

Online labs to introduce undergraduate students to scientific concepts and practices in tree-ring research

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ABSTRACT

Scientists rely heavily on tree-ring records to better understand climate variability of the past millennium. Tree rings can also be utilized to give students a window into paleoclimate research, the methods scientists use, and the importance of scientific findings. Here, we present five online labs that introduce undergraduate students to the field of dendrochronology. Students learn about foundational tree-ring concepts and are guided to use many of the same tools and strategies as scientists, including exploring important field sites, measuring tree-ring data from those sites, using online paleoclimate databanks, and evaluating climate trends and extremes. The labs have been classroom tested and were modified based on a professional assessment, and faculty and student reviews. Faculty and student surveys and student lab grades show that the majority of students were able to meet the learning goals of the labs. Students reported that they felt they were working as scientists would, and, after completing the labs, that they better understood tree-ring science methods and applications. These materials were developed collaboratively with faculty input from a variety of institutions to have broad appeal and allow for use in a variety of classroom settings.

ARTICLE HISTORY

Received 27 June 2019
Revised 5 May 2021
Accepted 5 May 2021

KEYWORDS

Dendrochronology; paleo-climate; climate change; climate literacy

Purpose and learning goals

Annual tree-ring records from long-lived trees are heavily relied upon to understand climate variability and extremes of the past millennium (Stokes & Smiley, 1968) and put recent warming trends into a long-term context (Wilson et al., 2016). From tree-ring records scientists have learned, for example, that places on Earth are undergoing rapid warming (Davi et al., 2015; Gou et al., 2007), that century-long droughts are possible (Harding & Cook, 2012), and that climate can play a role in human migration and cultural collapse (deMenocal, 2001; Stahle et al., 1998). The foundational concept of tree-ring science is easy to understand: that most trees grow annual rings, and the width of each annual ring is related to environmental conditions (Stokes & Smiley, 1968). This makes tree rings a useful tool to teach students about the methods scientists use to understand and visualize climate variability of the past, and about how scientists work to collect and analyze data.

Herein we describe Tree-Ring Expeditions (TREX, <https://serc.carleton.edu/trex/index.html>), five online labs that introduce students to the field of dendrochronology, or

tree-ring science, and guide them to use many of the same tools and strategies used by tree-ring scientists. Students are introduced to foundational concepts and methods of dendrochronology (Lab 1), are guided to generate and use authentic tree-ring data, and learn how this data can be used, for example, to reconstruct streamflow and drought for hundreds of years in the past (Lab 2 and Lab 4). They use tree-ring records to place exact calendar dates on ancestral pueblos in the U.S. Southwest (Lab 3), and learn how scientists reconstruct millennial-length temperature variability in the Northern Hemisphere (Lab 5).

The TREX labs are based on highly-cited tree-ring research that continues to generate citations, and in some cases is foundational for the field. When designing the labs, consideration was given to the geographic location of the study sites in order to appeal to a broad audience. Labs 2, 3, and 4, for example, are based on tree-ring research from the Northeast, Southwest, and West regions of the United States respectively, and Lab 5 focuses on tree-ring sites that span the Northern Hemisphere.

Introducing students to the field of dendrochronology and helping them develop a deeper understanding of how

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 Supplemental data for this article is available online at <https://doi.org/10.1080/10899995.2021.1927567>

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paleoclimate scientists work and evaluate evidence was our primary motivation in designing these labs. After working through the labs, students are expected to:

- describe what the science of dendrochronology is and what dendrochronologists typically do in terms of field-work and analysis (Lab 1);
- explain what types of research sites dendrochronologists look for and why these places give scientists the best chance to reconstruct past climate change (Labs 1–5);
- navigate public databanks, and locate datasets and meta-data (Labs 1–5)
- generate data, observe trends and extremes, produce graphs, and compare datasets (Labs 2–5);
- explain how the analysis of scientific data leads to a deeper understanding of the challenges we face as a society and can be used to help guide policy and decision making (Labs 4–5).

Literature context

Despite an ever-growing body of evidence that links human-caused climate change to an increasing frequency of droughts, floods, extreme weather events and other impacts around the world (Ainsworth et al., 2016; IPCC, 2014a, b; Joughin et al., 2014; Williams et al., 2020), we continue to see significant undergraduate misconceptions about climate change, climate science, (Huxster et al., 2015; Kirk et al., 2014; Lombardi & Sinatra, 2012), and how the scientific community works. Students, our decision makers of tomorrow, not only need to understand the range of climate-related challenges that they face now and in the future, but they also need a baseline understanding of the process of scientific inquiry and the methodology scientists use to obtain and analyze data (Kirk et al., 2014).

The field of dendrochronology is ideal to teach students about climate-change science and scientific methods because trees are familiar to students and are ubiquitous in many regions across the US and the world (Food & Agriculture Organization of the United Nations (FAO), 2020). In addition, a pencil-sized tree-ring sample can contain hundreds of annual rings (data points) which are relatively easy for students to evaluate. One sample can be compared to other samples from the same site, providing students the opportunity to learn how to develop and evaluate multiple datasets. In turn, this can be applied to larger scientific discussions about climate variability of the past and the connections between climate, people and ecosystems.

Generating one's own dataset is an opportunity that is often lacking for undergraduate students (Ledley et al., 2008). Key educational reports emphasize the importance of using real and relevant data in classrooms (American Association for the Advancement of Science, 1993; Barstow & Geary, 2002; National Research Council (NRC), 1996, 2000) and they emphasize that data-rich investigative activities can motivate learning through harnessing student interest in a particular problem and/or in the data themselves (Manduca & Mogk, 2002). Thus, using data that students

themselves have generated, from field sites that they have virtually explored, could help them stay motivated as they move on to learn about scientific methodologies, interpretation, and applications. Students can also get a more realistic perception of what geoscientists do, the tools they use, and the broad range of field and lab skills needed to do research.

Many students struggle with building quantitative skills, understanding why these skills are important, and how they are applied to real-world problems (Manduca et al., 2008). There are also challenges to incorporating real data in the classroom. A common difficulty instructors face is that scientific data are often not formatted for classroom use, can be too difficult to find, or the dataset descriptions are too narrow and cryptic. These issues make it difficult for instructors to discern if a dataset is relevant for their lessons and can be used effectively in their classrooms (Ledley et al., 2008; Sturtevant & Marshall, 2009). Despite the fact that there are a remarkable number of publicly available tree-ring records available through The International Tree-Ring Databank (ITRDB) managed by NOAA's National Centers for Environmental Information, the database is designed for researchers and therefore generally out of reach of classroom instructors and their students. The TREX labs utilize this databank and make it more approachable to students and instructors by guiding them to use the search engine, identify regional tree-ring datasets, and by explaining the data format and measurement unit.

