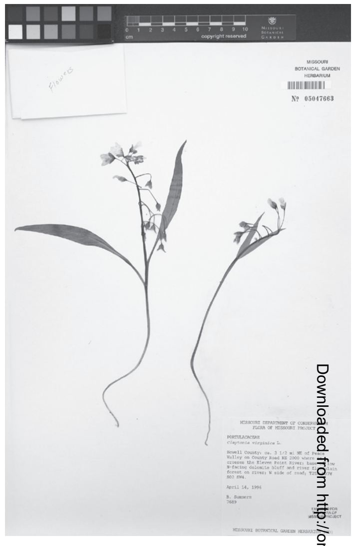
INQUIRY & INVESTIGATION

An Inquiry-Based Activity for Investigating the Effect of Climate Change on Phenology Using the R Programming Language



RECOMMENDED FOR *AP Biology*

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Abstract

Engaging students in research is increasingly recognized as a valuable pedagogical tool that can augment student learning outcomes. Here, we present an original activity that utilizes research as pedagogy to teach upper-division college students about phenological responses to climate change. By studying phenological responses in multiple species, this activity emphasizes interspecific variability in responses to a changing climate (i.e., that not all species respond in the same way), while demonstrating the relationship between environmental and phenotypic variability. In this activity, students collect data from herbarium specimens of spring ephemerals native to North America and are tasked with formulating and testing hypotheses about how the day of year that a species' flowering occurs (i.e., flowering phenology) has been affected by climate change. To accomplish this, students perform linear regressions using the R programming language—including data exploration and ensuring the dependent variable follows a normal distribution—and subsequently present their results via oral presentation. We taught this activity as a three-unit lab in an upper-division ecology course and observed quantifiable improvement in student learning outcomes. While designed as a three-unit, upper-division lab, this activity can be modified for other educational levels, blocks of time, and/or as a flipped classroom activity. Through this activity, students are provided with the opportunity to learn about the scientific method, biological collections, linear regressions, the R programming language, and scientific communication. Changes to flowering time are one of the most conspicuous effects of climate change, thus presenting an ideal topic for engaging students in biological inquiry.

Key Words: *climate change; flowering time; herbaria; inquiry investigation; linear regression; phenology; plant ecology; R programming; scientific method; upper-division biology laboratory.*

We present a three-unit, inquiry-based activity that teaches students about phenological responses to climate change by engaging students in the scientific process.

○ Introduction

Incorporating course-based undergraduate research experiences (CUREs) into college curricula can cultivate greater conceptual understanding of the scientific method and increase graduation rates of science, technology, engineering, and mathematics (STEM) majors (Auchincloss et al., 2014; Rodenbusch et al., 2016). To maximize the benefits gained from employing research as pedagogy, students should be involved in every aspect of the scientific process—from hypothesis formation and data collection to statistical analysis and presentation of results (Linn et al., 2015). Here, we present an inquiry-based activity that engages upper-division undergraduate students in the scientific process, while teaching students about phenological responses to climate change using the R programming language, one of the foremost software environments for contemporary biological analysis.

Changes to phenology (i.e., the timing of life history events) in response to warming temperatures is considered one of the best indicators of the ecological effects of climate change (Hufft et al., 2018). In particular, flowering phenology has been well documented as being sensitive to changing climatic conditions (Davis et al., 2023). In certain species, flowering date advances by > 1 week per °C increase in temperature, although interspecific variability exists in the magnitude of phenological shifts and the climatic cues that flowering time responds to (e.g., Hufft et al., 2018; Bartlett et al., 2023). Because flowering is readily observable in many species, the link between flowering phenology and climate change is an ideal topic for introducing students to the ecological impacts of global change, while also demonstrating the relationship between environmental and phenotypic variability.

A common method for studying how climate change has affected flowering phenology is leveraging herbarium specimens as sources of long-term flowering data (Davis et al., 2015; Davis et al., 2023). Herbarium specimens (Figure 1) are plants that were collected from the wild, pressed and dried, and mounted on heavyweight paper for long-term storage in an herbarium. Accordingly, herbarium specimens contain a wealth of data that can be used in phenological analyses, including the phenophase of the plant (e.g., whether the plant was flowering)

