1 Introduction

The Quaternary Period (2.6 million years ago to present) is a highly active area of integrative ecological, geological, and climatic research. Quaternary timescales range from the decadal and centennial scales of our lives and historical memory to deep-time geological timescales of millions of years and longer. In addition, the Quaternary has been a time of planetary-scale climate changes, operating at many timescales, recorded in many different types of datasets, and with strong and clear effects on cryogenic, biological, and physical systems. This combination of factors – the range of timescales including human history plus the data-rich record of planetary climate change – makes the Quaternary a natural entry point for teaching and learning about paleoecology, geologic time, and climate change via authentic data exploration (e.g., Manduca and Mogk, 2002; Hunter et al., 2007; Laursen et al., 2010; Resnick et al., 2011, 2012).

The Quaternary is of particular interest to scientists studying climate change (Masson-Delmotte et al., 2013), the ecological effects of climate change (Araújo et al., 2008), and the causes and effects of species range shifts and extinctions (Ordonez and Svenning, 2017), providing engaging questions for students. Climatically, the defining features of the Quaternary include: (1) the oscillation between long glacial periods and short interglacials, accompanied by the growth and collapse of continental ice sheets, sea-level falls and rises, and variations in global temperature and atmospheric greenhouse gas concentrations; (2) a pacing of these glacial-interglacial changes by variations in the Earth's orbit, known as Milankovitch cycles; and (3) large and abrupt temperature changes during glacial terminations such as Heinrich Events and Dansgaard-Oeschger events (Masson-Delmotte et al., 2013). During the Holocene interglacial (11,700 years ago to present), temperature variations have been muted but hydrological variability has intensified (Mayewski et al., 2004), linked to both internal processes such as shifts in ENSO variability and external forcings such as individual volcanic eruptions and variations in solar luminosity (Wanner et al., 2008).

Ecologically, species distributions repeatedly retracted and expanded during the glacial-interglacial cycles (Davis and Shaw, 2001), with high local community turnover during climatic events (Blois et al., 2010). The worldwide expansion of humans before and during the last deglaciation was accompanied by a global wave of extinctions of large animals (Pleistocene megafauna) and other hominid species (e.g., Neanderthals, Denisovians). During the Holocene, post-glacial range expansions of tree species continued, with population dynamics and range expansions often paced by hydrological variability and

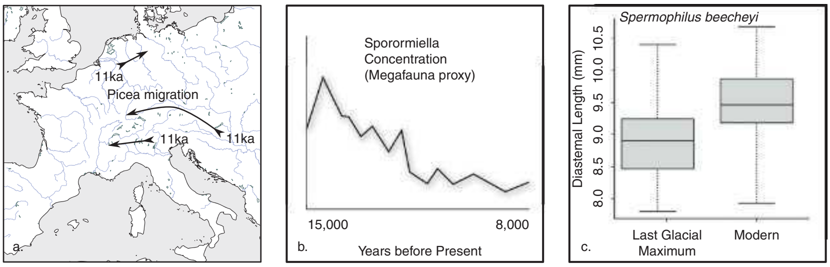

Figure 1. Examples of Quaternary datasets, simplified and adapted from their original publications: (1) Species migration through time beginning 11,000 years before present (11 ka), here, *Picea* (spruce) in Europe after the end of the last ice age (from Latalowa and van der Knaap, 2006); (2) Megafaunal extinction interpreted from the decline in the fungal spore *Sporormiella*, present in the dung of large herbivores (after Gill et al., 2009); and (3) change in mammal body size in the ground squirrel *Spermophilus beecheyi* (after Blois et al., 2008).

drought. Understanding these past ecological dynamics helps global change ecologists and biogeographers understand how species are likely to respond to current environmental changes and test the predictive ability of Earth system models.

Our understanding of climatic and ecological dynamics during the Quaternary is founded upon many individual site-level analyses of fossil organisms and paleoenvironmental proxies (Fig. 1). Fossil data are many and varied and include micropaleontological data (e.g., pollen, diatoms, ostracodes, foraminifera), macropaleontological data (e.g., vertebrate fossils, plant macrofossils), and, increasingly, molecular and organic geochemical tracers such as ancient DNA or organic compounds such as alkanes from leaf waxes. These paleoenvironmental records are collected from a diverse array of depositional environments, including excavations, lake sediment core sampling, or other fossil localities. Understanding the large-scale spatial phenomena that define the Quaternary requires gathering these many diverse datasets into larger databases that store information about age, taxonomy, spatial coordinates, depth or stratigraphy, and other related information (Williams et al., 2018).