Building on related innovations

The TREX labs build on successful pedagogical strategies that include using local contexts, teaching with scientific data, increasing access to and usability of scientific data and databases, and by creating a space to visualize and interpret such data (Kirk et al., 2014; Taber et al., 2012). We modeled the labs on the Interdisciplinary Teaching of Geoscience for a Sustainable Future (InTeGrate) project (Egger et al., 2019) and on Earthlabs (Ellins et al., 2014), and they were built collaboratively by faculty in the sciences and other disciplines, educational specialists, and evaluation experts across a diversity of institutions.

TREX labs are built around one scientific discipline—dendrochronology—rather than a specific problem or grand challenge facing society (e.g. drought, global warming). These labs guide students through foundational dendrochronological concepts, methods and analyses, by using several impactful and culturally relevant tree-ring studies. Our intent is to also give students a sense of exploration, as tree-ring scientists commonly travel to remote regions around the world in search of long-lived, climate-sensitive trees. Such expeditions are of inherent interest to broad audiences and allow students to make links between field and laboratory elements (Stott et al., 2014).

Study population and setting

The TREX labs were tested at a public university with *Hispanic Serving Institution* designation. In 2019, 61% of

Table 1. TREX labs and the classes that they were tested in, number of instructors, number of students, type of evaluation/feedback method, and type of instructor feedback.

	Undergraduate class	# of instructors	# of students	Type of student evaluation/ feedback method	Type of instructor feedback
Lab 1 & 2 combo	Intro to Sustainability (Four sections)	2	16, 22, 15, 18	Lab grades, student surveys, class discussion	Instructor survey and Informal discussion
Lab 1	Fundamentals of Earth Science (Section 1)	1	18	Lab grades, student surveys, class discussion	Instructor survey and Informal discussion
Lab 2	Fundamentals of Earth Science (Section 2)	1	9	Lab grades, student surveys, class discussion	Instructor survey and Informal discussion
Lab 3	Weekend Field Course	2	33	Student surveys & informal discussions	Instructor survey
Lab 4	Hydrology	1	18	Informal discussions	Informal discussion
Lab 5	Weekend Field Course	(same instructors as Lab 3)	(same students as Lab 3)	Student surveys & informal discussions	Instructor survey
	Global Climate Change	1	20	Informal discussions	Informal discussion

students were under-represented minorities, and nearly 30% of students were the first-generation in their family to attend college. Labs were tested and data collected in two introductory classes and two upper-level science classes in the Spring and Fall 2018 semesters. The introductory classes included Introduction to Sustainability, in four different sections and Fundamentals of Earth Science, in two different sections (Table 1). The introductory courses ranged from 9 to 22 students and included mainly first-year students and a diversity of majors. These classes included both a lecture and laboratory period and satisfied university laboratory requirements for many non-major students. The labs were run during the three-hour laboratory section of the class, and instructors were given leeway to decide when during the semester to run the labs based on when the materials were most relevant to their course goals. The upper-level classes included Hydrology and Global Climate Change, with 18 and 20 students respectively. The students from these classes were in their junior and senior year and were mainly environmental-science majors. Individual student demographic information was not collected from students.

The labs were also tested, and student feedback collected, during a weekend field course in April 2019 as part of a Partnership in International Research and Education project that focused on tree rings as paleoclimate proxies in the Americas. The field course was not affiliated with any class or with academic credit. This workshop was open to any State University of New York (SUNY) undergraduate student interested in Environmental Science. During this workshop students spent a three-hour lab working through selected materials from TREX Lab 3 and Lab 5. A variety of majors signed up for the field course including students from the sciences and humanities.

Lab overviews, materials, and implementation

In Lab 1, students are introduced to the science of dendrochronology. They learn how nondestructive tree-core samples are obtained and processed (Stokes & Smile, 1968), and take a virtual tour of a tree-ring laboratory. They watch videos of two accomplished dendrochronologists who describe their career paths, the role serendipity has played in their careers, and their advice to students interested in pursuing science. Students consider what types of study sites

dendrochronologists seek to help them answer questions about how our climate has changed in the past, and they explore tree-ring datasets available from the International Tree-Ring Databank (ITRDB), a public archive of global data.

In Lab 2, students virtually drop into a tree-ring site in Southern New York using 360° imagery in Google Maps. The hemlock trees at the site date back to the 1600s and grow on a rocky slope made of giant sandstone and conglomerate boulders. Because of the rocky terrain and lack of soil buildup to hold moisture, the annual tree rings are very sensitive to changes in growing season climate conditions. Students are asked to observe the ecological conditions of the site and evaluate ring patterns from digital scans of tree cores. They then compare annual growth patterns from several tree-ring samples and are guided to use KNMI Climate Explorer (van Oldenborgh, 1999), a powerful, yet easy-to-use, online tool that enables them to graph summer precipitation and compare it to annual tree growth. The trees from this site are some of the best examples of drought-sensitive trees in the U.S. Northeast (Cook, 2014). At the end of Lab 2, there are two “Meet the Challenge” final options where students can apply what they have learned to a different region of the world. In option one, students look for forests in state or national parks in the US and then use Climate Explorer to get a better sense of the climate trends and extremes of that region. In option two, students explore a forest growing on an ancient lava bed in Mongolia (Davi et al., 2006; Pederson et al., 2014), and compare annual growth rings to climate data that they downloaded from Climate Explorer. This challenge can be done in class, assigned as a take home assignment, or used as an assessment.