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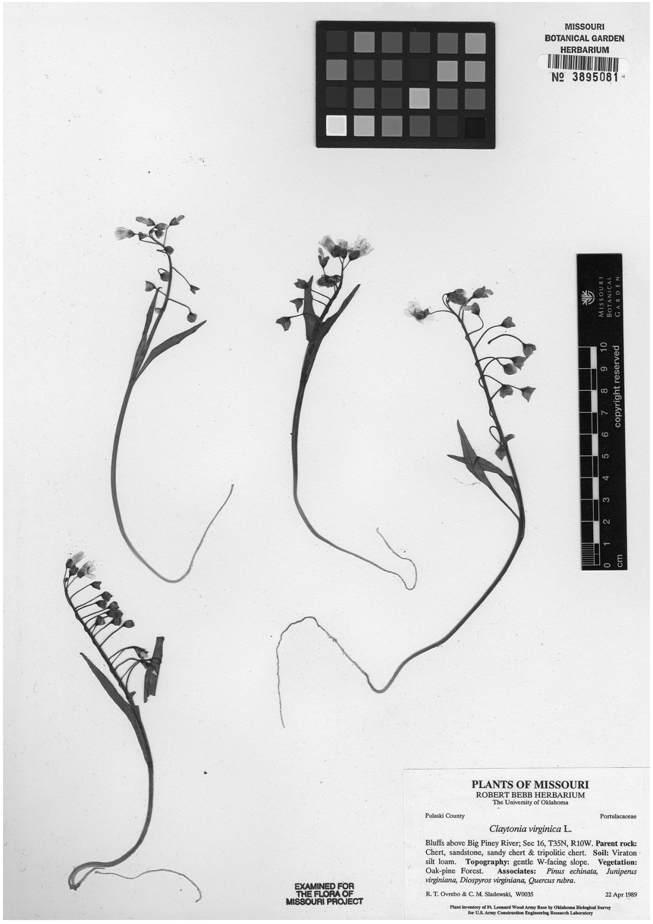

Figure 1. Herbarium specimen of spring beauty (*Claytonia virginica*) (Missouri Botanical Garden, Ovrebo, R. T. - W0035, http://legacy.tropicos.org/Image/100105250, CC BY-NC-SA 3.0; https://creativecommons.org/licenses/by-nc-sa/3.0).

when it was collected, the collection date, and the collection location. Moreover, collection date and location can be used to extract data on the weather a specimen experienced when and where it was collected, from publicly available, long-term climate databases (e.g., Parameter-elevation Regressions on Independent Slopes Model (PRISM); Daly et al., 2002).

There are two common analyses employed for testing whether flowering time of a given species has been affected by climate change: flowering date regressed against year and flowering date regressed against a climatic variable (e.g., mean spring temperature) (Jones & Daehler, 2018). Because these are standard linear regressions that can be readily coded in a variety of programming languages, these are ideal analyses for introducing students to statistical analysis and coding. Additionally, because linear regressions assume the dependent variable follows a normal distribution, engaging students in regression analysis provides students with experience performing data exploration and familiarizes students with common data transformations.

We present a three-unit, inquiry-based activity that teaches students about phenological responses to climate change by engaging students in the scientific process. In Unit 1, students explore how herbaria can be used in ecological analyses, by collecting data from herbarium specimens provided to them by their instructor. Subsequently, Unit 1 introduces students to linear regressions and the R programming language, by having students perform analyses on how the flowering time of spring beauty (*Claytonia virginica*) has changed across the past century (Figures 1 and 2). In Unit 2, student groups are provided with data for one of ten species (Table 1) and are tasked with hypothesizing how their species' flowering has responded to climate change and then are tasked with coding linear regressions in R to test their hypothesis. In Unit 3, student groups present their analyses and results from Unit 2 to the class. Collectively, these three units engage students in every aspect of the scientific process, while teaching about phenological responses to climate change—including interspecific

Table 1. Linear regression results from spring beauty (*Claytonia virginica*) and the ten species student groups can select from for performing their own analyses. By having student groups work on and present results for different species, the class is exposed to interspecific variability in phenological responses to climate change.

	Flowering date regressed against year			Flowering date regressed against temperature		
Species	***F***	***P***	***R*²**	***F***	***P***	***R*²**
Claytonia virginica	6.39	**< 0.05**	0.102	-	-	-
Aquilegia canadensis	0.14	0.71	0.00422	7.96	**< 0.01**	0.199
Dicentra cucullaria	8.67	**< 0.01**	0.194	3.18	0.084	0.0878
Erythronium albidum	2.21	0.15	0.0685	10.08	**< 0.005**	0.279
Hydrophyllum appendiculatum	3.01	0.097	0.125	10.18	**< 0.01**	0.361
Lithospermum canescens	2.71	0.11	0.0514	4.94	**< 0.05**	0.0950
Nothoscordum bivalve	2.85	0.10	0.0773	8.32	**< 0.01**	0.201
Phacelia purshii	4.91	**< 0.05**	0.260	10.26	**< 0.01**	0.441
Phlox divaricata	0.69	0.41	0.00988	13.91	**< 0.001**	0.174
Uvularia grandiflora	1.09	0.30	0.0264	16.33	**< 0.001**	0.301
Viola striata	2.94	0.096	0.0818	5.79	**< 0.05**	0.162

*Significant *p*-values are given in bold.