In response to these needs, the Neotoma Paleoecology Database (Neotoma) has emerged as a community-curated data resource (CCDR) with the mission of gathering, curating, and sharing paleoecological and paleoenvironmental data, to enable open, global-scale science (Williams et al., 2018). This resource also provides students and educators with a public portal for accessing data that can be used to understand ecological change through the last several million years. Authentic inquiry into real, complex datasets engages students in the learning process, thus deepening their understanding of species dynamics in changing environments, and simultaneously increasing their retention of key concepts (e.g., Laursen et al., 2010; Lopatto, 2010; Freeman et al., 2014). In recent years, new systems have been developed for finding, visualizing, exploring, and obtaining Neotoma data (Williams et al., 2018). Several recent educational and outreach activities have resulted in the production of a number of new resources for a wide range of audiences, including high school and college students, graduate students, and the general public (https://serc.carleton.edu/neotoma/index.html). Phone-based apps have been developed for travelers to understand the geological and ecological history of the world around them (Flyover Country®: http://flyovercountry.io).

This chapter reviews these resources and introduces Neotoma as a new platform for supporting authentic teaching and outreach, able to support a wide range of users and levels of expertise. We begin with an overview of the Neotoma database and its software ecosystem, then move to an introductory exploration of Neotoma's data holdings, using the map-based Neotoma Explorer and a variant of exercises developed with the Science Education Resource Center (SERC) at Carleton College (https://serc.carleton.edu/index.html). We then summarize teaching exercises for upper-level undergraduate and graduate students using the software package R (Goring et al., 2015) that have been developed through a series of workshops. Next, we show how the Flyover Country® mobile app can be used to discover and learn about Earth's history, drawing on and integrating resources at Neotoma and elsewhere. We conclude this chapter by examining the role of community-curated data resources as bridges between the research community and the public, with regard to educational outreach in particular.

2 The Neotoma Paleoecology Database

Neotoma comprises both a data repository (Neotoma DB) and an ecosystem of interlinked software for accessing and visualizing Neotoma data. Neotoma DB stores more than 25,700 unique datasets from 12,500 distinct sites, each containing observations of fossil organisms and associated geochronological and paleoenvironmental information spanning the last several million years from continental sites, including fossil beds, lakes, mires, and other depositional environments. Neotoma DB is built around a flexible data model

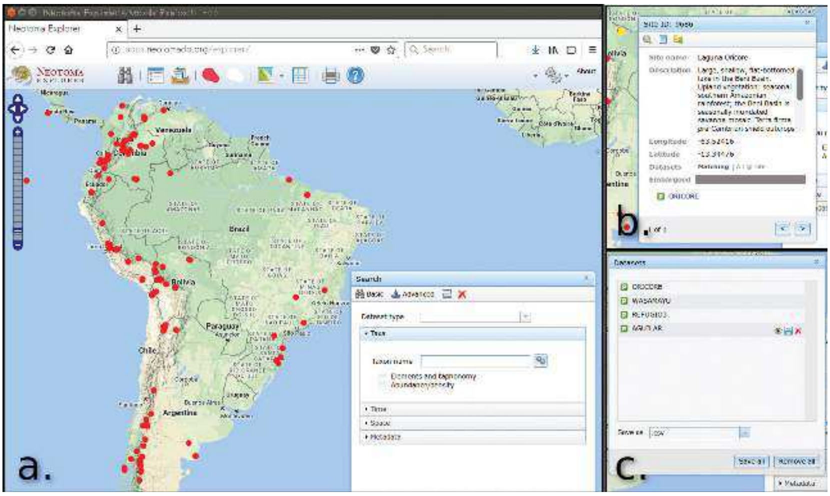

Figure 2. The Neotoma Explorer is a web-based data discovery tool that allows a map-based search for paleoecological sites using species names, site locations, site names, or other associated metadata (a). The tool provides the opportunity to examine individual sites (b) and to select a number of sites for download and later processing or study (c).

designed to describe paleoecological data records for many types of sites, depositional environments, taxonomic groups, and geochemical and sedimentological measurements (Grimm, 2008; Williams et al., 2018). The Neotoma DB includes information about researchers, locations, publications, time, and the raw paleoecological and paleoenvironmental records that underpin our understanding of Quaternary environments. The database includes site-level information for many of the datasets that includes a narrative description of the site, and can be linked to environmental data including water chemistry, regional climate, and other data based on spatial relationships.