In Lab 3 students learn about the establishment of dendrochronology as a field through its utility in calendar dating historical structures (Douglass, 1929). They virtually explore Pueblo Bonito at Chaco Canyon, New Mexico, an ancient ruin that was inhabited between 750 and 1250 CE, and then virtually search the site for samples of wood to analyze. Students use a qualitative method to create a skeleton plot, a graphical representation of ring width (Figure 1), from the scanned image of a sample of western juniper (*Juniperus occidentalis*), and use it to compare to a published record to determine the year the tree was felled to build the

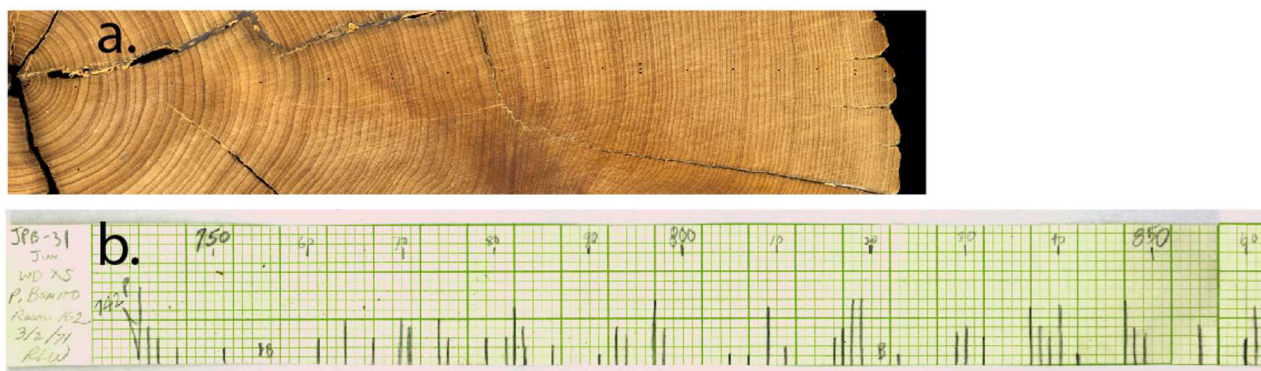


Figure 1. (a) Students learn to date and measure tree rings using a high-resolution scan of an original juniper sample from a pilaster at Pueblo Bonito, Chaco Canyon, New Mexico, that was collected in 1922 by A.E. Douglass and Neil Judd. Students are guided to develop their own “skeleton plot” (b) and compare it to the one pictured here to see if they can determine the year the tree was felled to build the pueblo.

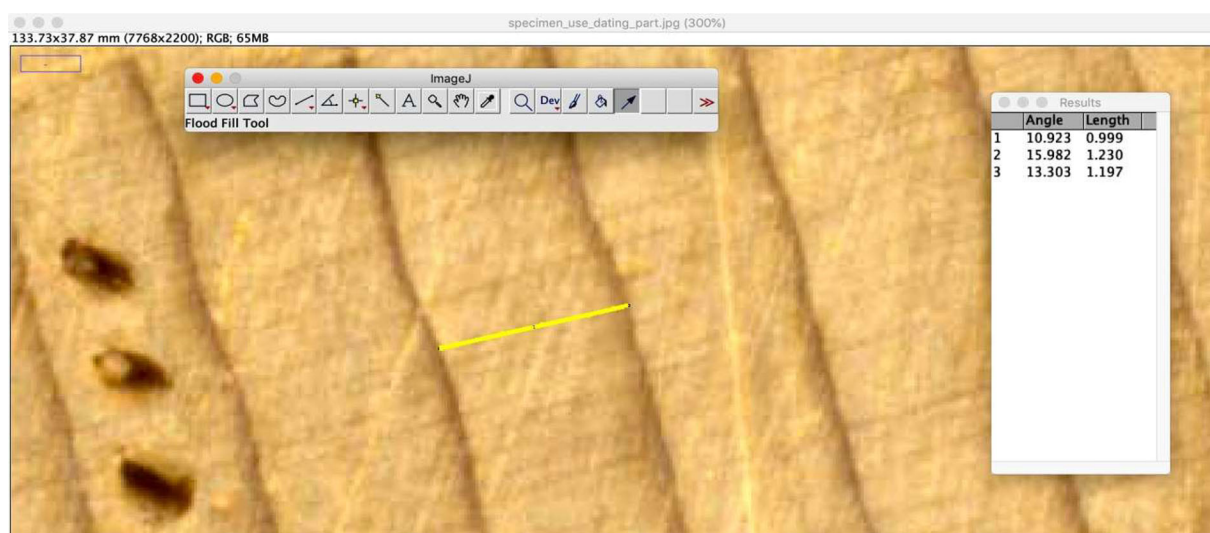


Figure 2. A screen capture showing how student measure annual ring width from a high-resolution scan using ImageJ software. The yellow line shows the measurement of one annual ring, in this case the year 2002. The results tab shows measurements from three rings, starting with the ring with three dots on it, an indicator of a century ring, in this case the year 2000.

pueblo. Students also learn how to measure annual tree rings using a public domain image processing program developed by the National Institutes of Health (ImageJ, Figure 2). Students produce a graph of their measurements, and compare their work to their classmates. Students then investigate an interactive millennial-scale drought reconstruction produced by tree-ring records (Stahle et al., 2009) to identify the existence of megadroughts and extreme years. They also consider if an extreme period of drought could have contributed to the abandonment of the pueblo.

Students virtually explore parts of the Colorado River in Lab 4 and learn about how stakeholders draw water from the river to serve the needs of seven western states and Mexico. Students collect data on where the water comes from, who is using the water, and how much is being used. In the second part of the activity, they focus their attention on a tree-ring site in New Mexico and work in small groups to measure tree-ring width using ImageJ on laptops and then compare their results with published tree-ring records from the same sites. Students then evaluate an interactive millennial-length streamflow reconstruction (Meko et al.,

2007; Woodhouse & Lukas, 2006) and are asked to estimate how often major droughts occur.

In Lab 5, students explore some of the remote tree-ring sites that scientists have sampled to develop a better understanding of warming in the Northern Hemisphere over the past 1,000 years (Wilson et al., 2016). They also evaluate tree-ring datasets that are publicly available from the ITRDB and the Paleoclimatology Data Map (Figure 1, Supplementary material) and research related peer-review publications using Google Scholar. Using an interactive feature, students evaluate a millennial-length Northern Hemisphere temperature reconstruction (Wilson et al., 2016), based in part, on tree-ring records from the sites that they have explored virtually. The lab then guides them to measure data from several of the sites and to research potential causes for some of the extremely narrow rings that they have identified in the record—in this case, many of the extreme years coincide with large-scale volcanic eruptions (Briffa et al., 1998).