Table 2. Relation of lab to *Next Generation Science Standards* (NGSS) (NGSS Lead States, 2013).

NGSS Standard	Relation to Lab Activity
HS-LS2-2 Ecosystems: Interactions, Energy, and Dynamics. Use mathematical representations to support and revise explanations based on evidence about factors affecting biodiversity and populations in ecosystems of different scales.	Linear regressions are used to test hypotheses on how flowering date has been affected by climate change. Specifically, regressions test how flowering day of year has changed across the past century and changes with increases in mean spring temperature.
HS-LS2-6 Ecosystems: Interactions, Energy, and Dynamics. Evaluate the claims, evidence, and reasoning that the complex interactions in ecosystems maintain relatively consistent numbers and types of organisms in stable conditions, but changing conditions may result in a new ecosystem.	By evaluating how flowering date has been affected by climate change, students are introduced to the concept that temporally changing environments can induce novel co-flowering species assemblages.
HS-LS3-3 Heredity: Inheritance and Variation of Traits. Apply concepts of statistics and probability to explain the variation and distribution of expressed traits in a population.	The R programming language is utilized to perform data exploration, data transformation, and linear regressions, with the goal of understanding how variation in flowering date is distributed and how the expression of flowering date relates to mean spring temperature.

variability in these responses—and how herbaria, linear regressions, and R can be used to test for such responses. Accordingly, this lab touches on multiple standards in the Next Generation Science Standards (NGSS) (Table 2) and adheres to the Ecological Society of America's Four-Dimensional Ecology Education (4DEE) Framework (https://www.esa.org/4dee). While students should have some familiarity with spreadsheet data entry (e.g., Microsoft Excel or Google Sheet experience) and algebra prior to performing this activity, no prior coding experience is required. In fall 2022, we taught this activity as a lab in an ecology course at Webster University and tested whether this activity produced a quantifiable improvement in student learning outcomes among the 13 students who participated. We designed this activity to be employed across three 2-hr 50-min lab periods; however, this activity can be modified to accommodate fewer and shorter class periods, and can be employed as a flipped classroom activity in a lecture-based course.

○ Materials & Preparation

All materials required for this activity—including procedures, worksheets, R scripts, data, and an instructional slideshow—can be found in the Supplemental Material (available with the online version of this article). To help guide instructors through implementing these materials, we have done the following: (1) under the description of each unit below, we have listed the Supplemental Material files used in each respective unit, and (2) we have given the file name for each Supplemental Material in parentheses after it is first mentioned. In addition to becoming familiarized with these materials, prior to teaching this activity, we recommend that instructors (1) obtain herbarium specimens for use in Unit 1, (2) make the spreadsheet for compiling the class's herbarium data in Unit 1 (i.e., CompiledHerbariumDataSpreadsheet.csv) available online for all students in the class to edit, and (3) download RStudio on student computers. In the following, we briefly elaborate on these three recommendations.

Obtain herbarium specimens for use in Unit 1

We recommend that the herbarium specimens provided to students in Unit 1 are specimens of spring beauty (*Claytonia virginica*) (Figure 1). This recommendation is based on *C. virginica* being a common species across Eastern North America, and being readily available in many North American herbaria. Furthermore, the data on *C. virginica* that we provide to students in the latter half of Unit 1, demonstrate that *C. virginica* has shifted flowering times earlier across the past century, and is thus an ideal species to use to introduce the concept of climate change affecting flowering phenology. However, any plant species for which instructors have herbarium records could be used. When we taught this activity as a lab in Webster University's fall 2022 Ecology course, we obtained a loan of *C. virginica* herbarium specimens from the Missouri Botanical Garden. For instructors who are unable to obtain herbarium specimens of *C. virginica*, we have provided imaged *C. virginica* herbarium specimens in the Supplemental Material provided with the online version of this article (InstructionalSlideshow.pdf).

Another alternative for providing herbarium specimens to students is to obtain images of herbarium specimens from the Global Biodiversity Information Facility (GBIF). In addition to this method allowing the instructor to not obtain physical herbarium specimens, a benefit of this approach is that the instructor can search for herbarium specimen images of any species of their choosing. To accomplish this, the instructor should go to https://www.gbif.org, navigate to "Occurrences," and perform a simple search with the following criteria: "Occurrence status" set to "Present," "Scientific name" set to the species of the instructor's choosing, "Basis of record" set to "Preserved specimen," and "Media type" set to "Image." After performing this search, clicking "Gallery" in the results section will show the images of herbarium specimens GBIF contains for this species.

