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CourseSource

Lesson

Climate Change Data in the Biology Classroom: Leveraging Long-Term Phenology Field Experiments to Teach About Change in Mountain Ecosystems

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Abstract

Climate change education in biology classrooms requires teachers to address complex ecological systems, change over time, and the interaction between organisms and their environment. Here we present a biology lesson plan to teach students about the ecological consequences of climate change by learning about plant phenological shifts in mountain environments. This skills-based inquiry teaches students about quantitative methods for measuring ecological change, R programming, and scientific writing. Modular activities are integrated with discursive modules built for student-directed exploration of ecological data. The modules are designed for early-stage undergraduate biology students, but we organize materials by skill-based learning objectives so that instructors at levels from high school through undergraduate may also find useful resources in a variety of classroom contexts. Students will gain experience with hypothesis testing, reading primary scientific literature, data analysis, and structured technical writing. Assessments are based on formative, low-stakes writing assignments that are peer-reviewed and summarily combined into a final technical report describing phenological change in montane wildflowers in the Rocky Mountains. We provide all necessary background information pertaining to the case study used in this paper, as well as recent popular science articles, fully reproducible R scripts, and pre-populated data sheets for easy analyses. Our aim is to support teachers who wish to discuss measurements of change over time, evidence-based climate change science, and science communication.

Primary Image: Ecologists (left to right graduate student Ellen Wright, middle school teacher Rhyne Gulley, college student Ellen Warmerdam and graduate student Fatima Alcantara) collecting phenology data from focal species at the Rocky Mountain Biological Laboratory in Gothic, Colorado. Data from this long-term phenology project are used in this teaching resource for guided data analysis and scientific writing about climate change.

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Learning Goals

Over the course of the module, students will:

◊ Understand how climate change is measured quantitatively.

◊ Evaluate the relationship between phenology and biodiversity.

◊ Discuss how graphs and figures communicate scientific results.

◊ Gain hands-on experience with data from a long-term mountain ecology field experiment.

◊ Synthesize multiple sources of information into a written scientific report.

Learning Objectives

At the end of the module, students will be able to:

◊ Write testable and falsifiable hypotheses.

◊ Interpret published results from primary scientific literature.

◊ Collaborate through peer revision of work.

◊ Describe changes in mountain plant phenology as a consequence of climate change.

Ecological Literacy Learning Objectives:

◊ Explain what a long-term study of plant phenology at Rocky Mountain Biological Laboratory teaches us about climate change in the mountains.

◊ Identify the parts of scientific papers.

◊ Distinguish between correlation and causation in ecological studies.

◊ Write and test hypotheses about flowering phenology and temperature in the Rocky Mountains.

Data Skills Learning Objectives:

◊ Download and analyze data from a real scientific study.

◊ Run scripts in the programming language R to produce figures.

◊ Translate numeric data to ecological information by summarizing code and results in plain English.

Science Writing Learning Objectives:

◊ Produce an abbreviated technical paper with key sections (Abstract, Hypothesis, Results, Figures with legends, Annotated References and a Personal Reflection).

◊ Engage in peer review with guidance from the instructor.

◊ Develop and revise their own understanding through the process of writing.

INTRODUCTION

As the planet warms and mountain environments change, flowering and reproduction of montane and alpine plants may be disrupted by loss of protective snow cover during critical stages of plant development, which can expose plants to early freezing temperatures (1). Long-term monitoring is critical for protecting our imperiled mountain habitats and is strengthened by improving scientific literacy through education about the science and data analyses used to measure change over time. Here we provide class materials to support inquiry-driven exploration of the impacts of climate change. Data used in this module were collected from a long-term study that monitors a montane habitat at the Rocky Mountain Biological Laboratory (RMBL), near Crested Butte, Colorado (2).

This sequence was originally developed for a first-year writing seminar offered under the umbrella of a Writing in the Disciplines program, which engages with practices characteristic of the "writing-to-learn" (WTL) movement in science education (3–6). The sequence presented here promotes conceptual scientific learning through tools and methods used by professional scientists (*e.g.,* statistical analysis of field data to study questions about the impacts of climate change) with structured writing activities that encourage students to engage with scientific knowledge as a learning process rather than a collection of facts (6). While not a direct representation of each step in the published pedagogical CREATE model ("Consider, Read, Elucidate the hypothesis, Analyze and interpret data, Think of the next Experiment") (7, 8), the present sequence does address each step of the scientific process in a level-appropriate, integrated way.