Putting exact calendar dates on tree-ring samples can be challenging, owing to the tendency for many trees to have

missing and/or false rings in certain sections of a sample (Stokes & Smiley, 1968). Here we have scanned tree-ring cores at high resolution, from many of the sites that the students have virtually explored, and we pre-marked them, with a dot for each decade, so that students can spend their lab time on generating their own data and interpreting what the ring patterns are telling them rather than marking up samples. Marking and cross-dating tree-ring samples is a basic principle and critical step of tree-ring science, but can take weeks to months to learn to do accurately, and is therefore neither feasible for a typical classroom lab period or two, nor was it intended as a goal of TREX. Still, when critical methodological steps were skipped for the sake of time, such as pre-marking core samples, we described the steps in the text so that students would not get an over-simplified and inaccurate idea of the time and skills required to do the research.

We likewise provided descriptions of some of the mathematics needed to process data. While working through the labs, students were asked to generate tree-ring measurements (Lab 2, 3, 4, 5), develop a simple index (Lab 2), record relative measurements through skeleton plotting (Lab 3), and interpret graphs and time-series datasets (Labs 2, 3, 4, 5). Though not asked to do calculations themselves, students did read about why higher-order mathematics would be necessary for data analysis (e.g. descriptive statistics, standardization, and regression analysis). Throughout the labs, students were able to work with widely-used and familiar applications, such as spreadsheets to plot data, and to learn how to interpret graphs and time-series datasets. These types of exercises support quantitative skills and help students prepare to enter the workforce by building the skills and competencies desired by the geoscience community (Mosher et al., 2014).

The labs are designed to be more challenging with each successive lab and are structured to build methodological and analytical skills as students work through each one. As students work through two or more of the labs, they revisit some of the same skills in multiple contexts, which allows them to build proficiency. Detailed guidance is given each time students are asked to perform a task as each lab is independent of the others.

Table 2 provides overview information about each lab, including student tasks required for each lab, key questions (which are aligned to the overall learning goals of the labs), datasets used, software, platforms, multi-media, and time requirements needed to run each lab. The TREX website includes instructor guides, answer keys, assessment options, teaching notes and tips, and multimedia background materials. There is also a separate section for students that guides them through the labs and provides downloadable student activity sheets. These activity sheets provide space for students to answer *Stop and Think* questions at the end of each lab section (Table 3), and a space to drag and drop graphs that they have generated and evaluated. The activity sheets can then be graded to determine if the students were able to meet the learning goals.

We recommend that all students do Lab 1, the introductory lab, and then any of the other labs could be done subsequently depending on instructor interest and course goals. The labs offer a variety of topics, from climate variability, to archeological applications in order to appeal to a wide variety of instructors. We envisioned the labs being used in a variety of undergraduate classes including those on introductory geology, physical geography, environmental science, and sustainability courses, or more advanced courses in research methods, water resources, and climate change. Although each lab was designed so that students could largely go through it as a self-guided exercise, we supply scaffolding for teacher input, class discussions, and data comparison. Instructors are encouraged to walk around the class, or drop into virtual breakout rooms, as students work through the labs and check in with students to make sure that everyone is making progress.

Ideally, these labs are best used in smaller classes (12–30 students) where instructors can check in on student progress and understanding more easily. Students can work in pairs or teams for most activities and when presenting their research results. After each activity, students have the opportunity to discuss and compare their results with the entire class. For instructors and/or students who would like more information about the science, additional resources, references and relevant links are provided at the end of the introductory page of each lab. Labs that are not finished in class could be assigned as homework.

Lab evaluation

Peer review

Prior to classroom testing, the labs were evaluated by graduate and undergraduate student consultants with experience in tree-ring research, through an undergraduate geoscience faculty consultant, through a faculty workshop, and through a faculty assessment team affiliated with the National Association for Geoscience Teachers (NAGT) and The Climate Literacy and Energy Awareness Network (CLEAN). All students and the faculty consultants worked through the labs and provided both written and verbal feedback about lab content, presentation, questions that arose, and ease-of-use of each lab. The faculty workshop, a day-long event held in May 2017, was run by the project PIs and included 24 faculty members from both a community college and a four-year public university. Their disciplines ranged from mathematics, to history, to art, and the geosciences. The main goals of the workshop and evaluations were to assess the clarity of the materials, the ease-of-use of the labs, and the overall impressions from a variety of faculty. After working through Lab 1 as a group and given an overview of all labs, faculty worked through the three sections of Lab 3 and provided feedback using a survey (Table 4). Project PIs circulated the room as faculty worked through the labs to take note if there were any questions or comments. Feedback was also provided through a group discussion at the end of the workshop.

Table 2. TREX labs, key questions addressed, datasets/multimedia used in each lab, and student tasks (Reproduced with permission from Davi et al., 2019).

