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INQUIRY &
INVESTIGATION

Modeling Tropical Diversity in the Undergraduate Classroom: Novel Curriculum to Engage Students in Authentic Scientific Practices

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Abstract

A feature of science is its production of evidence-based explanations. Scientific models can both provide causal explanations and be predictive of natural phenomena. Modeling-based inquiry (MBI) is a pedagogical strategy that promotes students' deep learning about phenomena via engagement in authentic scientific practices. Some university instructors have begun to facilitate MBI in their courses, notably those aimed at aspiring K–12 science educators who, per the Next Generation Science Standards, are encouraged to implement MBI. Yet exploration of curriculum and teaching with MBI in postsecondary environments is scarce. We detail a novel MBI curriculum implemented in a postsecondary ecology course that included students interested in future careers in education. The curriculum engages students in modeling why there is greater biological diversity in tropical than in temperate regions. This biological phenomenon continues to be of great interest to the scientific community. We briefly detail how the curriculum impacted students' understanding of participation in aspects of scientific practices and their comfort with facilitating MBI.

Key Words: *Biodiversity; diversity gradients; postsecondary education; scientific modeling.*

○ Introduction

A commonly acknowledged central feature of science is its production of evidence-based explanations of the natural world (Giere, 1999). Scientific models help organize data and aid in the process of identifying patterns, serving as the basis of causal explanations and predictions concerning natural phenomena. Indeed, models serve as powerful tools in the scientific community (Passmore et al., 2014), to the point of being recognized as a "core practice" essential for developing learners' science literacy (Schwarz et al., 2009).

Modeling-based inquiry (MBI) is a pedagogical strategy that encourages students to construct their own understanding of complex scientific phenomena. Students actively collaborate in analyzing data toward the development, revision, use, and presentation of models, evaluate the models, and may propose future investigations in light of them (Cartier et al., 2001). Various groups now promote wider commitment to the implementation of MBI across all educational levels. MBI is a premise of various science education standards in the United States, including the *Next Generation Science Standards* (NGSS Lead States, 2013), that present a clear call to engage K–12 students in MBI. The American Association for the Advancement of Science's *Vision and Change* report (Brewer & Smith, 2011) also promotes MBI in the postsecondary life sciences.

MBI is not new to the science education community. Various researchers and educators have confirmed the promise of MBI in fostering students' understanding of scientific knowledge and practices (e.g., Cartier et al., 2005; Stewart et al., 2005; Bouwma-Gearhart et al., 2009; Harlow, 2010). Notably, modeling helps students construct accurate causal models to account for complicated phenomena and thus deepen their understanding of phenomena about which they may hold multiple misconceptions (e.g., Passmore et al., 2009; Neilson et al., 2010). The literature on MBI describes its successful implementation, and resultant student learning, at the elementary (e.g., Magnussen & Palinscar, 2005), middle school (e.g., Schwarz & White, 2005), and high school levels (e.g., Campbell et al., 2011), with a limited postsecondary focus on students training to be K–12 science teachers (Windschitl et al., 2008a, b). Yet those training to be K–12 educators, like most undergraduate students, have often never experienced MBI themselves as K–12 or university science students (Windschitl & Thompson, 2006; Windschitl et al., 2008a, b; Harlow, 2010; Oh & Oh, 2011). Responding to these concerns, the curriculum detailed here provides postsecondary students, including those training to be K–12 educators, MBI opportunities within a university science course. With this curriculum, and facilitation that supports MBI, students engage in constructing an explanatory model for why there is greater diversity in the tropical than in the temperate regions of Earth.

