insect abundance (Figure 5A) and insect density (Figure 5B) are highest on the medium-sized rocks. A second-order polynomial regression model best fit the data and showed that insect abundance and density were correlated with rock size (R^2 = 0.60 and 0.28, respectively). A second-order polynomial also described the relationship between diatom richness and rock size (R^2 = 0.27), with the highest richness observed on the medium-sized rocks (Figure 5C).

○ Discussion

Drift Experiment

The drift experiment demonstrates one of the primary mechanisms for insect dispersal in streams and the colonization of open stream habitat. The polynomial curve observed (Figure 3B) in some of the students' data is common in natural settings and illustrates a leveling-off of the relationship between colonization and stream. To ensure the success of the drift experiments, make sure that students place rocks in a wide range of velocities.

Energy Experiment

The energy experiment illustrates the large amounts of insect biomass and calories that are in the stream drift and fluxing through stream ecosystems. This experiment always generates useful data; however, the main concern is with the accuracy of the biomass estimates. In the four experiments our students conducted, the estimated number of baetids in the drift ranged from 65,000 to 500,000 per day, which is within the range observed by Allan (1987) for a small stream in Colorado. We ask our students to consider whether they overestimated or underestimated the number of baetids in the drift and to give possible explanations for the error in their estimate. To ensure the success of this experiment, students should place the drift net in a moderate current, empty the net at least every hour, and ensure that the experiment is not conducted in the fall, when leaves in the stream will clog the net.

Life History Traits & Disturbance

The life history experiment documents the early stages of succession after a disturbance, when insects with *r*-selected traits

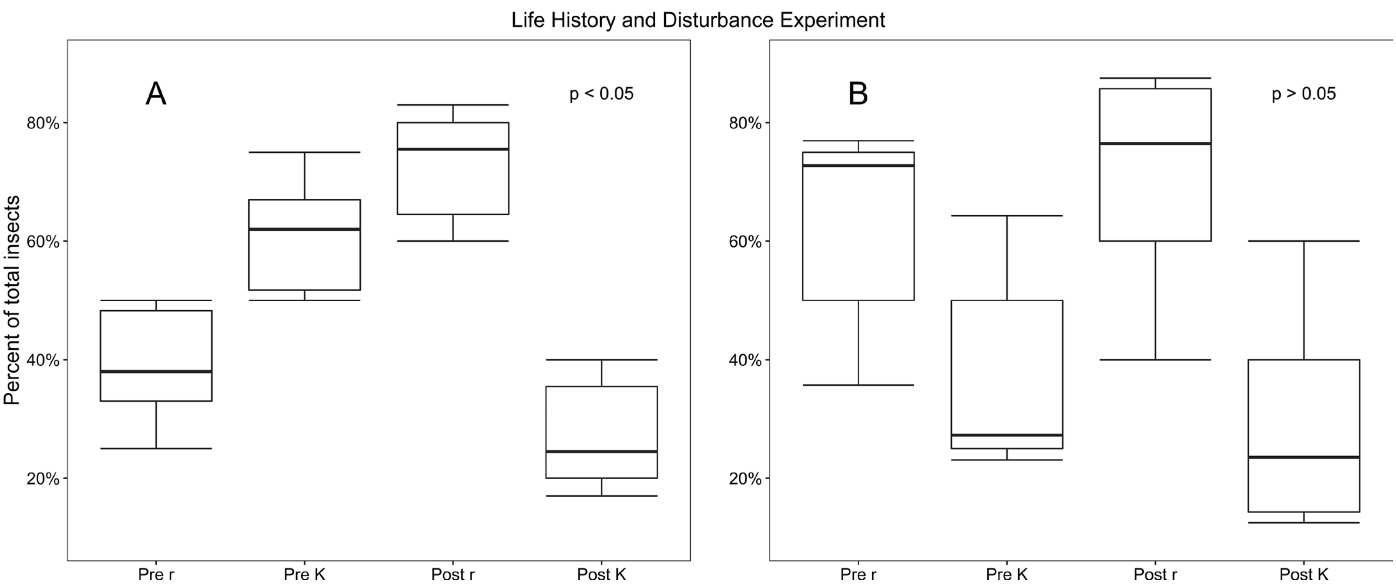

Figure 4. Examples of student data from the life history and disturbance experiments, showing the range of typical results obtained from this experiment. Box plots show pre-disturbance (pre) and post-disturbance (post) percentages of *r*-selected and *K*-selected insects. A *t*-test comparing the "pre" and "post" means of percentage *r*-selected were used to generate *p*-values.