TREX Labs:	Key Questions:	Datasets, Software, Platforms, and Media:	Student Tasks:
Lab 1. Launching an Expedition: Introduction to dendrochronology and the nature of science. Time required: 90 minutes.	<ul style="list-style-type: none"> How do scientists take tree-core samples? What site characteristics are important for tree-ring studies? How do scientists get funding for research? How do scientists learn about what has already been done? 	<ul style="list-style-type: none"> Virtual 360° field exploration ITRDB Google Scholar Scientist interviews NSF Research News Animation: Identifying Climate Sensitive Trees Video(s): Historical video 	<ul style="list-style-type: none"> Virtually explore and describe sites Watch interviews Explore NSF website Search the ITRDB
Lab 2. Humpty Dumpty and Drought in the Hudson Valley: Focuses on a premier climate-sensitive site in the US Northeast and on how scientists use tree rings to developed a drought record of the region. Time required: 180 minutes.	<ul style="list-style-type: none"> What site characteristics are important for tree-ring studies? Why are some trees more sensitive to climate than others? How do you take tree-core samples? Why are some rings narrow? Do trees record climate? 	<ul style="list-style-type: none"> Virtual 360° field exploration Video(s): Scientist interviews Video(s): Tree sampling High-resolution scans of tree cores from the site Meteorological databank (PDSI, KNMI Climate Explorer) 	<ul style="list-style-type: none"> Virtually explore and describe sites Identify narrow rings Find online meteorological data Compare ring patterns to meteorological data Meet the Challenge
Lab 3. Tree Rings and the Ancestral People of Pueblo Bonito: Focuses on the history of dendrochronology and how scientists calendar date historic structures. Time required: 180 minutes.	<ul style="list-style-type: none"> What site characteristics are important for tree-ring studies? How do scientists assign exact calendar dates to tree-ring samples and historical structures? How might have drought affected the ancient Puebloan people? How could a drought affect your life? 	<ul style="list-style-type: none"> Virtual 360° field exploration Video(s): History of dendrochronology High-resolution scans of tree samples. NIH ImageJ software and tutorial Drought reconstruction interactive 	<ul style="list-style-type: none"> Virtually explore and describe sites Skeleton plot Compare plots to historical work Determine tree felling year Measure tree rings Evaluate drought reconstructions Graphing
Lab 4. Sharing a River: The Colorado River Story: Stresses the importance of the Colorado River as a resource and how tree-ring data informs water resource management. Time required: 180 minutes.	<ul style="list-style-type: none"> Who are entitlement holders and how is the Colorado River used? What site characteristics are important for tree-ring studies? How are tree rings used to reconstruct drought? What information can we learn from tree rings about streamflow? How do we better manage water resources? 	<ul style="list-style-type: none"> Virtual 360° field exploration Video: Colorado River Map interactives Digital scans of tree cores NIH ImageJ software and tutorial National Weather Service drought maps Reconstruction Interactive 	<ul style="list-style-type: none"> Virtually explore and describe sites Evaluate current drought maps Compare supply/ demand data, snowmelt/streamflow Measure samples Compare work to published datasets Evaluate streamflow reconstruction
Lab 5. Warming and the Boreal Forests: Students learn how tree-ring records are used to develop a temperature reconstruction, evaluate trends, and relate extreme years to major volcanic events. Time required: 180 minutes.	<ul style="list-style-type: none"> What are the boreal forests? What site characteristics are important for tree-ring studies? How do you find previously published data and related science literature? How do scientists develop long tree-ring records? What do tree rings in the northern hemisphere tell us about climate? What role can serendipity play in science? Can large-scale volcanic events affect climate? 	<ul style="list-style-type: none"> Virtual 360° field exploration ITRDB Google Scholar Animation: Identifying Climate Sensitive Trees Video(s): Interview Video (s): History of Dendrochronology High-resolution scans of tree cores NIH ImageJ software and tutorial Temperature reconstruction interactive 	<ul style="list-style-type: none"> Explore the ITRDB Research: peer-reviewed articles Virtually explore and describe sites Measure tree samples Compare measurements to published data Evaluate interactive temperature reconstruction Identify short and long-term trends Identify extreme years. Research volcanic events

The NAGT affiliated reviewers were participants in the 2017 annual Earth Educators Rendezvous “Review Camp” (https://serc.carleton.edu/earth_rendezvous/index.html), where faculty volunteers reviewed collections of submitted teaching activities. Faculty reviewers were instructed to approach each of the five labs as single reviewable unit and to use a scoring rubric to evaluate each lab based on 1) scientific accuracy, 2) alignment of goals, activity, and assessment, 3) pedagogic effectiveness, 4) robustness, and 5) activity description (https://serc.carleton.edu/teachearth/activity_review_rubric.html). Three of the five labs received exemplary scores (Labs 2, 4 and 5) and two received a pass

(Labs 1 and 3). The reviewers felt that small changes could elevate all lab’s scores, and these suggestions were subsequently followed.

TREX Labs 1 and 4 were also reviewed by CLEAN’s Review Camp (<https://cleanet.org/clean/about/review.html>) in 2020. The CLEAN Collection is a digital collection of K–16 teaching resources aligned with the Climate Literacy Framework (U.S. Global Climate Change Program, 2009), the Energy Literacy Framework (U.S. Department of Energy, 2014), and with Benchmarks for Science Literacy (American Association for the Advancement of Science, 1993). Both labs were extensively reviewed for quality and accuracy of

Table 3. Selected “Stop and Think” questions, aligned to the learning goals, that are embedded within each lab.

Lab 1 Launching and Expedition	<ul style="list-style-type: none"> • What types of trees and tree-ring sites are the most useful for tree-ring research? • Why are trees growing in landscaped areas not useful to study past climate conditions? • What is the dominant limiting factor to tree growth at high altitudes? • How close is the nearest tree-ring research site from where you live?
Lab 2 Humpty Dumpty and Drought in the Hudson Valley, NY	<ul style="list-style-type: none"> • Why are the trees on the talus slope ideal for use in tree-ring research? • Which years consistently stand out for being very narrow or wide compared to their neighbors? • Describe any similarities you see between the data you graphed in Climate Explorer and the tree-ring “marker years” that you identified in Part 2.
Lab 3 Tree Rings and the Ancestral People of Pueblo Bonito, NM	<ul style="list-style-type: none"> • Describe the site based on your observations. Be sure to emphasize the types of vegetation you see (how many different types of trees, shrubs), the density of that vegetation, the soil or lack of soil, the presence or absence of water, and any other characteristics you may observe. • Post a screen capture image of a wood sample that you found inside the Pueblo that you believe would be suitable for further research. • How do megadroughts of the past compare to droughts that have occurred in the past 100 years? • Given what you have learned about drought through time based on tree rings, would it change your mind about living in that region? • If you were a water manager for New Mexico, how would this data affect your thinking about managing water?
Lab 4 Sharing a River: The Colorado River Story	<ul style="list-style-type: none"> • What three years had the lowest flow volume in the Colorado River? • What was the difference between water used and the total water available in 2002? • Give two reasons that you think would account for the rising demand for water in the Colorado River Basin. • Do you see similarities in tree growth compared with the stream flow records at both locations? Do narrow rings match up with low flow years?
Lab 5 Warming and the Boreal Forests	<ul style="list-style-type: none"> • Describe the nature of the forest along the East Glacial Trail. Are the forests diverse? Are there shrubs and other plants? Is there a lot of soil that you can see? Do you see mostly broad leaf deciduous trees, or conifers? • Describe the site conditions and forests you see in the two 360° images from Mongolia. • How does this Mongolian forest differ from the one you looked at near the Mendenhall Glacier in Alaska? • Compare the graph of your sample to the related master tree-ring chronologies above. Does the data from the core/cores that you measured look similar to the related master chronology from the same region? Why/why not? • Looking at the master chronologies above, describe the patterns that you see. What are the extreme narrow (reflecting cold) and extreme wide (reflecting warm) years? • List five periods of 5-10 years in duration that were unusually warm or cold over the past 1000 years.

Table 4. The survey given to faculty prior to classroom testing, and during the faculty workshop.