Intended Audience

We created and curated materials with instructors of early-stage undergraduate biology classes in mind, though adapted resources could also support teachers of advanced high school biology or upper-level undergraduate classes. Given the emphasis on peer revision and skills-based instruction, we anticipate that lab courses, seminars and other discussion-based classrooms of approximately 15–30 students will be best served by our materials. The original module was designed for early-stage undergraduate students, with and without science backgrounds, who were enrolled in a small writing seminar. It has also been taught, in whole or in part, in labs associated with lectures and data science courses. Differences in classroom contexts (*e.g.,* lab sections versus science writing seminars) were considered in how materials are presented here. While writing assessments were part of the original course and writing prompts are provided, they may be omitted or tailored to fit specific course objectives and assessment styles.

Required Learning Time

The suggested time to complete the full sequence of assignments is five 50-minute classes, plus homework assignments that support in-class activities. For instructors with more restrictive timelines, elements of the sequence can be chosen as stand-alone activities built around specific goals.

Prerequisite Student Knowledge

Ideally, students will already be aware that plants have different life stages that are affected, in part, by environmental conditions. Conversations about the consequence of changing flower phenology will have greater depth and accuracy if students are already familiar with the concept of evolutionary fitness and understand that flowering is a critical part of reproduction for many plant species. Though it is not strictly necessary, it would also be helpful for students to know how to work with data in tabular formats (*i.e.,* spreadsheets with multiple columns and rows).

Prerequisite Teacher Knowledge

Instructors will benefit from familiarity with principles of ecology and adaptation, the scientific method, and basic statistics. It is not necessary for teachers to be knowledgeable about alpine plants in particular, as accessible resources provide relevant background information on alpine plant adaptation to snowy, cold and highly variable mountain environments (Supporting Files S1–S3). To teach basic assignment sequences, instructors should feel comfortable with, or review, content related to plant reproductive biology, measurements of change over time and the components of primary scientific papers. In addition to primary and secondary resources provided in the supporting materials (Supporting File S3), we also summarize helpful information about (i) the science of phenological change in mountain plant communities and (ii) writing-based assessments and assignments for STEM courses.

i. Scientific Context

Mountains across the planet are characterized by harsh environmental conditions to which plants, animals, and insects have adapted through natural selection over many generations. There are different habitat types that occur in mountains, such as high elevation 'alpine' and below-treeline 'montane' zones. While there is overlap between these habitat types and the threats they are exposed to, they differ in the extremity of conditions to which plants have adapted. Montane environments are, for example, characterized by areas of tree cover, more diverse plant communities and longer growing seasons than alpine environments. As the climate changes, conditions necessary for montane and alpine plant species to thrive are likely to shift: temperatures will warm, snow will melt earlier, and drought conditions will persist for longer (9). Furthermore, invading plant species from lower elevations are likely to move upwards into montane and alpine habitats, potentially outcompeting and displacing mountain-specialist species (10–12). Finally, flowering and reproduction of montane and alpine plants may be disrupted by earlier freezing temperatures and loss of protective snow cover during critical stages of plant development (1). Long-term monitoring is critical for protecting our imperiled mountain habitats. Data used in this module were collected from a long-term study that monitors a montane habitat at the Rocky Mountain Biological Laboratory (RMBL), near Crested Butte, Colorado (2).

Phenology refers to both the cyclical life stages through which plants and animals pass each year and the study of these cycles, and is often described as "nature's calendar" (13). In this lesson plan, shifts in the life stages of montane plants are studied in the context of changing climate conditions. Warming temperatures and snow melt are key environmental cues that initiate phenological change from non-reproductive to reproductive life stages for many plants, such as the focal montane plant species represented in the data provided. Changing plant phenology can be a sign that broader ecosystem dynamics may also shift in response to climate change, so measuring plant stages under normal versus changed conditions is a useful ecological metric. Over the course of weeks to months, perennial plants shift from a vegetative stage (*i.e.,* 'dormant' during cold winter months) to flowering, then pollinated flowers produce seeds to be dispersed later in the growing season. In recent decades, mountain-dwelling plant species all over the world have experienced longer growing seasons and greater variability in temperatures and snow cover, which can change the timing of shifts among stages and may threaten long-term survival of mountain-specialist plants (14).

