**Investigating the ecological value of migratory fishes on stream ecosystems in southern Appalachia**

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**Summary:** Using the Ecological Society of America’s Four-Dimensional Ecology Education (4DEE) framework, students apply ecological concepts such as energy flow, nutrient cycling, migration, and climate change and practice interpretation and analysis of ecological data through a multi-class case study focusing on an inland migration of a group of freshwater fishes in headwater streams of southern Appalachia.

**Keywords:** stream ecology, fish, Appalachia, nutrient cycling, migration

**Ecological Question:** What is the ecological value and impact of inland fish migration to stream ecosystem dynamics?

**Ecological Content:** A study of fish migration is used to understand nutrient cycling, organismal response to environmental cues, and stream ecology and how these can be affected by changes in climate and human activity in landscapes.

**Four Dimensional Ecology Education (4DEE) Framework:**

* Core Ecological Concepts:
  + Autoecology – abiotic and biotic features; global climate change
  + Community – behavioral ecology
  + Ecosystems – energy flow – productivity; nutrient cycling – nutrients
  + Landscapes – watersheds
  + Biosphere – global climate change
* Ecological Practices:
  + Quantitative reasoning and computational thinking – Statistics; data skills
  + Working collaboratively
  + Communicating and applying ecology
* Human-Environment Interactions:
  + Human accelerated environmental change – Global climate change
  + How humans shape and manage resources/ecosystems/the environment – Conservation biology
* Cross-cutting Themes:
  + Pathways and Transformations of Matter and Energy
  + Systems
  + Spatial and Temporal – Scales; stability and change

**What Students Do:**

* Read articles on nutrient contribution to streams by migratory fishes.
* Hypothesize how changes in migratory fish populations may affect stream dynamics.
* Analyze a dataset on migration patterns for a fish species of conservation concern in a southern Appalachian stream.
* Predict how changes in migration patterns due to upon climate change may impact stream ecosystems.
* Illustrate and describe the connections between headwater stream productivity, migratory fishes, nutrient cycling, and climate change.

**Alignments:**

Resource Type – Teaching material; lecture

Audience Level – Undergraduate; introductory; non-majors

Activity Length – 4 distinct lessons with each designed for a 50-minute class session.

**Skills:**

Exploring peer-reviewed literature, navigating and analyzing data sets, creating graphs, connecting data analysis results to ecological concepts

* What students should learn from this lesson: Students should understand the importance of nutrient delivery by migrating species to an ecosystem, the importance of the timing of migration, and how climate change and human manipulation of the environment can disrupt migration processes.
* What skills students should acquire from this lesson: reading peer-reviewed literature, working with data sets, construction of graphs, connecting data and knowledge to an ecological issue

**Student Assessments:**

Formative assessments – completion of flipped learning worksheets prior to each lesson and in-class worksheets, concept mapping, written summaries, interpretations of figures and data.

Summative assessment – construction of a poster illustrating connections between ecological concepts described in the case study.

**Outcomes:**

The activity is designed using the Ecological Society of America’s Four-Dimensional Ecology Education (4DEE) framework. The 4DEE framework incorporates ecological concepts, ecology practices, human-environment interactions, and cross-cutting themes to teach ecology in a multi-dimensional process. The activity requires students to investigate scientific papers, work with data, create and interpret graphs, and connect finding to core ecological concepts such as nutrient cycle, abiotic factors, global climate change, and anthropogenic impacts to landscapes and watersheds. Students complete worksheet, draw a concept map, construct hypotheses and make predictions, interpret data and graphs, and construct a poster describing connections among ecological concepts.

**Transferability:**

This exercise is designed for a college course that may consist of both biology majors and non-majors in an introductory biology course. It can be adapted for incorporation into a majors level ecology course. The analysis of peer-reviewed literature and datasets is useful skills across most disciplines and fields and is necessary in graduate schools and post-graduate work. Because an underlying theme of this activity is water quality and productivity of waters, it is applicable to students living in and engaging with watersheds and who will contribute to decisions about watershed health in the future. The activity allows students to explore connections between conserving biodiversity, stream health and water quality, climate change, and anthropogenic activities in landscapes.

**Datasets:**

The data in this lesson are modified from their original sources and from publicly available locations.