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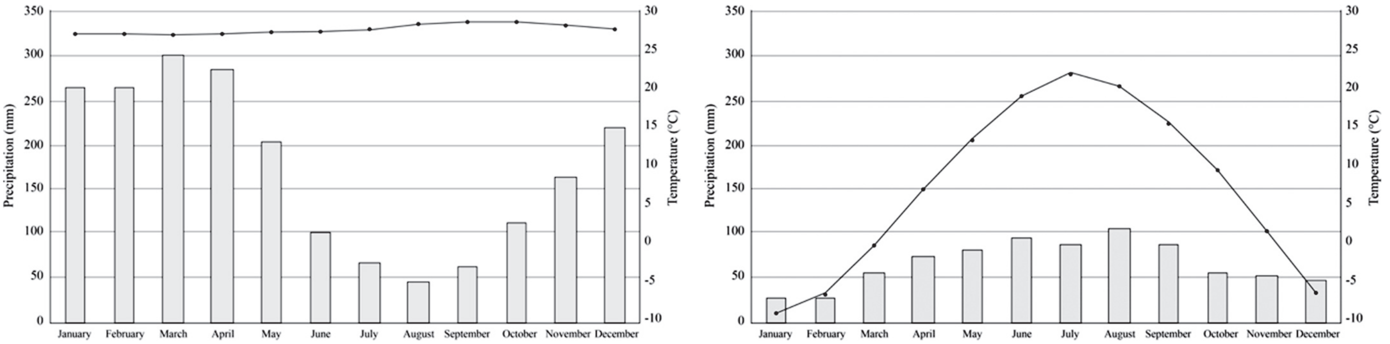

Figure 1. Climatograms of (**A**) tropical and (**B**) temperate regions of Earth, showing climate as measured by precipitation (bar graph) and temperature (line graph). Reproduced from Kricher (2011).

○ Course Overview

The evolutionary biology curriculum detailed below was implemented over a four-week summer university course and was designed to strengthen aspiring educators' ecology and evolution knowledge and their understanding of scientific inquiry. The course was cross-listed in the Department of Curriculum and Instruction and the Department of Biology and was cotaught by faculty from these departments at a large, public, land-grant research university in the midwestern United States. The university instructors had extensive experience with the science content and with supporting students as they construct explanations in an MBI environment. Some of the students were undergraduates majoring in the life sciences with the intention of becoming science educators, while others were earning their Master of Science degree and their initial secondary teacher certification. The students ranged in age from 18 to 35.

As is typical with MBI curriculum and instruction, instructors work as facilitators with distinct student learning outcomes in mind with respect to a specific scientific phenomenon. Students are engaged in modeling the phenomenon of greater species diversity in the tropics compared with temperate zones (i.e., the latitudinal diversity gradient). A general recurring lesson plan throughout this course consists of instructors providing students with relevant data and facilitating discussions that allow students to construct meaning based on the data. Students codevelop and revise models as a community of scientists. As with other constructivist pedagogies, MBI requires work that students may find frustrating to accomplish, given the demands of constructing their own understandings; although this work is an important component of constructivism and scientific model development, students are not often asked to perform such challenging work (Hewson et al., 1999; Cakir, 2008). Likewise, instructors are often not practiced in the type of facilitation that allows students to struggle with the challenge. Both students and instructors become more accustomed to such work as they progress through the multiple lessons in the curriculum that require them to work in groups on model development and assessment. Students build and assess models with respect to the criteria of empirical consistency (accounting for all data), conceptual consistency (how realistic the models are), and predictive power (Cartier et al., 2001). Students engage in argumentation concerning competing models that meet the criteria for a viable model. Once instructors determine that the class has collectively arrived at and understood competing models, students are presented with additional data that require them to account for new evidence and revise their models to be more empirically consistent. The data selected for this modeling activity follow the scientific community's historical development of competing models regarding evolutionary phenomena that are still being explored and debated.

○ Curriculum Details

This curriculum assumes a basic college-level understanding of evolution and genetics, namely natural selection. Students will also benefit from having some understanding of phylogenetic trees and experience with tree thinking. For an MBI activity to strengthen these understandings, see our previous article (Bouwma-Gearhart & Bouwma, 2015). We have included a Facilitator's Outline (Appendix A; to view supplements, please see the online version of the journal) to help instructors plan appropriate time for the curriculum/unit and each set of activities.

At the start, it is important for the instructor to frame the curriculum/unit for students, informing them that it will make use of the scientific practice of modeling. Students may not have had previous experience with modeling, so it is important to briefly describe modeling, especially toward helping students understand the iterative nature of this work, to manage potential student frustration regarding the lack of instantaneous and definitive answers. To help illustrate this, instructors should also indicate to students both the authenticity and the complexity of the problem under study; it is helpful to inform them that explaining the latitudinal diversity gradient has challenged scientists for decades and remains of interest in the scientific community.