Monitoring phenological changes in the same location year after year is critical for identifying how global changes impact local ecological communities including pollinators, herbivores, and other species dependent upon alpine plants. In the Colorado Rocky Mountains, research at the RMBL has documented the impacts of changing snow and temperature conditions on plant communities for over four decades. Here we provide data from this long-term ecological study, as well as analytical tools to help students explore their own questions about flowering phenology and climate change. We hope the present lesson plan contributes to the growing list of phenology-focused educational resources (15), and that students from anywhere connect with mountain plant diversity and feel inspired to explore nature wherever they live.

The RMBL is an independent field station, established in 1928, to promote the study of montane and alpine ecosystems. The RMBL hosts researchers from around the world, who work on a wide range of species and questions. Many researchers have recorded observations about the phenology of their study organisms, some of which are synthesized in a review of 62 species, including plants, birds, insects, mammals, and an amphibian (16). Dates of first sightings and early seasonal activities like flower bud production have advanced in time (*i.e.,* started earlier in the year) for many species in the Rocky Mountains, though some species have shifted their phenology more than others. The RMBL flower phenology project (1, 17–19) has detailed measurements of the timing and abundance of flowering for all plant species in 36 permanent 2m x 2m plots in montane meadows near the RMBL. Flowering observations for some plots started in 1973, and other plots have been added to the monitoring program more recently. Researchers visit the plots and count the open flowers of all plant species three times each week during the summer growing season, which provides a record of when each species starts flowering, achieves a peak number of flowers, and finishes flowering. These data can be compared to climate data that have been collected at the RMBL (16). In addition to the primary scientific papers cited here and lecture slides, we also encourage instructors to reference popular science articles detailing how data collected through the RMBL phenology project have documented the impact of climate change in the mountains (20). A map of some of the plots, as well as images of the key plant species and background on the project, can be found in the supporting lecture slides (Supporting File S1) and references for additional useful information can be found in the supporting materials (Supporting File S3).

Measuring ecological change requires that data on a variable of interest (*e.g.,* temperature, date of flowering) are collected repeatedly over the course of days, seasons, years, or longer. Most basically, change can then be measured as a function of how much the variable has increased or decreased across the sampling interval. This is often visualized using linear regression, where time is on the x-axis and a quantification of the variable is on the y-axis. The slope of this regression line can be interpreted as the rate of change. In the present module, students plot the number of flowers that are produced over the course of the summer growing season (the y-axis, or dependent variable) as a function of time, or abiotic factors like temperature and precipitation (x-axis or independent variables). Linear regression analysis can provide insights on the overall patterns in a dataset, but processes and patterns in ecology, and science more broadly, are often more complicated and do not always follow linear dynamics. In this lesson, we describe relatively clear patterns of change over time, but encourage instructors to discuss possible improvements, challenges or gaps as a way to develop further studies.

ii. Writing-To-Learn

Collaboration between science instructors and writing specialists has been suggested as a way to promote effective instruction and learning across disciplines (4). Specifically, longitudinal research into STEM pedagogical methods suggests that some of the most effective assignments use writing as a tool for learning, which facilitates conceptual understanding of the scientific content covered (4). In a recent study, researchers identified five features of successful STEM-content WTL assignments: "sticky topics," "meaningful purpose," "detailed guidelines," "high quality feedback" and "metacognition" (21). In this formulation, topics that are complex or prone to misinterpretation (*i.e.,* 'sticky') are best suited to WTL assessments with clear instructions or rubrics ('detailed guidelines') that encourage students to be creative and transform their knowledge rather than report on facts ('meaningful purpose'). These three components of successful WTL assignments are built into the assignment sequences provided here, in which students learn about climate change impacts by following the scientific method and interpreting their process and results. To promote inclusion of the final two features, "high quality feedback" and "metacognition," we suggest that instructors incorporate opportunities for peer revision, iterative editing and self-reflection. Instructors interested in using WTL best practices can find more information about these five features from Reynolds *et al.* (21), as well as additional research, in our supporting documentation document (Supporting File S3).