Make the spreadsheet for compiling the class's herbarium data available online

After students collect data on herbarium records in Unit 1, each student enters their data into a spreadsheet (i.e., CompiledHerbariumDataSpreadsheet.csv) that compiles the data collected by each student in the class. Accordingly, we recommend that instructors make this spreadsheet available to each student online, on a platform allowing each student to have editing capabilities, prior to teaching this lab. For example, Google Sheets (https://www.google.com/sheets/about) is a freely available platform that is appropriate for sharing spreadsheets with students. Google Sheets allows the owner of a spreadsheet to share the spreadsheet with others and grant editing capability.

Download R and Rstudio on student computers

Instructors should ensure that R and RStudio are downloaded on student computers prior to Unit 1. RStudio is an environment for running the R programming language, both of which are freely available for download online (https://posit.co/download/rstudio-desktop). Note that use of RStudio is dependent on R also being downloaded on a computer's operating system. We recommend that instructors have students run their code in RStudio, as opposed to base R, given that RStudio has features that are beneficial to users new to R programming. For example, RStudio allows students to write their code in an R script, run their code through the console, and view plots all within a single window. The only additional R package that needs to be installed for this activity is *ggplot2* (Wickham, 2016), which we recommend having installed in R on each computer prior to Unit 1.

○ Procedure

We designed this activity to be held across three consecutive labs in a course with 2 hour 50 minute laboratory periods, with each unit being covered in a single lab period. However, instructors can adapt this activity to occur across fewer or shorter lab periods, or to be implemented as a flipped classroom activity in a lecture-based course. In each unit, we have provided two or three learning objectives, relevant background information, detailed instructions, and assessment materials.

Unit 1: Herbaria as sources of ecological information

Supplemental Material (available with the online version of this article): Unit1Procedure.docx, Unit1Worksheet.docx, Unit1RScript.txt, CompiledHerbariumDataSpreadsheet.csv, ClaytoniaVirginicaData.csv

Students are provided with herbarium specimens by their instructor, so that each student has a unique specimen. Each student is guided through working independently and synchronously to collect data from their herbarium specimen that are relevant for analyses of how climate change has affected flowering time. After collecting these data, the class compiles their data into a single spreadsheet (CompiledHerbariumDataSpreadsheet.csv). As a part of this process, students are guided through converting the collection date of their herbarium specimen as year, month, and day to day of year (DOY).

Following compilation of the class's data, students are introduced to RStudio and the R programming language. We recommend having students work independently through compilation of the class's data and then split into groups of two or three students for working in RStudio. After students have split into groups, students read the compiled phenology data into RStudio and perform simple commands to explore the class's data. Subsequently, students are provided with an already compiled dataset of spring beauty (*Claytonia virginica*) herbarium data (ClaytoniaVirginicaData.csv) and are guided through running a linear regression in RStudio to test whether *C. virginica*'s flowering time has changed across the past century. Prior to running this regression, students are guided through checking the dependent variable—DOY—for a normal distribution. Because the distribution of DOY in the provided *C. virginica* dataset is left skewed, students perform a square transformation to induce normality (Figure 2). Finally, Unit 1 ends with students plotting the relationship between year and DOY in the *ggplot2* package (Wickham 2016) (Figure 2).

By having students collect data from herbarium specimens and be guided through performing linear regressions in RStudio, Unit 1 introduces students to the concepts that climate change can alter flowering phenology, that herbaria can be used to test for phenological responses to climate change, and that R is a dynamic programming language for performing regression analysis. Moreover, by compiling the class's herbarium data and having students explore these data in RStudio, students are exposed to the concept that the scientific process involves both independent and collaborative work.

Unit 2: Using R to analyze the effect of climate change on flowering phenology

Supplemental Material (provided with the online version of this article): Unit2Procedure.docx, Unit2Worksheet.docx, Unit2RScript.txt, AquilegiaCanadensisData.csv, DicentraCucullariaData.csv, ErythroniumAlbidumData.csv, HydrophyllumAppendiculatumData.csv, LithospermumCanescensData.csv, NothoscordumBivalveData.csv, PhaceliaPurshiiData.csv, PhloxDivaricataData.csv, UvulariaGrandifloraData.csv, ViolaStriataData.csv