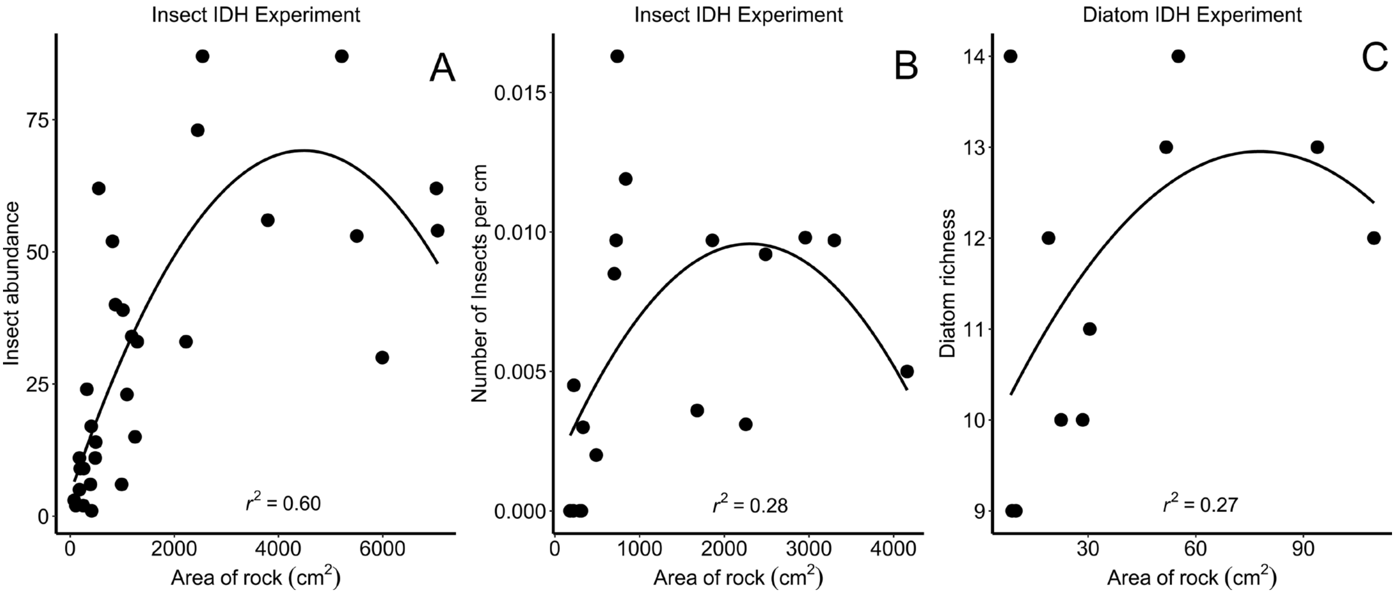

Figure 5. Example student results from the intermediate disturbance hypothesis (IDH) experiments. Scatter plots show the relationship between (**A**) insect abundance and rock size, (**B**) insect density and rock size, and (**C**) diatom richness and rock size.

rapidly colonize open habitat. Eighty-one percent of the experiments our students conducted showed a moderate to a strong increase in *r*-selected insects and a decrease in *K*-selected insects after disturbance. To ensure the success of this experiment, minimize the amount of time between pre- and post-disturbance sampling. In our experience, after more than 24 hours, the *r*- and *K*-selected insects are already reaching equilibrium. This experiment could be conducted with as little as an hour between pre- and post-disturbance samples.

Intermediate Disturbance Hypothesis

The IDH experiments show that the medium-sized rocks have the highest insect abundance and that diatom diversity is associated with rock size. These findings illustrate the importance of a diverse algal food source and the role of substrate disturbance regimes in maintaining biotic communities. Eighty-eight percent of the experiments conducted by students resulted in data that supported the hypothesis that medium-sized rocks will have the highest abundance of insects. While the diatom richness data were obtained from a smaller range of rock sizes, these findings suggest that diatom richness is also higher on medium-sized rocks. This provides a possible explanation for the patterns observed in the insect data; high diatom richness on the medium-sized rocks provides more insect feeding opportunities and thus results in a higher abundance of insects. However, it is important to recognize that this experiment only provides correlational evidence of this relationship and there could be other explanations for the observed results, including stream pollution, substrate type, or overall habitat stability. We encourage our students to explore alternative explanations for their results and have found that this generates in-depth conversations about experimental design and causation. To ensure the success of this experiment, make sure that a wide range of rocks sizes are collected, from small pebbles to the largest rocks that students can reasonably handle.