The "Pre-model": Students Explain Differences in Tropical vs. Temperate Climate

Students first view the climatograms in Figure 1 and respond to the question "What regions on Earth might these climatograms represent?" They make observations about the seasonal changes, predict which global areas these graphs might depict, and solidify the requisite understanding that different climates on Earth are a compilation of long-term weather factors such as temperature and precipitation. On the basis of their previous experiences, postsecondary students label climatogram A as depicting "tropical" regions and climatogram B as indicative of "temperate" climates relatively easily.

Students essentially begin their modeling by proposing explanations of the phenomenon of the different climates (here defined by average precipitation and temperature over a year) in tropical and temperate regions. Although instructed to focus on temperature, they also attempt to explain precipitation differences. Students are required to create a drawing that illustrates their global climate model. With assistance from instructors using probing questions to activate students' thinking, after about 10 minutes of discussions in groups and using their prior understanding of seasons and climates, students are able to construct a physical representation of their mental models similar to that shown in Figure 2.

Most student groups correctly deduce that the equator receives more "direct" sunlight throughout the year, or more sun energy per unit area, which helps them explain the temperature patterns noted in Figure 1. In addition, a few students may be able to explain that heavier rainfall patterns in the tropics are due to rising warm air. If not, instructors support this understanding through discussion that Earth's climate is also based on the location of hot and cold air-mass regions and the atmospheric circulation created by warm equatorial air and trade winds. Warm air masses rise at the equator, and this rising air is replaced by trade winds north of the equator blowing in from the northeast, and by trade winds south of the equator blowing in from the southeast. The instructor can detail how the trade winds of the two hemispheres meet near the equator, while the warm equatorial air rises and cools, causing clouds and rain to develop, creating tropical rainfall conditions near the equator. After these discussions, alongside their prior basic understanding of evolutionary processes, students have climate-specific understandings needed to engage with pertinent data and begin to model the greater biodiversity in the tropics.

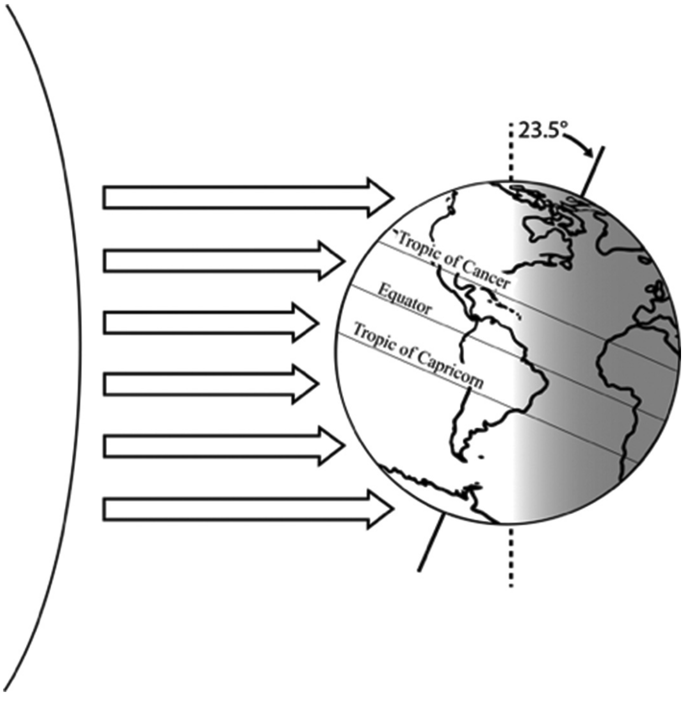

Figure 2. Students' initial model depicting the different climates in the tropical and temperate regions of Earth.

The Main Biological Phenomenon of Focus: Latitudinal Diversity Gradient

Next, students work with data from Fischer's classic paper on latitudinal variation in species richness. Fischer's (1960) paper is data-rich and provides specific data on a wide variety of organisms, including ants, nesting birds, snakes, and corals (for examples of data included in this article, see Figure 3). Data can be presented on handouts or slides.