In Unit 2, students build on their skills learned in Unit 1 by coding their own linear regressions in RStudio to test for effects of climate change on flowering phenology. Specifically, student groups are provided with herbarium data on one of ten different species (Table 1) and are tasked with hypothesizing how climate change has affected their species' flowering time. We recommend having the student groups from Unit 1 continue working together in Unit 2. While Unit 1 had students test how flowering time changed across years, in Unit 2, students are also tasked with testing how flowering time changes with increases in temperature. Thus, Unit 2 has students use their code from Unit 1 as a guide to write code for two linear regressions: one model that regresses flowering DOY against year and one model that regresses flowering DOY against mean spring temperature (°C). Across these ten species there is interspecific variance in whether flowering DOY is normally distributed; while flowering DOY is normally distributed for some species, it follows a skewed distribution for others. Accordingly, students are asked to use their knowledge on data normality learned in Unit 1 to evaluate whether their data requires transformation to induce normality, and if so, implement the proper transformation. Table 1 gives the results of both regressions for each species, which students should obtain if their models are coded correctly.

All data required for these analyses are given in the CSV files provided for each of these ten species (see Supplemental Material provided with the online version of this article). Note that the mean spring temperature (°C) and total spring precipitation (mm) data provided in these CSV files were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) at a 30 arcsecond resolution (Daly et al., 2002). Specifically, for each specimen, we randomly sampled 1,000 coordinates from throughout its county of collection and used the *airUpThere* package (www.github.com/adamlilith/airUpThere) to assign each of the 1,000 coordinates to mean monthly temperature (°C) and total monthly precipitation (mm) data in March, April, and May. Mean spring temperature was calculated by first taking the mean of mean monthly temperature across the 1,000 coordinates per month and then taking the mean across months. Total monthly precipitation was calculated by first taking the mean of total monthly precipitation across the 1,000 coordinates per month