We encourage instructors in STEM fields to consider building WTL modules into their courses because writing assignments can improve student learning outcomes and encourage clear, organized comprehension and communication of science (5, 21). For instructors teaching about ecology and climate change, we provide a WTL assignment sequence that can be adjusted to meet specific instructor needs. These are critical skills necessary for all students interested in climate change and ecology (22) and will be developed using the course materials presented here. At a more discipline-specific level, students will gain familiarity with the scientific method and practice steps from hypothesis writing through peer review.

SCIENTIFIC TEACHING THEMES

Active Learning

All provided materials, apart from the introductory lecture slides, are designed to encourage formative learning through active participation (23). Students work independently or in small groups to complete each sequential activity and provide peer support at multiple stages, which encourages higher-order learning and overall performance. For example, students read a scientific paper independently as homework to complete the in-class paper dissection worksheet with a small group, which then encourages high quality participation in the full group discussion. Individual activities have been designed for flexibility and enable instructors to expand or reduce the length of the lesson plan by focusing on interpretation of quantitative climate change data rather than actual practice of working with these data. Across the module, we provide materials that support fundamental active learning principles (23) with evidence-based writing (6, 21), reading (24, 25) and quantitative (26) methods so that students gain science process skills while learning about phenological change.

Assessment

This module is designed to assess student learning through sequential writing assignments that cumulatively amount to a technical report on ecological change in a montane plant phenology study. Informal writing assignments and worksheets are formative components that build to a more summative final assessment. We suggest iterative revisions of the final assessment via peer feedback but acknowledge this adds time and may not be possible for all components. In either case, the graded final report represents a synthesis of conceptual knowledge built actively through worksheets and activities (Supporting File S12).

Inclusive Teaching

Using real data from a prominent ecological experiment motivates students by placing their educational process in a real-life scientific context (27), which improves the complexity of student comprehension (28) and sense of belonging and self-efficacy in science (29, 30). All modules are structured with the objective of exposing students to methods and resources used by professional scientists, such as command line coding and data analysis. Exposure, rather than proficiency, is the intended outcome of each data analysis exercise; variable student experience with data can be accommodated using the materials we provide, and we encourage instructors to emphasize the importance of familiarity rather than mastery in the context of data analysis, statistics and particularly the software R. Given that feelings of familiarity and self-efficacy can promote belonging, acceptance and retention in STEM (29, 31), we make this suggestion with a view towards increasing inclusiveness for those students who may not yet feel a sense of belonging in the biosciences or data sciences such as female students (32) or students of color (33).

LESSON PLAN

The original module was designed and taught twice to first year students enrolled in a non-majors composition course at a large research university. We integrated insights gained from teaching the module into adapted materials and summarized anonymized student feedback in Supporting File S15.

Broadly, there are three content sections that should be taught in sequence for the full module (Figure 1). First, students learn about montane and alpine plant ecology and the impact climate change is having on plant phenology in the Rocky Mountains (Supporting Files S1–S4). Second, students practice working with real data and produce figures demonstrating phenological change over time (Supporting Files S5–S11). Finally, students compose a technical report interpreting their results in the larger context of alpine ecology and shifting precipitation patterns and provide a first-person reflection on the value of data in science communication (Supporting Files S12 and S13).

For each of the objectives in this sequence we provide interchangeable options for instructors teaching students at different levels. The original materials require students to (i) work with real data from a long-term phenology study at Rocky Mountain Biological Laboratory; (ii) discuss the measurement of ecological change over time, (iii) become familiar with R and Rstudio; and (iv) produce basic figures that address their stated hypotheses. Finally, students create core components of a scientific paper and interpret their results in the broader context of mountain ecology and climate change. Instructors can pick and choose from the materials provided: we have provided an extensive bank of resources so instructors can tailor their lesson plans for their specific goals.