Relying on their global climate model and other relevant prior knowledge (e.g., regarding natural selection), students make observations about the data and pose possible scientific explanations for the species diversity. After allowing groups ample time to complete this work (about 30–45 minutes), the class discusses possible explanations (models). Students offer a wealth of explanations, most of which (as they will soon come to realize) the scientific community has also offered historically. Students' explanations mainly match one of the following two (not mutually exclusive) hypotheses:

The "living is easy in the tropics" hypothesis:

- In the tropics, the climate is gentler compared with temperate climates.
- More organisms survive to and through reproductive age.
- More reproduction begets more organisms of the same species, some with additional random genetic advantages, potentially conferring additional advantages to their own offspring and begetting more diversity.
- More surviving organisms (within and between species) means more competition, which increases selection for niche specialization, begetting more diversity.
- A relatively stable climate makes being a generalist less favorable than being a specialist.

The "more diversity begets more diversity in the tropics" hypothesis (a "circular" or tautological argument):

- More favorable conditions for the lowest trophic levels directly influence the diversity of higher trophic levels (e.g., the abundance of plant species in the tropics – perhaps due to faster recycling of nutrients or the abundance of water – favors more specialization on the part of organisms that consume them, thereby lessening competition between consumers and allowing more consumers to survive; similar patterns occur with trophic levels up the chain).
- Because of the wider variety of ecosystems than in temperate regions, there are more niches available in an area of the same size. With more niches, there is greater capacity to support a higher diversity of organisms.
- More species exist that are able to crossbreed, which leads to formation of new species. More diversity begets more diversity.

The various models offered by students are summarized, and the instructor explains that they will be investigated further before the next activity begins.

Further Progress in Historical Modeling via Engagement with Primary Literature

Next, students read Fischer's (1960) seminal work and see how Fischer identified an ultimate cause of the greater species richness in the tropics as the intertwined processes of evolution of species

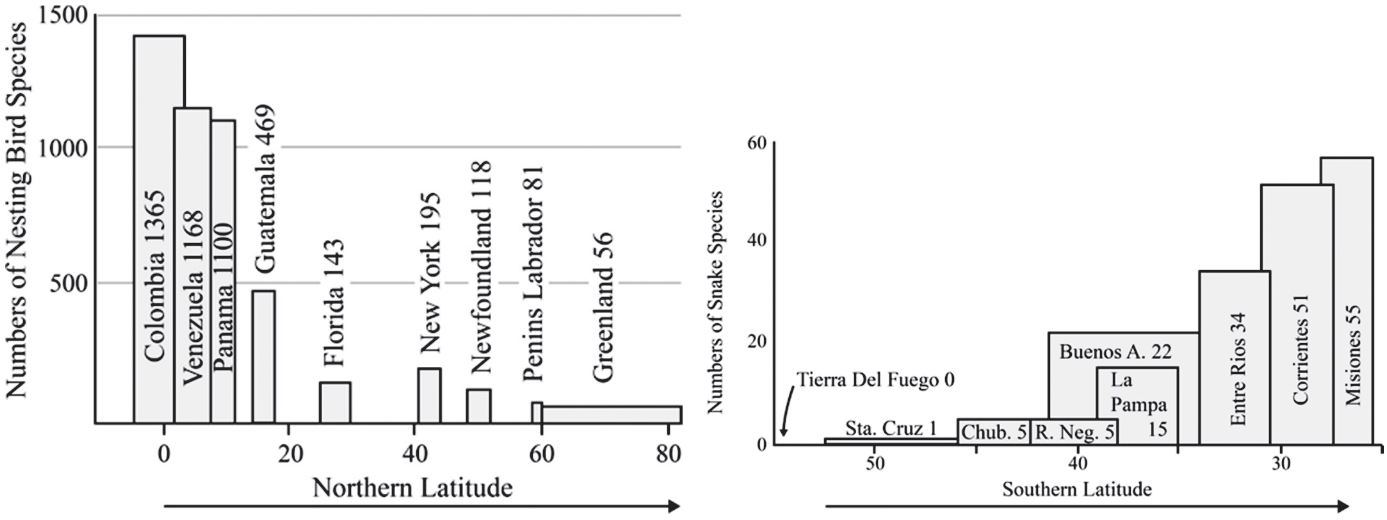

Figure 3. Example of data included in Fischer's classic article on the latitudinal diversity gradient in (**A**) birds and (**B**) snakes. Reproduced from Fischer (1960).

and evolution of habitats. They also come to understand how Fischer (1960) explored more specific causal mechanisms, such as stability of climates and reproductive rates of species, but ultimately concluded there were insufficient data at the time to provide a conclusive explanation/model for the greater diversity in the tropics compared with temperate regions.