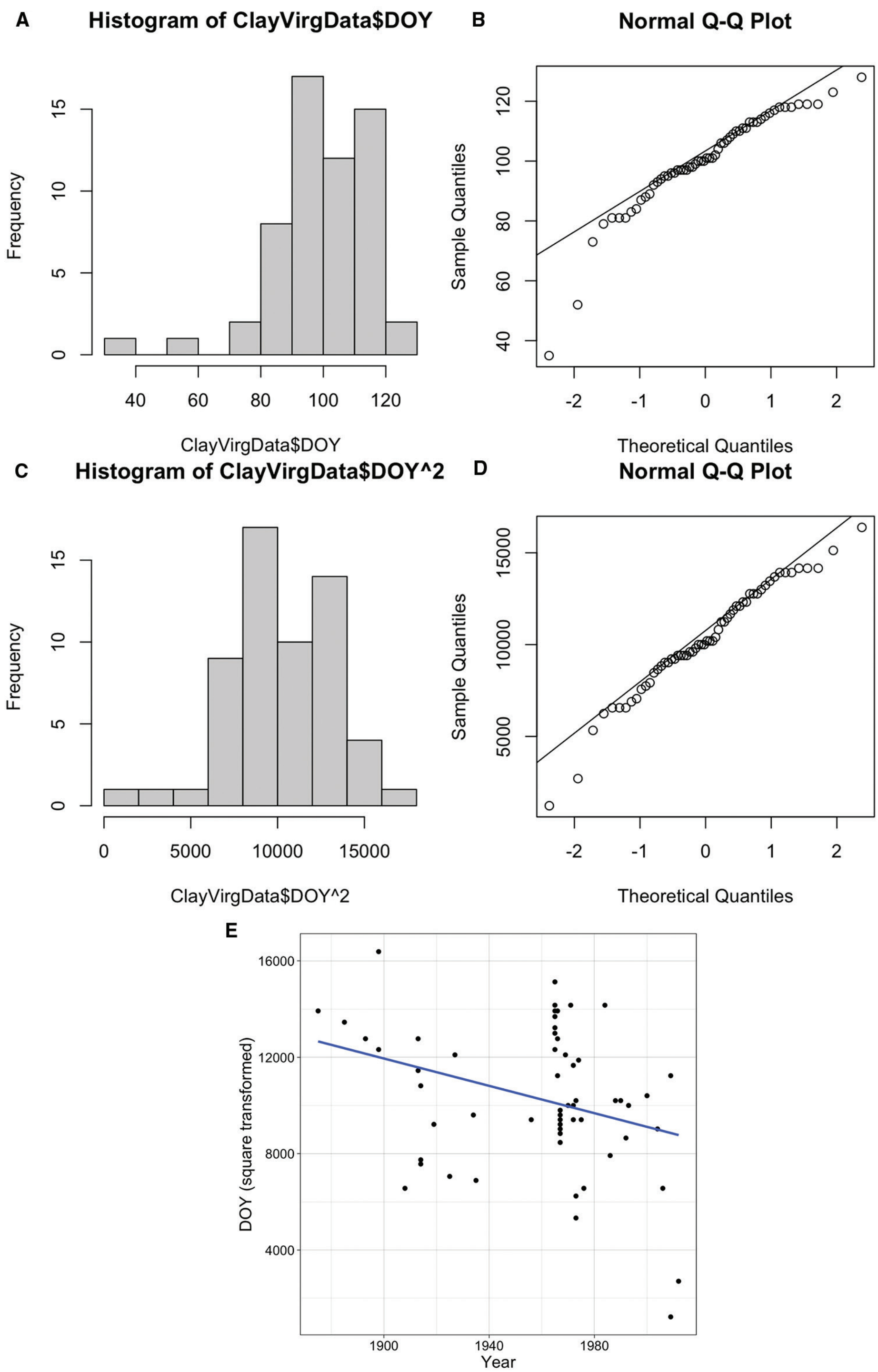

Figure 2. Results of spring beauty (*Claytonia virginica*) linear regressions in Unit 1. (A) Histogram and (B) quantile-quantile (Q-Q) plot for untransformed day of year (DOY) data. (C) Histogram and (D) Q-Q plot for DOY data following square transformation. (E) Spring beauty's flowering DOY has shifted significantly earlier across the past century ($p < 0.05$, $F = 6.39$, $R^2 = 0.102$).

and then taking the sum across months. Note that specimens collected < 1895 do not have associated climate data, as PRISM data were not available for this period. While our activity does not explicitly have students perform a linear regression that tests how flowering DOY changes in response to total spring precipitation (mm), we have included precipitation data in case motivated students would like to be challenged with an additional exploratory analysis.

Unit 3: Presentation of the phenological analyses to peers

Supplemental Material (provided with the online version of this article): Unit3Procedure.docx, PresentationRubric.docx, PeerEvaluationForm.docx

In Unit 3, each student group presents the work they performed in Unit 2. We recommend structuring these as seven- to eight-minute presentations, with students splitting time evenly during the presentation. This allows students in the audience time to ask questions at the end of each presentation. Furthermore, we recommend having students complete peer evaluations of each presentation; thus, this timing also allows students sufficient time for completing their peer evaluations between each presentation. The peer evaluation includes the evaluation rubric and encourages the reviewer to devise and ask questions regarding the background, methods, results, and discussion.

For instructors implementing this activity in a larger class, an online class, or a class with limited time, we recommend modifying Unit 3 so that student groups either record a video of their presentation or create a research poster of the work they performed in Unit 2. Implementing either of these modifications would conserve class time, by allowing students to upload their final product (i.e., video or poster) online for assessment.

○ Student Assessment

Assessment of student learning occurs in each of the three units. In Units 1 and 2, student learning is assessed via worksheets (Unit1Worksheet.docx, Unit2Worksheet.docx). The beginning of each worksheet functions to track student progress via a series of questions, most of which consist of recording data collected throughout the unit. Each worksheet ends with a section titled "Integrate what you learned," which consists of open-ended prompts that engage students in critical thinking of the unit's material. We recommend grading the beginning of each worksheet as complete/incomplete, while using the "Integrate what you learned" sections as the primary assessment for Units 1 and 2. In Unit 3, student presentations are assessed by the instructor via a presentation rubric (PresentationRubric.docx) and are assessed by student peers via a peer evaluation form (PeerEvaluationForm.docx). If Unit 3 is modified so that students record videos of their presentations or create research posters, these assessments can be easily adapted to accommodate the chosen final product format.

When we taught this activity as a lab in Webster University's Ecology course, we assessed the impact of this activity on student learning outcomes by administering a pre-lab quiz and a post-lab quiz (Table 3). Specifically, we developed a short quiz that poses questions related to this activity's learning objectives (PrePostQuiz.docx), and asked students to complete the quiz both prior to Unit 1 and after Unit 3. Accordingly, by comparing students' answers between the pre-lab quiz and post-lab quiz, we were able to quantify an estimate of the impact of this activity on student learning outcomes. Student performance on the pre-activity quiz was used solely for our quantification of student learning outcomes and did not impact student grades. The post-activity quiz can be used as a summative or formative assessment, depending on the instructor's goals.

○ Results & Discussion

Here, we present an inquiry-based activity that involves students in every step of the scientific process—from hypothesis development, through statistical modeling, to the interpretation and presentation of results—by studying phenological responses to climate change. By employing research as pedagogy, students are introduced to how herbaria can be used as sources of long-term data for ecological analysis. Moreover, this activity introduces students to regression analysis and the R programming language, by having students code their own analyses in RStudio that use herbarium data to test for changes to flowering day of year (DOY) across the past century and in response to increases in mean spring temperature (°C). This activity builds upon a growing body of resources available for instructors to teach students about phenological responses to climate change (e.g., Haggerty et al., 2012; Pecor & Batko, 2017; Neil, 2009). We recommend instructors use this activity in upper-division college courses that focus on ecology and/or plant biology.