○ Conclusions & Recommendations

Our findings show that the disturbance experiments can be used as a framework for inquiry-based learning about important ecological principles related to disturbance, dispersal, colonization, and succession. Of the 57 times we conducted these experiments, 45 resulted in data that supported the hypothesis. The value of these experiments is that they are reliable, ethical, require very little equipment, and are quick to set up and harvest (<1.5 hours). There are several sources of error related to the disturbance experiments that are important to recognize. Type 1 errors (false positives) in these experiments are likely associated with mistakes in data collection or the influence of other variables such as flow, substrate texture, or upstream disturbance that could not be controlled in the field or was not measured by students. Type 2 errors (false negatives) are likely due to low statistical power, mistakes in harvesting of substrates, or mistakes in data collection. Table 3 summarizes the potential error for each experiment. All of the experiments are vulnerable to being confounded by a disturbance upstream of the experimental reach that causes insects to drift down into the experiments. As already noted, to ensure that confounding disturbances do not occur, students should install experiments moving downstream and harvest experiments moving upstream. Harvesting rocks slowly or haphazardly can result in a major loss of insects from the rock surface.

As with all inquiry-based learning that takes place in the field, it can be challenging to implement curriculum, conduct the experiments, and account for the uncertainty in experimental outcomes. We encourage teachers who conduct these experiments to communicate the challenge and uncertainty of field experiments, letting students know that there are no failed experiments and that the results that do not support the hypothesis are still a valuable outcome. The research approval process is a critical point in

Table 3. Summary of the potential scientific error associated with each experiment. This information will help students think about their experimental error. A type 1 error occurs when the hypothesis *is* supported by the data. A type 2 error occurs when the hypothesis *is not* supported by the data.

Experiment	Potential Causes for a Type 1 Error (False Positive)	Potential Causes of a Type 2 Error (False Negative)
Insect drift and colonization	Recent disturbance upstream. Confirmation bias when counting insects. Confounded by some other stream variable such as food availability or rock texture.	Velocity gradient too short. Mistakes harvesting rocks. Placement of experimental rocks behind large logs or boulders that block drift.
Energy in the drift [a]	Inaccurate measurements of flow. Assuming baetid drift is the same across the stream cross section or the same throughout the day.	Net clogged or placed in high-velocity/turbulent section of the stream. Not counting very small specimens.
Life history and disturbance	Misidentification or misclassification of insects. Confirmation bias when counting insects.	Misidentification or misclassification of insects. Collecting outside of the pre-disturbed area. Too much time between pre- and post-disturbance.
Intermediate disturbance hypothesis (IDH)	Confounded by another stream variable such as flow, food availability, or rock texture.	Gradient of rock sizes too short. Too few samples. Mistakes harvesting rocks.

[a] This experiment is not based on a hypothesis, so we evaluate causes of underestimating or overestimating energy in the drift.

the curriculum and should be a collaborative and guided learning experience so that students fully understand the design of the experiment and are prepared to conduct a successful experiment. When experiments cannot be successfully completed, for example because of high-flow events or when experiment substrate is lost, we let students use data from a previous class. And finally, most experiments will have a sample that is an outlier or whose accuracy is questionable. We ask that students make field notes about anomalous data and encourage discussions about how to deal with confounding data. In our experience, anomalous data generate valuable in-depth discussions about experimental design, hypothesis testing, and sources of error or bias when collecting data.

We were unable to formally assess the student outcomes of these experiments, but we did evaluate student learning as part of the regular classroom activities. We gave students an exam about their experiment, asking them to describe the independent and dependent variables, draw a graph showing the results, and explain the potential type 1 and type 2 errors associated with the experiment. We also graded posters using a rubric that assessed students' content knowledge and their understanding of experimental design, data analysis, and communication of science. In general, the exams and posters showed that students understood the material associated with the experiments and had an in-depth understanding of experiment design. These anecdotal results suggest that our curriculum and student outcomes are addressing and meeting the NGSS standards.

○ Acknowledgments

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