* Data from the U.S. Geological Survey from a gauging station from a stream near the site of migration data collection that includes data from March 1 – June 31, 2017 and March 1 – June 31, 2018, is stored as an excel file and used to construct a histogram. This time period encompasses the migration period for sicklefin redhorse.
* This exercise include data on the movement patterns of sicklefin redhorse from a southern Appalachian stream that was collected in Spring 2017 and 2018. Sicklefin Redhorse Movement data consisted of detections of 149 individuals tagged with a passive integrated transponder (PIT) tag who moved across an antenna detection wire buried in the substrate of a stream. The first detection corresponds to the time at which the first enters the spawning area, and the last detection corresponds to the time at which the first leaves the spawning area. Residence time in headwater stream spawning sites is calculated as the time from the first and last detection. Data on the total length of each fish at the time of tagging and capture is included along with sex of the individual. Thus, students can investigate if residence time varies by year, sex and total length. With inclusion of data on stream discharge and water temperature (see below), students can ask additional questions.

**Downloads and Resource Files:**

Module Description

* Investigating the ecological value of migratory fishes on stream ecosystems in southern Appalachia.docx
* Overview – Investigating the ecological value of migratory fishes

Assigned Readings

* Kamnitzer, R. 2024. Salmon and other migratory fish play crucial role in delivering nutrients. <https://news.mongabay.com/2024/01/salmon-and-other-migratory-fish-play-crucial-role-in-delivering-nutrients/>
* White, M., K. Wheeler, R.R. Hudson, and J.N. Murdock. 2023. Salmon of the southeastern U.S.: Sucker migrations deliver resource subsidies to oligotrophic stream. Ecology of Freshwater Fish 32(1):181-194.
* Hudson, R.R., K. Wheeler, M. White, and J.N. Murdock. 2023. Migratory redhorse suckers provide subsidies of nitrogen but not phosphorus to a spawning stream. Ecology of Freshwater Fish 33(2):1-12.
* Miltner, R.J., White, D., and C.O. Yoder. 2004. The biotic integrity of streams in urban and surburbanizing landscapes. Landscape and Urban Planning 69:87-100.
* Jones, N.E. and R.W. Mackereth. 2016. Resource subsidies from adfluvial fishes increase stream productivity. Freshwater Biology 61:991-1005.
* <https://www.fws.gov/story/fish-wears-feather>. The fish that wears a feather. U.S. Fish and Wildlife Service.
* Robinson, R.A. et al. 2009. Traveling through a warming world: climate change and migratory species. Endangered Species Research 7:87-99. Students should read the abstract, introduction, and the “Timing of arrival” section on p. 92.

Datasets

* MeanDischarge 2017 and 2018.csv
* SFR Movement Data.csv

R Code for Data Analysis

* Lesson 3 Analysis of Residence Time\_RMarkdown.Rmd

Pre-Class Handouts

* Lesson 1 Flipped Learning Assignment\_instructor copy.docx
* Lesson 1 Flipped Learning Assignment\_student copy.docx
* Lesson 2 Flipped Learning Assignment\_instructor copy.docx
* Lesson 2 Flipped Learning Assignment\_student copy.docx
* Lesson 3 Flipped Learning Assignment\_instructor copy.docx
* Lesson 3 Flipped Learning Assignment\_student copy.docx
* Lesson 4 Flipped Learning Assignment\_instructor copy.docx
* Lesson 4 Flipped Learning Assignment\_student copy.docx

In-Class Handouts

* Lesson 1 In-class Inquiry Activity\_instructor version.docx
* Lesson 1 In-class Inquiry Activity\_student version.docx
* Lesson 2 In-class Inquiry Activity\_instructor version.docx
* Lesson 2 In-class Inquiry Activity\_student version.docx
* Lesson 3 In-class Inquiry Activity\_instructor version.docx
* Lesson 3 In-class Inquiry Activity\_student version.docx
* Lesson 4 In-class Inquiry Activity\_instructor version.docx
* Lesson 4 In-class Inquiry Activity\_student version.docx

Assessment

* Poster Rubric

**Acknowledgments**

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**Introduction**

Rivers and streams are characterized by flowing water and are referred to as a **lotic** systems. Streams are small, often have steep gradients, and are mostly reliant on secondary production from leaves, twigs, grasses, and other material that originates from outside the stream. This is referred to as **allochthonous** material. Streams typically receive little production from photosynthesis. Streams are cooler, shallower, have clear flowing water, and often have bottoms with stones of various sizes. The composition of the bottom combined with the volume of flowing water, the **discharge**, are the primary features of the various stream habitats. Streams change greatly from their sources to their terminus. **Headwater streams** are small streams in the upper portion of the watershed. They generally have the clearest water and are shaded by vegetation in the **riparian zone**, the area of land adjacent to the stream. The shaded riparian vegetation keeps water temperatures low to support cold water biological communities and minimizes erosion of sediment, which supports clean substrates used by bottom-oriented species.