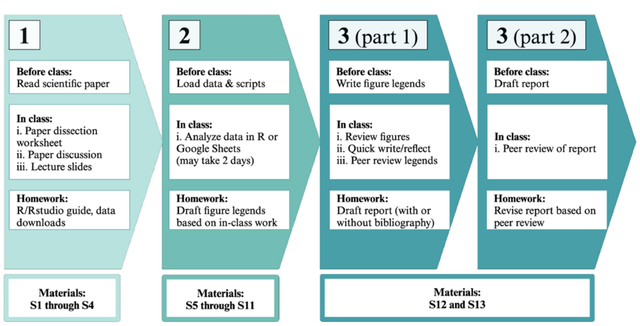

Figure 1. Assignment sequence workflow diagram. Each phase of the assignment sequence (1 through 3; top left corner of each panel) has specific steps to help instructors and students progress. Phase 1 = introduction to scientific papers, phenological change and the Rocky Mountain Biological Laboratory dataset. Phase 2 = data analysis in either R or Google Sheets. Phase 3 = scientific writing and revision based on results of data analyses and broader phenological research. Activities may be added or dropped, and there is flexibility built in so that instructors may meet logistical requirements of their course.

See Table 1 for the recommended teaching timeline table.

TEACHING DISCUSSION

This assignment sequence was intended to introduce students to primary scientific data and technical scientific writing, and to encourage non-majors to explore data interpretation and methods. Students reported feeling initially frustrated by R and RStudio, but ultimately proud of what they accomplished through the sequence of assignments (Supporting File S15).

i. Peer Revision and Building a Learning Community

In post-module surveys, multiple students identified peer review as a particularly useful practice, and the mixed formal and informal writing exercises helped students stay engaged with the material (Supporting File S15). We also asked students to reflect critically on how effectively technical writing communicates scientific information about changing ecological dynamics, which resulted in creative and diverse responses regarding science communication. In summary, students reported feeling challenged by the content and format of the module. They also felt supported and successful thanks to (i) collaborative, supportive peer-to-peer revision; (ii) class time that was leveraged as work time; and (iii) writing-based assessments that support diverse student skills.

Most students enrolled in the two classes intended to major in biology or another STEM field. In each class, however, there were multiple undergraduate students interested in studying climate change through creative writing, art, sociology and other disciplines. Students in the latter category experienced greater obstacles when it came to data analysis, whereas some of the STEM-oriented students were able to work more independently and expand analyses beyond the scripts that were provided to them in the Core Module. To support all students, regardless of their level of previous experience working with data, we encourage instructors to set aside one to two class hours for conducting data analyses with guidance and support, and to consider adjusting data analysis expectations using the adaptations available.

ii. Why Did We Adapt the Materials for Different Skill Levels?

We provide the adapted materials to make the RMBL dataset accessible and useful for instructors in various biology classrooms so that students at many levels develop connection with, and skills-based knowledge of, how ecological change is measured across time. The adapted materials consist of spreadsheets of the RMBL dataset for analysis in Google Sheets (Supporting Files S9 and S10). We envision the materials as a tool to build a bridge between biology classrooms and ongoing ecological research in the changing Rocky Mountains.

We anticipate that the data resources provided here, as well as additional data that have been collected as part of the long term phenology study at RMBL (*e.g.,* [34, 35]), could be fruitfully developed into a number of additional teaching resources (*e.g.,* [35]). Immersing students in the digital resources available from ecological field stations like RMBL is an approach that can be used to teach biology, ecology and biodiversity-related concepts with skills-based, real-world methods. Similar opportunities to connect students with real scientific data are available through organizations like DataNuggets, Data Story Bytes or through virtual field trip programs (*e.g.,* The Nature Conservancy's Virtual Field Trips), which improve student data literacy and self-efficacy (36, 37). The core and adapted activities provided here are additional resources for leveraging long-term scientific studies to support critical skill practice in students, and we encourage further development of data and materials to meet additional learning goals, as instructors see fit.

iii. Process-Based Learning Outcomes Accomplished Through Guided Exercises

We provide materials that support student-centered, skills-based lessons focused on building familiarity with empirical evidence for ecological change, scientific research and organized technical writing. This 'hands-on' approach to understanding how climate change impacts biological organisms complements a growing body of research showing that students learn better when the classroom is active and structured around science skills practice (8).