When we taught this activity in Webster University's Ecology course, we found evidence that this activity improved student learning outcomes. Specifically, students scored higher across nearly every question on the post-lab quiz, compared with the pre-lab quiz, indicating that involvement in this activity increased student proficiency of the learning objectives (Figure 3). For example, the question that showed the greatest improvement in student scores from the pre-lab quiz to the post-lab quiz (Question 6; Figure 3) asked students to "Briefly explain why data may need to be transformed via square or log transformation before conducting a linear regression." The percentage of students giving the correct answer to this question—that a transformation is needed to normalize a skewed distribution—shifted from < 25% on the pre-lab quiz to > 75% on the post-lab quiz, indicating that this activity improved student comprehension of data transformation and regression analysis. Two questions (Questions 2 and 3; Figure 3) were answered correctly by every student on the post-lab quiz, but were only answered correctly on the pre-lab quiz by ~50% of students. Both of these questions relate to herbaria and how herbarium data can be used to test how climate change has affected phenology, indicating that this activity effectively taught students about what herbaria are and how they can be used in ecological analysis.

There was only one question (Question 4; Figure 3) that students did not receive higher scores for on the post-lab quiz compared with the pre-lab quiz. This was a true/false question that asked students whether the following statement is true: "Climate change is causing flowering to occur earlier in the year across all flowering plant species." Due to the interspecific variability observed across species in changes to flowering time across the past century in Unit 2 (i.e., results from analyses of DOY regressed against year), the correct answer to this question is *false*. In addition to students not answering this question correctly at a higher rate on the post-lab quiz, this is the only question that < 50% of students answered correctly on the post-lab quiz. Accordingly, we have updated this activity to more strongly emphasize that interspecific variability exists in phenological responses to climate change, with some species shifting flowering earlier, some shifting flowering later, and others not shifting flowering at all. We have also clarified that this interspecific variability can be observed across species analyzed in Unit 2; i.e., while some species shifted flowering significantly earlier across years ($p < 0.05$), others do not show a significant shift ($p > 0.05$), which is consistent with no change in flowering time across the past century. We recommend that instructors employing this activity emphasize that interspecific variability exists in phenological responses to climate change and that non-significant results are consistent with there being no relationship between a dependent and an independent variable.

Changes to flowering time are a conspicuous biological effect of climate change, which may impact fitness (Freimuth et al., 2022) and can be used as indicators of broader ecological effects imposed

Table 3. Questions on the pre-lab and post-lab quizzes.

Number	Question	Answer
1	Define phenology.	The timing of life history events.
2	Define herbarium.	A collection of plants that were collected from the wild, pressed and dried, and mounted on heavyweight paper for long-term storage.
3	What information can be obtained from herbarium records that are useful for studying how climate change has affected phenology? Select all that apply. a. day of collection b. month of collection c. year of collection d. presence/absence of flowers	a, b, c, & d
4	True/False? Climate change is causing flowering to occur earlier in the year across all flowering plant species.	False
5	If you were to conduct a linear regression that tests for the effect of mean spring temperature on flowering time of spring beauty (*Claytonia virginica*), which of the following gives the proper designation of variables in your model? a. dependent variable = flowering time; dependent variable = mean spring temperature b. dependent variable = flowering time; independent variable = mean spring temperature c. independent variable = flowering time; dependent variable = mean spring temperature d. independent variable = flowering time; independent variable = mean spring temperature	b
6	Briefly explain why data may need to be transformed via square or log transformation before conducting a linear regression.	To normalize a skewed distribution.
7	After performing a linear regression, what does the multiple R^2 statistic describe? a. whether the best fit line is different from zero b. the proportion of variation of the dependent variable that is explained by the independent variable c. statistical significance d. whether the data follow a normal distribution	b
8	After performing a linear regression, what does the *p*-value describe? a. whether the best fit line is different from zero b. the proportion of variation of the dependent variable that is explained by the independent variable c. statistical significance d. whether the data follow a normal distribution	c

by a changing climate (Hufft et al., 2018). Accordingly, the impact of climate change on flowering phenology is an ideal topic for introducing students to how human-induced environmental changes can impact ecology. Furthermore, because flowering time is cued by the environment, the relationship between climate and flowering phenology is ideal for exploring the relationship between environmental variation and phenotypic variation. As demonstrated by the interspecific variation in responses of flowering DOY to mean spring temperature that are observed in the ten species available for study in Unit 2 (Table 1), there is interspecific variability in the environmental conditions that cue flowering (e.g., Hufft et al., 2018). While we have written this activity to have students test the effect of only one environmental variable (i.e., mean spring temperature) on flowering time, we have also included data on total spring precipitation (mm) in the CSV for each species. We have included these precipitation data in case students would like to perform additional exploratory analyses that test the effect of another climatic variable on flowering time.