Small streams occur through the U.S., resulting in a diverse network of stream ecosystems. Although their small size results in diverse habitats, it also makes them very sensitive to disruption and degradation. Harmful activities include logging, construction and development, surface water withdrawal, removal of streamside vegetation, and erosion. Removal of the riparian zone results in a rise in water temperature from loss of shade, increased variation in flow rates, intensified erosion that leads to turbidity, siltation, loss of nutrient inputs from falling leaves and fruits, and limits inputs of woody debris. Because of their small size, the degradation, value, and importance of small streams are often overlooked. In terms of area, small streams are the greatest reserves of aquatic biodiversity, supporting unique and endemic species. Moreover, recent loss of legal protection for headwater streams may increase their vulnerability to ecosystem impairment, reduce water quality and ecosystem services, and affect the sustainability of cultural services that headwater streams have for many native peoples (Colvin et al. 2019).

The ecological processes of small streams are a critical component of the network of streams in a watershed. In small, headwater streams, organic matter and nutrients that support the living biomass comes mostly from allochthonous material, the course organic matter that enters from the riparian zone. Specialized organisms known as shredders take this organic matter, such as leaves and twig, and convert them into smaller, more digestible parts for other organisms located downstream that specialize in collecting and filtering. Thus, the contribution of organic material affects the amount of production and nutrients available for organisms living downstream. To maintain the ecological health and productivity of a network of streams, ensuring proper connectivity of headwaters to downstream segments is important, but ensuring that adequate nutrients are available from upstream sources is critical also.

Headwater streams heavily influence downstream waters, but movement by migrant organisms in the other direction, from downstream to upstream, can also influence upstream headwaters. Small streams are important spawning habitat for species that live in larger streams but migrate upstream to reproduce. Various fish species, including salmonids, darters, and suckers, migrate upstream to headwaters that serve as spawning and nursery habitats. These headwaters can provide protection from high flows, competitors, and predators and provide abundant food resources (Meyer et al. 2007).

Salmonids are perhaps the most publicized and known migratory fishes in the U.S. Salmon are born in natal headwater streams and then progress downstream as juveniles, eventually entering into the ocean to feed and grow as adults. Famously, adult salmon then complete a long migration upstream back to the stream from which they were born, reproduce, and then die. This act of reproduction and death in the headwater stream is critical to both the aquatic ecosystem and surrounding terrestrial ecosystems. Many studies have documented the importance of migratory salmon as transporters of energy (i.e. carbon, nitrogen, phosphorus, and calcium) between marine and freshwater ecosystems. Migrating salmon are captured by terrestrial predators; eggs and gametes are released into water; and dead carcasses of salmon litter the stream after reproduction. These are sources of nutrients that affect the productivity of local food webs and affects the flora and fauna in these ecosystems.

Whereas salmon are **anadromous**, making long distance migrations as adults from the ocean to freshwater streams, some fishes complete shorter migrations from large inland rivers and lakes to upstream headwaters. Many species within the taxonomic group of fishes known as suckers carry out annual spawning migrations. Having received very little consideration and attention compared to salmon, recent research suggests that upstream migration of suckers may deliver nutrients at a critical time when headwater streams have low nutrient availability (Childress and McIntyre 2015; Jones and Mackereth 2016; Hudson et al. 2023). The quantity of these nutrients is substantial and may be ecologically important to the function of headwater streams where migrations occur (White et al. 2022).

This exercise investigates the importance of inland migrations by redhorse suckers (*Moxostoma spp.*) in headwater stream ecosystems, using a redhorse species of conservation concern in southern Appalachia as an example. Because of their potential to deliver nutrients to inherently low nutrient headwater streams, redhorses and other migratory suckers likely play an important ecological role and, as a result, warrant greater consideration for conservation.