Asking students to work with real ecological data in a classroom provides connection to an otherwise abstract concept. In teaching about climate change, instructors who connect planetary phenomena to specific, local consequences are more likely to achieve student learning outcomes in line with contemporary climate change education (CCE) best practices (38). Specifically, we endeavor to provide an opportunity for students to gain place-based education (PBE) regarding the science of climate-mediated ecological change (39). Change over time is an accessible and foundational concept that is critical to understanding the mechanisms of climate-mediated ecological change (40), which we teach students through experiential formative assignments and in-class work with real alpine phenology data.

Many undergraduate courses require students to read primary scientific literature, and there are pedagogical resources to support teaching students how best to approach this process (for discussion of various papers and strategies see [41]). Other guides to reading primary literature can be used in the present assignment sequence, but we also provide a document to guide active reading of primary scientific papers. The key paper we suggest is an early paper from the RMBL phenology project (1) but there are multiple resources from this same long-term study that might be useful (Supporting File S3).

It is also common for STEM-based seminar classes to teach students technical writing skills by giving assignments aimed at mimicking the production of a full scientific article on a research topic in order to prepare them for future positions in science fields (42, 43). While this approach may be successful in upper-level or thesis-focused undergraduate classes, our experience suggests it is not necessarily an effective strategy in non-major classrooms or those that have tightly packed content schedules. Instead, we suggest a 'cherry-picking' approach to teaching scientific writing in undergraduate classrooms. This approach holds that particular parts of scientific papers are more approachable for non-expert audiences to produce well. Specifically, we suggest that asking testable questions, interpreting data and integrating results into larger scientific frameworks are important skills for all students, STEM-major or otherwise, to practice as part of their higher education experience. These skills help develop the core competency of quantitative reasoning, which is central to many curricula in higher education (44) and to science literacy (45), in general.

In addition to interacting with scientific papers through reading and writing exercises, we encourage instructors to introduce students to quantitative data analysis in either command line or tabular formats (Supporting Files S8 and S9). While this is the most challenging skills-based element, reframing the stated objective as exposure to, rather than mastery of, data analysis methods may reduce the intimidation and frustration associated with early stages of learning data skills. Indeed, recent studies suggest that anxiety is a major obstacle to learning R across undergraduate populations, particularly in female-identifying students (32). In-class, guided data analysis familiarizes students with the R/RStudio resource, demonstrates basic commands and encourages them to overcome these initial challenges (Supporting File S8). Given that data analysis is also commonly done using tabular data, we adapted the R activity so that instructors using the Basic module can help students analyze data in Google Drive's Sheets (Supporting File S9), which can be used in complement to the Teacher version of the Basic module in which plots have already been generated (Supporting File S10). Finally, we have provided basic plots that students can use for written components even if the R script or tabular analysis did not go as planned (Supporting File S11).

iv. Biology Concepts and Standards Met by Activities

Activities address some common gaps in undergraduate biology education as described in a recent assessment (EcoEvo-MAPS) (46), and meet Next Generation Science Standards (NGSS) for high school biology classrooms (Supporting File S14). We have provided a table that matches activities with key learning outcomes based on *CourseSource* learning frameworks, EcoEvo-MAPS or high school NGSS outcomes (Table 2).

Conclusion

In this lesson plan, we describe materials that can be used to teach students in biology and ecology courses about phenological change, data analysis and technical writing. We provide modular materials so that teachers may tailor their use to different levels and timelines. Our goal is to help biosciences educators engage their students with ecological change, data and the scientific process. We hope that resources provided here encourage further development of educational resources based on long-term data, particularly from the RMBL phenology project.

SUPPORTING MATERIALS LIST

- S1. Climate Change Data – Ecological Metrics Lecture Slides
- S2. Climate Change Data – Focal Paper (Inouye, 2008). PDF of the main scientific paper
- S3. Climate Change Data – Additional Papers and Resources. Helpful additional resources and background for instructors
- S4. Climate Change Data – Paper Dissection Worksheet. Student aid for reading scientific papers
- S5. Climate Change Data – Guide to Using R and RStudio. Guide to downloading R and RStudio