Neotoma Explorer (https://apps.neotomadb.org/explorer/) is the primary data portal and discovery interface for finding and exploring paleoecological records within Neotoma (Fig. 2). Neotoma Explorer relies on a map-based user interface, in which users can search for data by taxonomic name, site name, spatial domain, time range, or many other dimensions. Discovered data are shown as sites on maps, which users can click to discover more information and download data. Neotoma Explorer is powered by an application program interface (API; http://api.neotomadb.org) that can be separately and directly accessed through any standard browser or programmatically. The use of an API provides a mechanism to build new tools on top of Neotoma's data resources. The API also supports the neotoma

R package (Goring et al., 2015) and the inclusion of Neotoma data within the Flyover Country® mobile app, and search tools that can jointly search Neotoma and other paleobiological resources (http://earthlifeconsortium.org/).

3 Neotoma Explorer: Data Discovery and Exploration

The following introductory exercise is based on Neotoma Explorer and is designed to help individuals understand how paleoecologists interpret and process proxy data, ranging from a single site to continental scales and from the recent past to deep time records. The exercise, based on "Exploring the Neotoma Paleoecology Database" (https://serc.carleton.edu/neotoma/activities/121251.html), is directed toward college undergraduates and explores changes in mammal and vegetation distributions since the Last Glacial Maximum. This exercise, along with others, was developed in 2015 at a workshop hosted by SERC. The workshop provided an opportunity for paleoecologists to work with science education researchers to develop high-quality teaching materials for a variety of educational levels. Additional educational modules are available on the SERC-Neotoma webpage (https://serc.carleton.edu/neotoma/activities.html) and are described further below.

"Exploring Neotoma" teaches users how to search for paleoecological data through a variety of starting points (by site name, dataset type, and taxon name), find publications, and create simple mapped visualizations that show (1) how species ranges changed as climates changed and ice sheets retreated and (2) changes in associations among plant and animal taxa. The exercise introduces students to research questions that paleoecologists might ask; for example, questions about species co-occurrence and shifting distributions under changing climate scenarios. "Exploring Neotoma" engages students through the authentic exploration of paleoecological datasets, and provides a foundation of skills they can use for further exploration and inquiry in subsequent exercises. The following sections, through to Research Questions, are cumulative and are expected to follow one another.

3.1 Searching for Data with Neotoma Explorer: A Student-Centered Walkthrough

The Neotoma Explorer provides the spatial overview and search capabilities for Neotoma. One of the simplest things you can do with the database is to search for a single research site. To do this, look for the *Metadata* search option under the *Advanced* tab of the search panel (Fig. 3). Marion Lake is an important paleoecological record from western North America, which provided one of the first quantitative reconstructions of Holocene climate from

Table 1 Data tabs presented in the data view of the Neotoma Explorer for selected datasets. Data tabs are labeled in the dataset view. Information presented in each tab is described here.

Data Tab	Table Description
Samples	A table showing individual pollen counts, depth information, and summary chronology
Diagram	A tool to view the change in the changes in taxon presence or abundance over depth or time
Site	Site-level information for the data
Chronology	The age-depth model used at that site and dataset
Publications	Publications related to the dataset

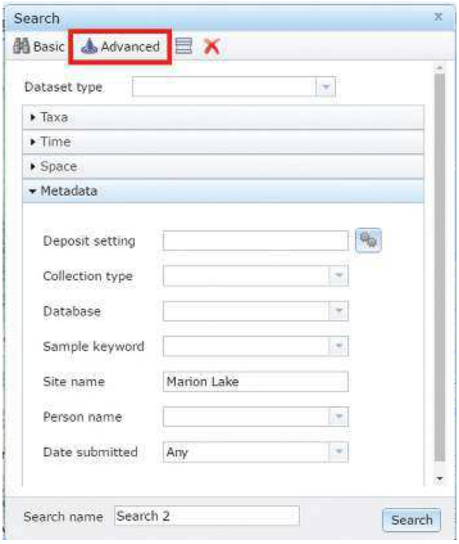

Figure 3. Searching for Marion Lake using the Neotoma Explorer's search tools (https://apps.neotomadb.org/explorer/).

western North America (Mathewes and Heusser, 1981). Search for Marion Lake under the *Site Name*. You may find more than one site. Which one is the pollen dataset? How do you know?