Migratory fishes face many threats, and the decline of migratory fishes and disruption to their migratory processes can greatly alter stream dynamics. The decline of salmon populations due to commercial harvest, dam construction, and habitat loss is well-documented and has resulted in a 90% decrease of nutrients in some headwater stream ecosystems (Naiman et al. 2012). Anecdotal evidence suggests that spawning runs of suckers historically were also of a much greater magnitude. Human activities that convert landscapes to agricultural and urban uses disrupt stream processes, reduce water quality, and change ecological communities (Miltner et al. 2004). Human disturbance and urban development in the southeastern U.S. has resulted in significant loss of stream fish biodiversity and biomass (Scott 2006). On a small scale, small dams and road crossings can negatively affect fish migration, and thus, nutrient amounts in headwater streams. More broadly, freshwater biodiversity is highly vulnerable to climate change with coldwater organisms, such as those in headwater streams, predicted to suffer the greatest impacts (Heino et al. 2009). This exercise concludes with a consideration of how these threats may alter headwater nutrient availability by disrupting migration processes.

**Literature Cited**

Childress, E.S. and P.B. McIntyre. 2015. Multiple nutrient subsidy pathways from a spawning migration of iteroparous fish. Freshwater Biology 60:490-499.

Colvin, S.A. et al. 2019. Headwater streams and wetlands are critical for sustaining fish, fisheries, and ecosystem services. Fisheries 44(2):73-91.

Heino, J., Vikkala, R., and H. Toivonen. 2009. Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in northern regions. Biological Review 84:39-54.

Hudson, R.R., K. Wheeler, M. White, and J.N. Murdock. 2023. Migratory redhorse suckers provide subsidies of nitrogen but not phosphorus to a spawning stream. Ecology of Freshwater Fish 33(2):1-12.

Jones, N.E. and R.W. Mackereth. 2016. Resource subsidies from adfluvial fishes increase stream productivity. Freshwater Biology 61:991-1005.

Meyer, J.L., D.L. Strayer, J.B. Wallace, S.L. Eggert, G.S. Helfman, and N.E. Leonard. 2007. The contribution of headwater streams to biodiversity in river networks. Journal of the American Water Resources Association 43(1):86-103.

Miltner, R.J., White, D., and C.O. Yoder. 2004. The biotic integrity of streams in urban and surburbanizing landscapes. Landscape and Urban Planning 69:87-100.

Naiman, R.J. et al. 2012. Developing a broader scientific foundation for river restoration: Columbia River food webs. Proceedings of the National Academy of Science 190(52):21201-21207.

Scott, M.C. 2006. Winners and losers among stream fishes in relation to land use legacies and urban development in the southeastern U.S. Biological Conservation 127:301-309.

White, M., K. Wheeler, R.R. Hudson, and J.N. Murdock. 2023. Salmon of the southeastern U.S.: Sucker migrations deliver resource subsidies to oligotrophic stream. Ecology of Freshwater Fish 32(1):181-194.

**Activity Structure**

This case study is designed to align with an active learning environment in which class time is spent on hands-on activity and guided inquiry with passive learning via lecture kept to a minimum. This activity best aligns with flipped learning design in which students engage with important course content and concepts prior to class to prepare for in-class work. Thus, the lessons are designed to incentivize the completion of pre-class work and recommend formative assessment to monitor student activity and accomplishment of learning objectives. Completion-based, failure-tolerant assessment methods are also recommended for pre-class work.

The activity also assumes a previous introduction to the ecological concepts pertinent to the case study. The case study is designed to be taught over 4 50-minute class sessions but can be modified to reduce the number of class days required. It is described here as an implementation at the end of a course but may be modified to be integrated over multiple weeks, revisiting the case study where appropriate.

Several readings and videos are required as pre-class work. It is recommended, where possible, that instructors utilize resources such as EdPuzzle for videos, which allow students to receive credit for watching the video and instructors to embed questions in videos to check for student understanding, and Perusall, which tracks student engagement with readings and allows students and instructors to converse digitally with assigned readings.

**Lesson 1**

Required Background Information:

An introduction to energy flow in ecosystems and nutrient cycling, particularly carbon, nitrogen, and phosphorus cycles.

Pre-class requirements**:**

Students should watch the following videos prior to class.

<https://www.youtube.com/watch?v=KzlBtMFc43s> Did you know? Fish migrate too! Publisher: U.S. Fish and Wildlife Service. Run time: 2:03.