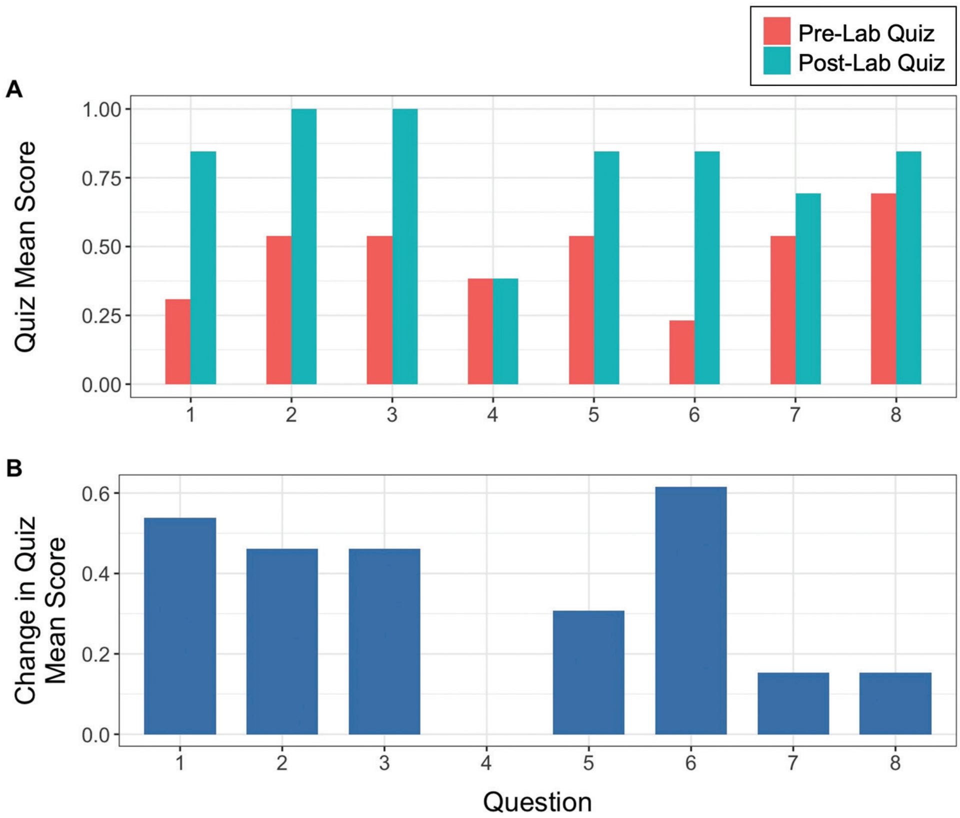

Figure 3. Student performance on pre-lab and post-lab quizzes. (A) Mean score across students per question on the pre-lab quiz and post-lab quiz. (B) Change in mean score per question from the pre-lab quiz to the post-lab quiz (i.e., post-lab mean score – pre-lab mean score). Data derive from 13 students in Webster University's fall 2022 Ecology course. Each question was worth a maximum of 1 point.

As the field of biological education moves toward increased adoption of active and inquiry-based learning, the benefits of engaging students in the scientific process are increasingly appreciated (Auchincloss et al., 2014; Rodenbusch et al., 2016). Through this activity, we provide instructors with a resource for engaging students in research, in a format that is suited to a time-limited, classroom setting. While we have developed this activity to be held across three consecutive laboratory periods in an upper-division college course, this activity can be adapted to be implemented as a shorter activity, which is suitable for a lab or flipped classroom. For example, instructors wishing to implement this activity in a shorter period of time may consider implementing only Unit 1 or implementing all three units, but modifying Unit 3 to consist of recorded presentations or research posters, which may be submitted online. By having students test hypotheses on how climate change has affected flowering times, we introduce students to data exploration, statistical analysis, and plotting in the R programming language, which is one of the foremost software environments used for scientific analysis in contemporary biology. Note that the students in Webster University's fall 2022 Ecology course had modest prior experience with R programming; however, we have written this activity to be suitable for students with no prior coding experience. For students more familiar with regression analysis in R, Unit 2 can be modified to build on their prior knowledge. Through leveraging herbaria as sources of long-term ecological data, this activity teaches students about the biological effects of climate change, while engaging students as active participants in a scientific education.

○ Acknowledgments

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