The northernmost site is the Marion Lake pollen sample site. When you click on the point, you should see some site information and a description, along with a green *P*, as well as a small clock (*clock*) icon. Both have the word *MARION* beside them. The icons represent pollen data and geochronological data respectively. Click on the icon that represents the pollen data (the green *P*) first and scroll through the tabs available within the window (Table 1). You'll see the following:

These window tabs provide you with a pretty good overview of the dataset, long-term changes at the site, and a list of the publications available to learn more about the sample record.

3.2 Searching by Dataset Type

Neotoma can also be used to look for a large number of datasets within a particular dataset type. Create a new search (make sure you clear the site name). Next to *Dataset Type*, click the down arrow to display a list of choices. What do you see? Select *water chemistry datasets*, perform the search, and then click on a site to view the data, as you did for Marion Lake. How do the variables in the water chemistry diagram differ from those in the pollen diagram? What similarities in the data can you see? Are rates of change different? What might be driving differences or similarities between these records?

3.3 Searching by Taxon Name and Time

One very quick, informative search in Neotoma Explorer is to look for a particular species or taxon, within a set time range. (You can also restrict searches spatially; Explorer's default is to look within the bounds set by the mapped view on your computer.) Let's look for fossil pollen sites with *Picea* (spruce) present between 15,000 and 12,000 years ago. This time period is of interest because it is right at the end of the Pleistocene, as ice sheets are retreating, humans are arriving and dispersing across the Americas, and plant species ranges are shifting north. Go to the *Advanced* tab, make sure all prior searches are cleared, then select the term "pollen" in the *Dataset* type field and "*Picea*" in the *Taxon Name* field. Then check *Abundance/density* and set abundance to ">20%" (to only show sites with a lot of *Picea* pollen at them). Last but not least, click on the *Time* bar and enter a time range of "15,000 – 12,000" ybp (years before present).

3.4 Mapping Ice Sheets

After the last search you should have a map with dots showing all the fossil pollen sites with at least 20 percent spruce pollen between 15,000 and 12,000 years ago. Feel free to explore them further. But where were the ice sheets? Click on the *white polygon* on the top bar to display glacial boundaries. This supports the addition of overlays to map glacier extents through time. Enter

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a date (say 12800 ybp), hit *enter*, and then *zoom* out the map so it shows most or all of North America. You should now see a white polygon, representing the continental ice sheets, overlain on the map of sites. You may also see blue polygons, which show the large lakes (proglacial lakes) that formed around the glacial margins, fed by meltwater. If you still have the spruce (*Picea*) sites displayed, you should see that spruce was growing just south of the ice sheets. If you move the time window for the spruce search to a more recent date, you should see that the site distribution has moved northwards, which represents migration in response to warming climate.

3.5 Research Questions

We all know that a whole bestiary of large animals roamed the Earth during the last age, many of which are now extinct. In North America, representative species of the Pleistocene megafauna include mastodons (*Mammut*), mammoths (*Mammuthus*), saber-toothed tigers (*Smilodon*), and many others. Where did these animals live, did their distributions change over time, and were they associated with particular habitats? We have already mapped the spruce trees and ice sheets, so now let's see where the big animals were. Let's use mastodons in this example. Do a taxon search (making sure that "Mammals" is entered under *Taxa Group*) for *Mammut* (mastodons) and select all *Mammut* taxa using the *Multi Taxon Search* tool, presented as a *Set of Gears* beside the *Taxon name* field (Fig. 4). Look at the site distribution. What happened? Describe the site distribution. Mastodons are known to have been browsers, eating leaves and woody plant tissue. What can we say about the kinds of habitats or environments that mastodons may have occupied?