<https://www.youtube.com/watch?v=P_ROqvC59D4> Salmon’s life cycle and their incredible impact on our ecosystem. Publisher: Ocean Wise. Run time: 3:47.

Students should read the following article prior to class.

Kamnitzer, R. 2024. Salmon and other migratory fish play crucial role in delivering nutrients. <https://news.mongabay.com/2024/01/salmon-and-other-migratory-fish-play-crucial-role-in-delivering-nutrients/>

Students should complete the “Lesson 1 Flipped Learning Assignment” prior to class.

During class:

The activity for class can be structured in various ways to create an active learning environment, and instructors are encouraged to modify the activity to suit their teaching style and class structure. Students should have previously been introduced to energy flow and nutrient cycling and specifically the nitrogen and phosphorus cycle (N/P) prior to this lesson.

Warmup Activity – Ask students to discuss their answers to the Lesson 1 Flipped Learning Assignment.

Lesson 1 In-class Inquiry Learning Activity - Students work through a handout to apply the concepts of energy flow and nutrient cycling to Pacific Salmon migration. The class starts with a student discussion reviewing the Lesson 1 Flipped Learning Assignment. Discussion prompts asks students to draw connections between the Pacific salmon and ecological concepts and highlight the contribution of Pacific Salmon in the nitrogen cycle. Students produce a concept map that traces the effects of salmon migration on aquatic and terrestrial ecosystems.

After class:

An optional extension activity asks students to research a species with a terrestrial migration and summarize its effects on ecosystems and how humans are impacting migration. The summary can be constructed in a written format or as a visual diagram. Additionally, this extension can be modified for students to construct an AI-generated summary that is then translated into a diagram by the student. After class, student can conduct pre-class work for Lesson 2.

**Lesson 2**

Required Background Information:

An introduction to watersheds and aquatic ecosystems; familiarity with aquatic organisms

Pre-class requirements:

Students watch three videos describing headwater streams and watersheds, energy flow and nutrients in streams, and inland fish spawning migration of smallmouth buffalo, a type of sucker fish in the Appalachian Mountains.

<https://www.youtube.com/watch?v=xT_ww9f6BQU> Conservation 101: Headwaters and watersheds. Publisher: Southern Appalachian Highlands Conservancy; Run time: 5:09

<https://www.youtube.com/watch?v=dDnk0PEo98k> Follow that Nutrient. Publisher: KQED QUEST; Run time: 5:33

<https://www.youtube.com/watch?v=m78c066ZBVo> Behold the Smallmouth Buffalo migration – the southeast’s answer to the salmon run. Publisher: Tennessee Aquarium; Run time: 3:27

Students should complete the “Lesson 2 Flipped Learning Assignment” prior to class that corresponds to the content on the videos.

Student are assigned two papers to review describing the nutrient contribution of spawning suckers to the supply of nutrients in mountainous streams. It is suggested that software such as Perusall is used to track and assess student engagement with readings.

White, M., K. Wheeler, R.R. Hudson, and J.N. Murdock. 2023. Salmon of the southeastern U.S.: Sucker migrations deliver resource subsidies to oligotrophic stream. Ecology of Freshwater Fish 32(1):181-194.

Hudson, R.R., K. Wheeler, M. White, and J.N. Murdock. 2023. Migratory redhorse suckers provide subsidies of nitrogen but not phosphorus to a spawning stream. Ecology of Freshwater Fish 33(2):1-12.

During class:

Students apply their understanding of nutrient dynamics of headwater streams, specifically discussing how stream productivity is subsidized by the import of nutrients from redhorses through a review of Hudson et al. (2023). Students interpret data and draw conclusions from the study. They apply their understanding and conclusions from the study to new data that is introduced and analyze how migration, and therefore, stream productivity may be influenced by climate change in the southeastern U.S.

Warmup Activity – Ask students to discuss their answers to the Lesson 2 Flipped Learning Assignment and construct a diagram of nutrient pathways in a stream.

Lesson 2 In-class Inquiry Learning Activity – Students complete a handout that reviews Hudson et al. (2023), including interpretation of figures from the paper. Students hypothesize about the ecological relevance of redhorse migration on headwater stream nutrient dynamics. Students review a histogram of stream discharge from two years, comparing the differences between years and discussing how discharge can influence migratory patterns and nutrient dynamics. Students consider the role of discharge and water temperature on migration and analyze the predicted changes in these factors in the southeastern U.S. due to climate change. Students then draw connections between redhorse migration, headwater stream productivity, nutrient dynamics, and predicted climate change.