- Was the point of the lab clear? Were the tasks and instructions clear? If not, what problems did you see? Any suggestions for improvement?
- Were the *Stop and Think* questions appropriate? Did the material support them?
- Were the materials comprehensibly written? Any suggestions for improvement?
- Are the directions for the technology components included in the lab adequately outlined for students?
- If you were to use this lab in your class, do you think it would be engaging and interesting to your students?
- If you were to use this lab in your class, do you think it would be challenging? Too easy?
- What difficulties might you anticipate for yourself or your students?
- How many class sessions or hours do you estimate this lab would take in your class?
- Does the sequence of activities flow coherently from activity to activity?
- Do you have any suggestions of additional learning experiences to include in the sequence? Should any parts of the existing activities be deleted?
4. Other suggestions or comments on lab structure, format, or content?

scientific content for inclusion in the CLEAN Collection. Labs 2, 3, and 5 are in the queue to be reviewed at the next camp in 2021.

The labs have been modified based on feedback from all assessments. Many of the modifications included grammatical changes, clarification and simplification of the text, more emphasis and/or explanation on the materials that faculty felt would be most relevant for their classes and students (e.g. mapping, exploring, data generation, using Excel, and data interactives), and several modifications related to Diversity, Equity, and Inclusion. Several lab sub-sections that generated low faculty/student interest were removed. Captions were added to all videos to aid hearing impaired students.

Classroom testing

TREX Labs 1 and 2 have been tested in six undergraduate classes, and feedback was collected from students through surveys, lab grades, and from class discussions with instructors (Table 1). Classes included four sections of Introduction to Sustainability using a combination of Lab 1 and 2 (Lab 1, Part 1, and Lab 2, Parts 1–3), and also in two sections of Fundamentals of Earth Science (Lab 1 and 2). Labs 3 and 5 were run during the SUNY weekend field course, where student surveys were given, but grades were not collected (Table 1). Lab 4 and 5 were also run in two upper-level classes, hydrology and climate change, although in both cases only informal feedback was solicited from instructors

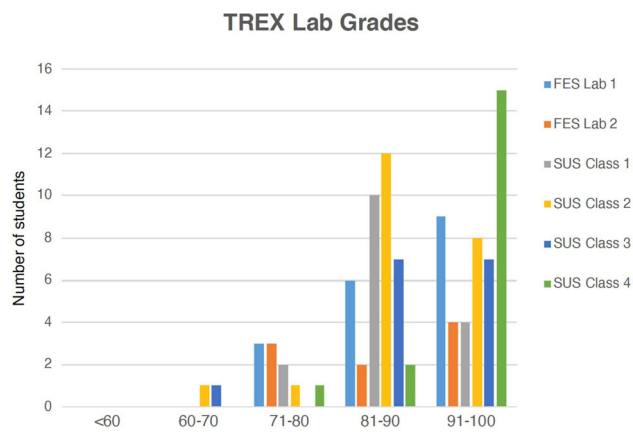


Figure 3. Stop and Think question grades for Fundamentals of Earth Science (FES) TREX Lab 1. (light blue, $n=18$), Lab 2 (orange, $n=9$), and for Introduction to Sustainability (SUS) using a combination of Lab 1 (Part 1) and Lab 2 (Part 1-3), Class 1 (grey, $n=16$), Class 2 (yellow, $n=22$), Class 3 (dark blue, $n=15$), and Class 4 (green, $n=18$).

guided by the questions asked on the instructor survey shown in Table 4. Lab grades were based on completion of each lab task and the *Stop and Think* questions that accompany each lab section.

Results

Student activity sheet grades (Figure 3) show that the majority of students did well on Labs 1 and 2 scoring an 80% or higher demonstrating that they were able to perform the tasks in each lab and successfully meet the learning goals by answer the *Stop and Think* questions. From the student surveys collected in class (Figure 4), our goals were to determine if students were interested in the materials, felt comfortable using the technology, felt that they were learning the materials and were working like tree-ring scientists, and had a better understanding of how the data was applied to real world issues. The surveys showed that most students felt that the labs were easy to navigate (Figure 4: Q2, Q3, Q7, Q9), and generally had positive feedback about their experience (Figure 4: Q1, Q2, Q7, Q8). The surveys also showed that students felt that they gained a better understanding about the field of dendrochronology (Figure 4: Q5, Q8), about how tree-ring records are applied (Figure 4: Q10), and about the nature of science (Figure 4: Q4, Q5, Q6, Q8, Q10) as it applied to the field of dendrochronology. Open-ended questions about what parts of the labs worked well and what difficulties students had were included in the surveys, but got a lower response rate than the Likert-scale questions in Figure 4. Students that did answer these questions provided valuable feedback that is summarized from two Fundamentals of Earth Science classes in Table 5 and discussed further below.

Discussion

TREX engages undergraduate students to learn more about paleoclimate science and the process of scientific inquiry by guiding them to generate and evaluate tree-ring data. To

support student learning, we provide virtual exploration, societal relevance and “big-picture” context, visualizations and other interactive media (Table 2: Datasets, Software, Platforms, and Media) and guiding *Stop and Think* questions (Table 3) where students reflect on what they have learned. To successfully answer these questions, students needed to be able to describe foundational tree-ring concepts, identify datasets from online platforms, and accurately identify trends and extremes within datasets. For example, in Lab 1, students read about the importance of “Site Selection”, a foundational concept in tree-ring based paleoclimate research;