Having become oriented to the phenomenon of interest and some preliminary models to explain it, students engage with additional primary literature to review models of explanation offered by researchers since 1992. Some of these explanatory models bear a striking resemblance to those that students, themselves, recently offered. This first primary resource is an article by Rohde (1992), who provided a then current review of models offering specific and proximate causal explanations for the latitudinal diversity gradient. Rohde provides critiques of some of these models, namely those deemed tautological (circular), lacking an empirical basis, or based on unreliable or conflicting evidence. While many postsecondary students are often neophytes in engaging with primary literature, Rohde's writing is understandable enough for students to come to understand critical flaws that would decrease the robustness and acceptability of these proposed scientific models. Rohde concludes by proposing a model of enhanced evolutionary speed in the tropics, driven by a number of factors (e.g., available energy in the system and shorter generation times), but also suggests that more research is needed.

To assist in keeping track while exploring the main phenomenon and building their models in light of the new information offered by Rohde (1992), students complete Worksheet 1 (Appendix B). Throughout this activity, five different models may emerge and be discussed. It is especially important that students identify two models (which they typically do). One of these, Rohde determines, is based on "circular explanations" and ultimately does not explain the origins of greater biodiversity in the tropics; instead the model relies on attributes of the resulting communities and, thus, results in a model that is not "conceptually consistent." The other model states that greater evolutionary speed in the tropics happens as a result of shorter generation times, higher mutation rates, and acceleration of selection. Students ascertain that the "evolutionary speed" hypothesis is viable in its conceptual consistency and predictive power, but they also conclude that more research is needed to strengthen its empirical basis. Overall, students' engagement with the Rohde article helps them gain insight into the development of scientific models over time. In addition, the summary of relevant data and scientific analysis regarding the phenomenon up to a historical point further helps students create a conceptual base from which they can participate in analysis of additional pertinent data as they are provided.

The next paper introduced is by Wright et al. (2006), who investigated the rate of microevolution (evolutionary speed) in temperate versus tropical plant species. Unlike the Rohde article, the Wright et al. article is challenging for many undergraduates to fully grasp. Thus, students use Worksheet 2, which summarizes the methodology, data, and implications (Appendix C). As a class, most likely guided by the instructor (given the complexity of the methodology and conclusions in this paper), students review the existing knowledge that Wright et al. (2006) worked from (i.e., that organisms with higher body temperatures have been shown to exhibit higher rates of nucleotide substitution [molecular evolution] than cooler-bodied organisms and that higher rates of metabolism may increase rates of oxygen-induced damage to DNA). The rate of DNA nucleotide substitution is likely a good estimate of the mutation rate, although other causes such as genetic drift and natural selection are also considered (Wright et al., 2006). Wright et al. (2006) studied plants (which do not engage in seasonal migration and, thus, truly exist as either tropical or temperate organisms), specifically 45 phylogenetically diverse taxon pairings (spanning 18 genera) of congeneric pairs of woody plants. Each taxon of each pairing occurred in either the tropical rainforests or in the temperate zone.

As in the preceding activity, students are asked to work in groups and record conclusions/patterns noted, in comparison with the null hypothesis, to develop a model to explain the data at hand and to determine what they still would like to know to strengthen their model. In response to questions, students are typically able to identify at least one possible explanation for the greater biodiversity in the topics: that of a higher rate of nucleotide substitution (an estimate of the mutation rate) in the tropics than at higher latitudes.

Students are also able to point out that their current tropical diversity model is not robust enough, given its reliance on data solely concerning plants (ectotherms). When asked to verbally propose an experiment that might help remedy this issue, students typically offer one to test whether similar patterns are seen among endotherms (such as mammals).