After class:

Instructors can implement a post-class assessment if they choose. However, next lesson involves statistical analysis of data as pre-class work, which may be time consuming.

**Lesson 3**

Required Background Information:

An introduction to statistical hypotheses (null and alternative), interpretation of P-values, some familiarity with comparisons among two groups and linear regression preferable, and familiarity with interpretation of box plots and scatter plots.

Pre-class requirements:

Students are provided with a data set that provides migration data on a threatened species of redhorse, the sicklefin redhorse, and a handout describing the dataset. Students watch videos introducing the sicklefin redhorse and read a story on sicklefin redhorse. In the handout, students construct several hypotheses based upon a description of the data, propose methods of analysis and graphing, and prepare to conduct an analysis in class.

Students should watch the following short videos prior to class:

<https://www.youtube.com/watch?v=RBSMCUYHakE>. Sicklefin Redhorse Release. Publisher: Tennessee Valley Authority. Run time: 3:12

<https://www.youtube.com/watch?v=sjpMt0vSF6k>. Sicklefin Redhorse (Fyke Net Trap and Tag). Publisher: Arledge Armenaki. Run time: 2:20

Students should read the following story or listen to the podcast episode before class:

<https://www.fws.gov/story/fish-wears-feather>. The fish that wears a feather. U.S. Fish and Wildlife Service. This link also includes a podcast episode from the USFWS’s “Fish of the Week” podcast that can be assigned.

During Class:

Lesson 3 In-class Inquiry Learning Activity – Students review the results of an analysis from a data set describing the migration timing and duration of sicklefin redhorse (“SFR Movement Data.csv”) and determine how migration patterns vary by year, sex, and fish size. Students are presented a handout that includes a series of hypotheses, R code, results from the R code and statistical tests, and graphs produced by the code. The R code and results are provided for efficiency, but an R Markdown file is available as well for instructors to modify and so that students can conduct the analysis themselves if this is desired.

Students must interpret the results from analyses and data presented in graphs to draw conclusions and evaluate the findings in the context of their understanding of ecological concepts and apply the findings relative to nutrient cycles of redhorses that were reviewed in Lesson 2. Students are presented with discussion questions that can be completed in class or assigned as an after-class assessment.

After Class:

Students can complete the discussion questions from the Lesson 3 handout. Alternatively, students can write a summary of the findings from Lesson 3.

**Lesson 4**

Required Background Information:

An understanding of climate change and phenology and demonstrated knowledge from previous lessons.

Pre-class requirements:

Students read a section of an article describing the impact of climate change on migratory species as it relates to the timing of migration. Students watch a video on phenology and migration timing. Students search the literature to find two studies on phenological shifts in migratory fishes. Students complete the Lesson 4 Flipped Learning Assignment, which contains questions related to the reading and video and requires students to summarize the findings of the two studies they found.

Students should watch the following video prior to class:

<https://www.youtube.com/watch?v=RNs3XpRmRfI> Publisher: TED-Ed; Run time: 3:41

Students should read the following article before class:

Robinson, R.A. et al. 2009. Traveling through a warming world: climate change and migratory species. Endangered Species Research 7:87-99. Students should read the abstract, introduction, and the “Timing of arrival” section on p. 92.

During class:

Students consider the impact of climate change on redhorse migration in Brasstown Creek. Students are presented with information on redhorse migration, particularly that the migration is a feeding migration in which a major food source is riverweed. Students are presented with a scenario in which riverweed abundance in the spring is based upon photoperiod. Students must consider the phenological changes in redhorse migration and potential phenological mismatches with their food supply. Students consider this in light of findings from previous lessons. This can include potentially differing effects on fish of different sexes and sizes and the effect on nutrient subsidies and stream productivity.

Students can research how human activities such as erosion and riparian zone removal can impact stream temperatures. Students discuss how this also affects stream temperatures and phenological mismatches.

Students work together to create a poster summarizing the case study and drawing connections between the concepts covered in the lessons. This poster serves as a summative assessment of student learning. A rubric is provided in the case study resources.

After class:

Students work to construct the poster for submission at a later date. Instructors can consider an additional class day for presentation of posters or organize a digital display of posters.