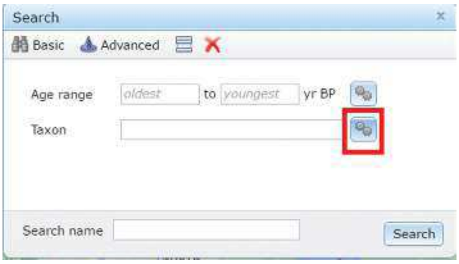

Figure 4. The search tools provide the opportunity to search for a single taxon or for multiple taxa simultaneously.

4 More Exploration with Explorer: Additional SERC Teaching Exercises

Additional exercises, focused on undergraduate, or senior high school students, are available on the SERC website (https://serc.carleton.edu/neotoma/activities.html). Other examples include: (1) Species distributions in response to environmental gradients in the Upper Midwest of the United States – an example using the Neotoma database is a unit for undergraduate students, focused on examining environmental gradients over short spatial scales and the ways these gradients can change over time; and (2) Climate Change and Mammal Dispersal, which is directed toward senior high school and early undergraduate students, helping them understand dispersal in small mammals through time in response to climate change.

Each of these exercises guides students through the process of accessing and exploring data from the Neotoma database to answer a scientific question or questions. This kind of pedagogical process can be referred to as scaffolding, or guided inquiry. Scaffolding provides a knowledge framework that allows students to discover their own answers while preventing the frustration they might experience if simply turned loose to answer the question (e.g., Hmelo-Silver et al., 2007).

5 Educational Modules for Climate Change, Paleoecology, and Biogeography

An additional series of seven modules was developed by vertebrate paleontologists at Penn State University for participants to learn about climate change, paleoecology, and biogeography using the Neotoma Paleoecology Database. These modules have also been posted to the SERC website for distribution (https://serc.carleton.edu/neotoma/activities.html). These modules are primarily focused on mammals but can easily be adapted to other organisms such as beetles, plants, ostracodes, and other groups with rich data holdings in Neotoma. There are two basic module types: (1) Modules that provide background information about climate change, paleoecology, and biogeography (background modules 1–4), and (2) modules in which learners apply knowledge from the set of background modules to examine hypotheses using data taken from the Neotoma database (applied modules 5–7).

Background modules can be used to introduce learners to fundamental concepts in climate change, paleoecology, and biogeography. For instance, in the paleoecology background module (Module 2), relationships among climate

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variables (moisture and temperature) are discussed and illustrated (e.g., the correspondence between latitude and temperature and correlation between longitude and precipitation in the eastern United States). Relationships between the modern distributions of mammals within the Neotoma database are compared to climate variables. From this, students can see that eastern and western limits of many species' distributions in the eastern United States are limited by water availability, whereas northern and southern range limits are temperature-dependent. The paleoecology background module (Module 2) also briefly discusses underlying assumptions linking climate variables and species distributions and how additional factors can come into play. For instance, the distribution of the prairie dog (*Cynomys ludovicianus*) may be controlled by climate but also by soil properties such as depth, grain size, and moisture. A series of questions reinforce the learning objectives at the end of each module. The modules also provide links to other web pages and literature that provide further explanation of the principles.

In the applied modules, learners build on the knowledge they have gained from the background modules and apply it to analyses of Neotoma data. Each module begins with a statement about the process to be learned, and an example of similar analysis is provided. Learners develop a hypothesis (e.g., "If the climate warms, then a species distribution will expand westward"). The student can then test the hypothesis, by examining changes in the distribution of the species during different times of climate change using climate data from the Greenland Ice Core Project (GRIP: NGRIP members, 2004), covering the transition from full glacial to late glacial (~20,000 to 13,000 years ago) or late glacial to late Holocene (~13,000 years ago to present). Mammal species are assigned to students as they continue the exercise. If the hypothesis is false, then the student is asked to think about why it failed. The student is then taken to a file that explains what potentially happened with their analysis. Finally, on the basis of these analyses, the student is asked to draw lessons from the past, thinking about the potential response of these species to current climate trends.

For biogeographic analyses, students are asked to examine changes in species distributions through time. Various exercises then focus on when a species arrived in an area and how long it persists. With the addition of FAUNMAP II and MIOMAP data that are currently being uploaded, participants will be able not only to work with the glacial-to-interglacial warming of the late Quaternary, but also to go back through the Miocene (25 million years ago). The Miocene time period spans a long-term cooling in the Earth system, the onset of ice sheets in the Northern Hemisphere,