As is often the case in an MBI setting, instructors help guide student thinking through questioning, discussion, and presenting new evidence to further develop the explanatory model. Thus, after working with Wright et al.'s (2006) paper, students examine a study by Gillman et al. (2009), who researched this phenomenon using mammals (endotherms). This experiment, too, needs some elaboration, so students use Worksheet 3 (Appendix D), which explains how Gillman and colleagues assessed rates of microevolution in 10 orders and 29 families of mammals. Comparisons were made between 130 sister-species (closely related) pairs, in which one species occurred at a lower latitude or elevation than the other species of the pair. The students are prompted by Worksheet 3 to consider performing some basic calculations for ascertaining patterns in the data. Students can calculate means of branch length ratios (distance from common ancestors for the tropical species vs. distance from the common ancestors for the temperate species), both for organisms overall and for organism subcategories (within specific orders/families [e.g., Rodentia] or by latitude and by elevation). They will find that the mean value of the ratios is >1, meaning that tropical species or lower-elevation species have higher rates of molecular evolution than their temperate or higher-elevation counterparts. Indeed, Gillman et al. (2009) concluded that tropical mammals have higher rates of molecular evolution than their temperate relatives. On the basis of these data, students are again asked to revise their models of greater biodiversity in the tropics and offer thoughts regarding needs for next steps toward a more viable class model. Discussion is focused on the fact that since mammals are endotherms, their metabolic rates do not vary with temperature. Gillman et al.'s (2009) finding that mammals also have higher rates of molecular evolution in the tropics suggests a model based on the Red Queen hypothesis, stating that the speed of mammalian evolution is influenced by the evolutionary speed of ectotherms.

After engagement with Gillman et al.'s (2009) data and paper, as after the Wright et al. (2006) activity, we have found students able to conclude (as did Gillman and colleagues in 2009) that they need more data (across additional organisms) to build more viable models – specifically data concerning other tropical and temperate taxa. They are given three additional papers to read and summarize in groups of three (each student reading one article and reporting to the other two). Each new paper reports on research that seems to strengthen the empirical consistency of their developing model, that greater biodiversity in the tropic zones is ultimately caused by higher rates of mutations per greater solar energy per area. The papers report findings similar to those of Gillman et al. (2009) but in plants (Gillman et al., 2010), fishes (Wright et al., 2011), and amphibians (Wright et al., 2010).

At this point, students are working from a class model that posits higher mutation rates as one cause of the greater biodiversity in the tropic zones. Inferred is the mechanism of higher tropical temperatures causing greater oxidative damage to DNA, on average, resulting in more mutations and greater genetic "raw material" for subsequent evolutionary processes (like natural selection and genetic drift) to act upon.

○ Discussion

Modeling-based inquiry is a constructivism-based pedagogy that allows learners to engage with authentic science practices. Yet many science educators have not experienced this way of learning and therefore are ill-prepared to teach via MBI (Windschitl, 2008b; Harlow, 2010). Here, we have described a new postsecondary MBI-based curriculum taught to undergraduate university students, including those aspiring to be K–12 educators. Via class assessments, exit interviews, and surveys, students demonstrated an increased felt efficacy of participating in and facilitating MBI and scientific modeling overall. They increased their understanding and their ability to help other learners engage in scientifically oriented questions based on evidence, develop and evaluate explanations based on evidence and specifically in light of new evidence, weigh the worth of competing or alternative explanations, and communicate and justify their evidence-based explanations (for a more in-depth detailing of these results, see Adumat et al., 2011).

Since the development and last implementation of this curriculum in 2012, various researchers have advanced data that add to the fascinating story of model building around the latitudinal diversity gradient. Recent studies suggest that there are other factors in addition to temperature (e.g., spatial relationships, historical factors, productivity) that have important effects on species richness (Brown, 2014; Jablonski et al., 2017). Educators who would like to have students trace these scientific developments may want to include student interaction with papers and data that now challenge the evolutionary speed model. For instance, new data on Squamata (lizards and snakes) do not demonstrate a relationship between species diversity and latitude or temperature, which challenges the evolutionary speed model for this large and important group of animals (Rolland et al., 2016).

This novel curriculum can be used effectively in the postsecondary setting by those who teach aspiring science educators about ecology and evolutionary phenomena. Given that K–12 teachers are required to implement inquiry standards, such as those indicated in the *Next Generation Science Standards*, they will require experiences that help them develop as educators who can support authentic science practices. Such practices include supporting students in constructing explanatory models to explain natural phenomena. As other education-related organizations and policies dictate, postsecondary faculty teaching science courses that include aspiring educators will need curricula and related pedagogy to help their postsecondary students explore phenomena in ways that parallel scientists' practices. Ultimately, this teaching environment requires postsecondary educators who understand not only the processes of inquiry (including modeling), but also how to facilitate such learning experiences in their classrooms.

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