- S6. Climate Change Data – RMBL_climatedf. Climate data from RMBL
- S7. Climate Change Data – RMBL_flowersdf. Flowering data from RMBL
- S8. Climate Change Data – PhenologyScript. R script to run basic phenology analyses (reproducible)
- S9. Climate Change Data – RMBL Data Spreadsheet Analyses-Student. Tabular data analyses in Google Sheets [student version]
- S10. Climate Change Data – RMBL Data Spreadsheet Analyses-Teacher. Tabular data analyses in Google Sheets [instructor version]
- S11. Climate Change Data – Plots. Google slides with simple graphs of data that can be used as needed
- S12. Climate Change Data – PaperPrompt_ TechnicalWriting. Writing prompt and final paper instructions
- S13. Climate Change Data – Peer Review Guidelines. Guide to help students with peer review [optional]
- S14. Climate Change Data – Next Generation Science Standards. Information about Next Generation Science Standards (NGSS) met
- S15. Climate Change Data – Anonymous Student Reflections. Reflections from previous students on module

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Table 1. Teaching timeline table.

Activity	Description	Estimated Time	Notes
Phase 1: RMBL Alpine Plant Phenology			
Pre-class homework: Read Inouye (1) (Supporting File S2)	Students read and discuss a foundational paper on the topic of phenological change in the focal study system, and are oriented to the plant species, habitat and ecology of plant phenological change in mountains.	60 minutes (at home)	Class objective: students will gain understanding of the RMBL phenology data and technical scientific writing process.
In class: Paper Dissection worksheet (groups of 3) (Supporting File S4)		20–40 minutes	
In class: Paper discussion		20 minutes	
In class: Lecture (Supporting File S1)		20 minutes	
Phase 2: Data Analyses			
Pre-class homework: Download R, RStudio and data (Supporting File S5–S8)	Students examine real-world ecological data, climate data and commonly used data analysis software. In class time is dedicated entirely to working in R/Rstudio or Google Sheets. Students save figures produced by scripts in PDF format, or teachers may provide them (see Supporting File S11) so that all students may proceed to technical writing stage.	30 minutes (at home)	Class objective: students will gain skills-based understanding of data analysis regarding ecological change over time.
In class: R and RStudio introduction and overview (Supporting File S5)		10 minutes	
In class: RMBL data analysis (Supporting File S8)		Minimum 45 minutes	
Post-class homework: Write figure legends for each of their results (see Supporting File S11 if needed)		30 minutes	
Phase 2: Technical Writing and Data Synthesis, Day 1			
In class: Review components of a technical scientific paper using paper dissection (Supporting Files S4, S12)	Students practice synthesizing graphs, data and ecological literature into their own written reports. A focus on writing about the variables and relationship between them is structured into the hypothesis exercise.	10 minutes	Class objective: students will synthesize and interpret information about alpine plants, climate change and their data analysis.
In class: Quick write exercise reviewing what the students know about the RMBL phenology study		5 minutes	
In class: Peer review of figure legends and discuss results section		15–20 minutes	
Phase 2: Technical Writing and Data Synthesis, Day 2			
Pre-class: Compete draft of technical report paper	Students are introduced to the common scientific practice of peer review, and support each other through positive, collaborative revision.	1–2 hours	Class objective: students will improve their technical writing skills through guided peer to peer engagement and instruction.
In class: Friendly peer revision of technical report paper (groups of 3) (Supporting File S13)		Full class period	

Table 2. Learning standards and frameworks.

Module Activity	Next Generation Science Standard Met	*CourseSource* Learning Framework	EcoEvo-MAPS Themes
Interpretation of phenological data collected across time	Cross-cutting concept: Cause and Effect	Ecology: Biological diversity, species/habitat interactions	Modes of change (differential reproduction)
Structured reading and writing of primary scientific literature	Science and Engineering practice: Constructing Explanations and Designing Solutions		Heritable variation (variation within a population)
Synthesis of biological information across species and scales	HS-LS2* (items 2 and 6)	Ecology: Interactions within ecosystems	Biological Diversity
Production of technical writing report as assessment	Science and Engineering Practice: Using Mathematics and Computational Thinking		Populations (population growth-factors affecting population size)
Description of the effect of abiotic change on mountain plant communities	HS-LS2* (items 2 and 6); Cross-cutting concept: Stability and Change	Ecology: Impacts of Humans on Ecosystems	Human impact (global trends, contributors to climate change)

*HS-LS2 refers to the Next Generation Science Standards in High School Life Science classrooms that align with group 2 topics (ecosystems).

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