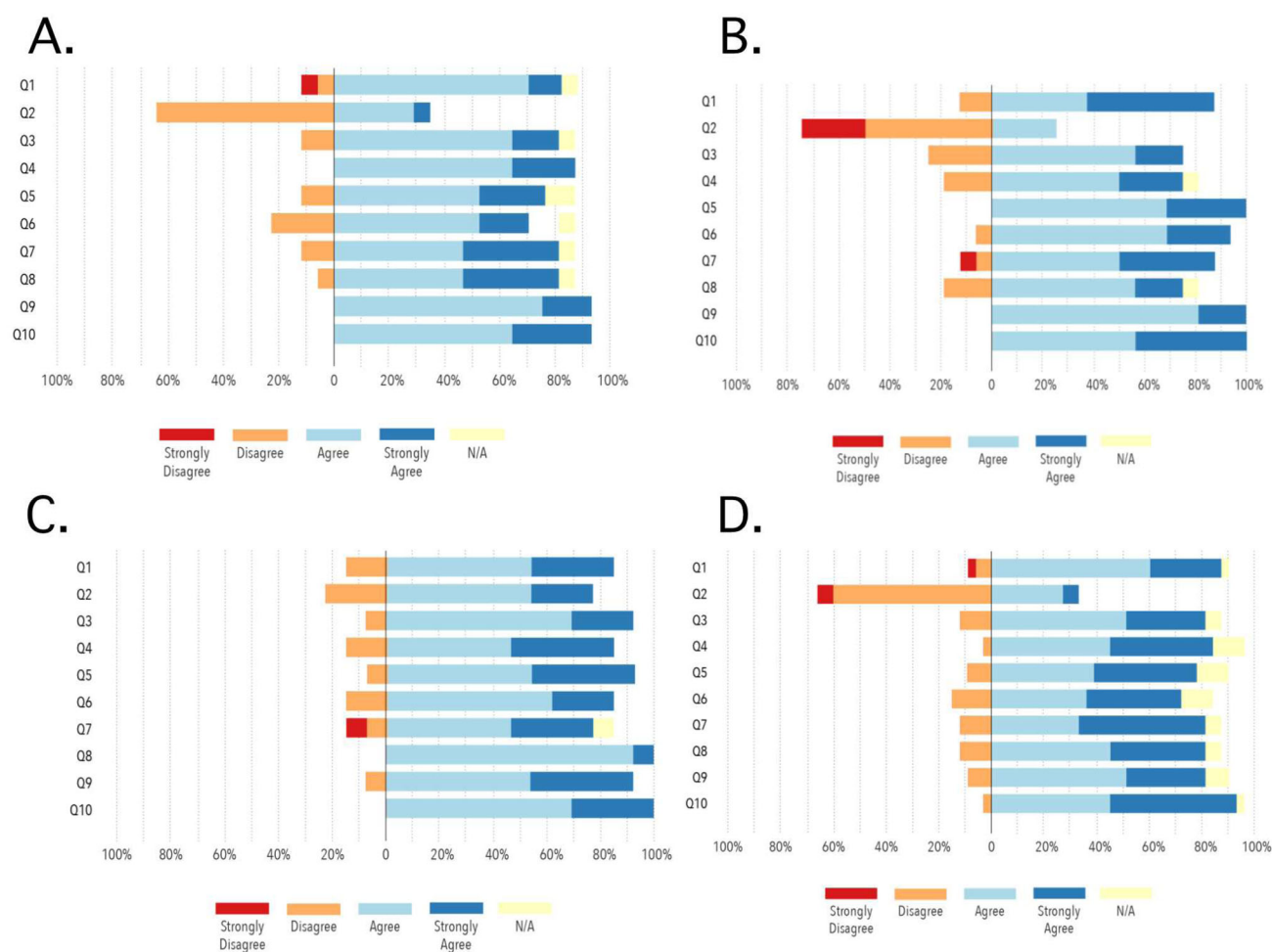
Conducting tree-ring science isn't as simple as it might first appear. The vast majority of trees we see on hikes or while driving will not have captured a good climate record over long periods of time. Dendrochronologists need to search for long-lived trees that grow in fairly harsh environments, making them very sensitive to the surrounding conditions, where their growth is slow— so slow that many years will be recorded in their lifetimes. One such tree is the bristlecone pine, which grows in Arizona, Colorado, New Mexico, Utah, Nevada and eastern California, sometimes under very cold and dry conditions. The oldest known specimen is named Methuselah and is 4,765 years old! You'll have a chance to explore a bristlecone pine site in Part 2 of this lab.

After reading the section, students watched an animation that demonstrates how tree-ring width records from these stressed sites relate to growing-season climate conditions. Site selection is a fundamental concept in dendrochronology that determines the questions scientists are able to answer (Stokes & Smiley, 1968). As such, we made it a focus of the beginning of each lab (Table 2), where students must virtually drop into a new site and answer questions about site characteristics they observed that could indicate that trees may be stressed and therefore sensitive to climate conditions. Student lab grades show that they were able perform the assigned tasks and successfully answer the *Stop and Think* questions (Figure 3). They also reported that the virtual explorations “worked well” (Table 5) and most students “enjoyed using Google Earth to explore a tree-ring expedition site” (Figure 4, Q7).

Generating and evaluating data is also an overarching goal of the TREX labs, and there are *Stop and Think* questions within each lab that are used as a learning assessment of these goals. For example, in Lab 2 students evaluate annual ring patterns over several decades and then compare those patterns to a nearby record of summer precipitation, allowing them to confirm the climate signal in the trees. The *Stop and Think* questions measure their ability to do this accurately, by having them list the years with the narrowest/widest annual tree rings and describe the relationship between the tree ring and precipitation patterns. Similar tasks are required in subsequent labs, although students also evaluate data that they themselves have generated and they start to evaluate longer, millennial-scale, records of climate variability.

Student and instructor survey feedback

After working through Labs 1 and 2, students from the introductory classes and the field weekend reported that



Q1: Doing this TREX lab was an interesting experience for me.

Q2: I found the content of this lab to be difficult for me.

Q3: I was able to complete the technology-related components without major difficulty.

Q4: Doing a TREX lab has increased my understanding of how science is done.

Q5: Completing "Launching an Expedition" gave me a good introduction to the nature of dendrochronology and tree-ring science.

Q6: The video(s) embedded in the lab was/were useful to me for understanding the nature of science and what scientists do

Q7: I enjoyed using Google Earth to explore a tree ring expedition site.

Q8: I felt like I was doing tree-ring science using the same methods that dendrochronologists use.

Q9: The text, diagrams, and images in the introductory text were useful and important in understanding what I was going to learn and do in the lab.

Q10: After doing the lab, I understand how tree rings can be used to reveal the nature, scale, and duration of past climate events such as droughts

Figure 4. Student survey results for; A. Intro to Sustainability based on a combination of Labs 1 and 2 (n = 71); B. Fundamentals of Earth Science, Lab 1 (n = 18); C. Fundamentals of Earth Science, Lab 2 (n = 9); and D. A combination of Lab 2 and 5 for a two-day field workshop for mixed-majors with two groups of students (n = 33 total).

Table 5. Summary of student feedback after completing the TREX Labs 1 and 2 in Fundamentals of Earth Science.

Main themes from student survey feedback

Difficulties:

- using technology (e.g. Excel)
- more time needed
- not comfortable interpreting data
- intimidated by mapping
- intimidated by graphing
- navigating multiple screens at the same time
- prefer to work with the actual wood cores

Worked well:

- virtual exploration
- video interviews
- introductory materials
- generating maps
- manipulating interactive graphs
- working on digital cores
- connecting annual tree growth to annual climate
- connecting climate to people

they agreed or strongly agreed that they “felt that they were doing tree-ring science using the same methods that dendrochronologists use” (Figure 4, Q8), and in the Introduction to Sustainability class and both sections of Fundamentals of Earth Science, all students agreed or strongly agreed that “after doing this lab, I understand how tree rings can be used to reveal the nature, scale, and duration of past climate events such as droughts” (Figure 4A–C, Q10).

In the open-ended survey questions (Table 5), students reported that the videos included in Labs 1 and 2 were parts that they liked best. These videos, entitled “A Brief History of Dendrochronology” and “Identifying Climate Sensitive Trees”, demonstrated how scientists take nondestructive samples from living trees using an increment borer (a hand drill) and also included several scientist interviews. Students also reported that they liked working with the time-series interactives, which allowed students to magnify different time periods of the millennial-scale reconstructions. The interactives helped them to more easily view year-to-year variation and evaluate decadal-scale climate trends.

From the open-ended student survey questions, we also learned what students struggled with and liked least. Here, some students reported feeling intimidated by data interpretation, using spreadsheets, and graphing. Given that many of the students in the introductory classes were freshman and came from a variety of majors, they may have had limited prior knowledge and exposure to these types of data-intensive exercises.

From TREX peer-reviews (Text 1, [Supplementary material](#)) we learned that the overall concept of dendrochronology was interesting for students and that the labs and structure encouraged students to ask questions. Instructors also liked the progression of the labs from the physical science of dendrochronology in Labs 1 and 2, to the societal connections with the research in Labs 3, 4 and 5. Instructors found the activities to be well scaffolded, so that students were able to build knowledge progressively and then apply their skills to a new study region, such as in the *Meet the Challenge* section of Lab 2.

Based on our classroom testing of the TREX labs, including student lab grades and feedback from instructor and student discussions and surveys, we feel that the TREX labs have met the intended goals—for students to learn about basic dendrochronological concepts, to generate and evaluate data, and to learn about how tree-ring records are applied and inform decision makers.

Limitations

Surveys

Our ten-question survey was developed to assess if students felt that the labs were navigable, to determine if students felt that they were learning about the science, about the nature of science, and about how the data is applied. We considered switching to validated survey instruments, tools of the burgeoning field of discipline-based education research. However, we found that many of the questions within the validated question sets were outside the scope of the TREX

labs. We felt that it would be confusing for students to answer some questions that were relevant to the labs while ignoring questions that were not (pertaining to longer-term summer research programs, for example). Therefore, we continued using the ten-question survey throughout classroom testing for consistency and time constraints, but recognize that validated survey instruments would be useful in measuring student learning outcomes, in addition to surveys and student grades.

Part of how we assessed lab effectiveness was through self-reported survey data from students. Although these types of student surveys are common in evaluating curriculum and provide valuable lab feedback, they do not provide information about why students liked or disliked the labs. For example, our survey instrument did not capture whether students had prior experience working with data or if the website failed to load properly, which could happen with out-of-date web browsers.

Another limitation was that we did not collect lab grades and surveys for all classes that ran the TREX labs (Table 1). We only collected lab grades and student surveys in the introductory classes for Labs 1 and 2. Some instructors found that completing the class surveys after running the labs was burdensome because of time constraints and also because students tend to finish the labs at different rates. In this case, we relied on informal discussions with instructors and students’ discussions with their instructors. Instructors were sometimes more detailed in their comments when discussing their experience in person rather than filling out the survey, and we therefore accommodated instructors as much as possible.

Implications

Tips for classroom use and adoption

When running the labs, it is important that instructors not make assumptions about student understanding of graphics and maps within the labs. For example, while running Labs 1 and 2 in the Intro to Sustainability class, some students struggled to interpret color meaning in spatial maps of drought in the Northeastern U.S. In this case, blue indicated areas that were wetter than normal, and red represented areas that were drier than normal (Figure 2A, [Supplementary material](#)). The use of these colors for wet/dry regions would be typical for maps representing meteorological information on weather websites or in the news, but the color representations were not necessarily clear for all students, and some students did not speak up about their uncertainty unless asked directly.

Likewise, some students were confused about the meaning of positive and negative values in the time-series drought data (1900–2017) in the Northeastern U.S. (Figure 2B, [Supplementary material](#)). In this case, positive values equate to wetter years and negative values equate to drought years. Even though this relationship was described in the lab text, we recommend that instructors check in with students to make sure they understand it before moving on to the interpretation activities. Similarly, reminders about graph

meaning are highlighted in the lab text for students and repeated in some cases. Since it is still possible for some to miss these reminders, we also recommend checking in with students as they progress through the labs to make sure that they are interpreting maps and graphs accurately.

When starting activities that ask students to evaluate data, we recommend modeling what to look for (i.e. trends and extremes) using a different but related example. These examples are provided in the main text of the labs. In the introductory classes, students verbally reported that they were more comfortable interpreting data after working through several examples. Within the TREX labs, students are guided to generate and interpret graphs repeatedly, and guidance and answer keys are provided in the instructor guides.

Conclusion

Although outdoor field-experiences are highly motivating for students (Boyle et al., 2007) and support geoscience competencies (Kastens et al., 2009), these types of experiences are not always available to all students owing to limited resources, time constraints, liability concerns (Semken et al., 2017), disabilities (Gilley et al., 2015), and more recently, due to the global COVID19 pandemic. In TREX, we created virtual field experiences and guided scientific activities so that a diversity of students, and more students, could participate in authentic tree-ring activities in a classroom setting over several lab periods.

These labs have been extensively reviewed by faculty-peers and have been classroom tested. The TREX labs introduce students to foundational dendrochronological concepts, methods, and analyses, and provide guidance and infrastructure so that students can experience measuring and interpreting paleoclimate data first hand. The labs are based on highly cited and impactful tree-ring research that the scientific community has relied upon to understand climate variability over the past millennium. The labs also guide students to reflect on climate's impact on human wellbeing and about how paleoclimate data can be used to inform decision making for the future.

Acknowledgements

Thanks to faculty, staff, and student lab reviewers, and P. Lea, F. Wattenburg, I. Greidanus, C. Manduca, S. Fox, J. Wolfe, R. D'Arrigo, E. Cook, G. Wiles, C. Sinton, R. Wilson, N. Weisemburg, C. Cairns, M. DaSilva, E. Klein, C. Leland, and M. Rao. We also thank the manuscript reviewers and the JGE Associate and C&I Editor. LDEO contribution #8502.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This project was supported by the National Science Foundation, under grant DUE #1405664.

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