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ARTICLE

Special Feature: Tropical Forest Responses to Repeated Large-Scale Experimental Hurricane Effects

Scientific communities of practice: K–12 outreach model around organism responses to repeated hurricane disturbances

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Abstract

Collaboration between ecologists and learning scientists can give rise to powerful models for scientific outreach within ecology. This paper presents a process by which learning scientists and ecologists codesigned a science curriculum that invites students to join an ecological community of practice. In the *Journey to El Yunque* middle school science curriculum, students engage with simulation models generated from data gathered by Luquillo Long Term Ecological Research (LUQ LTER) scientists. *Journey to El Yunque* students can explore post-hurricane population changes in yagrumo (*Cecropia schreberiana*), tabonuco (*Dacryodes excelsa*), coquís (*Eleutherodactylus coqui*), snails (*Caracolus caracola*), anoles (*Anolis stratulus* and *A. gundlachi*), veiled stinkhorn mushrooms (*Dictyophora indusiata*), and caterpillars (*Historis odius*). Ecology-based revisions to *Journey to El Yunque* have included adding models of the effects of repeated hurricanes on limiting factors, based in part on findings from a canopy trimming experiment. Revisions based on classroom testing include simplifying student-facing model controls to allow students to focus on the essential model components. The ongoing collaboration that keeps the *Journey to El Yunque* curriculum on the cutting edge of ecological and educational advances has been sustained for over two decades. We attribute the longevity of this work to (1) the long-term nature of LUQ LTER, (2) a sustained interdisciplinary collaboration, and (3) our long-term relationships with schools.

KEYWORDS
educational outreach, hurricane disturbance, long-term ecological research, Luquillo experimental forest, population models, scientific modeling, Special Feature: Tropical Forest Responses to Repeated Large-Scale Experimental Hurricane Effects, tropical forest, tropical forest communities of practice

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INTRODUCTION

As climate change accelerates the frequency and intensity of hurricanes and other disturbance events (Emanuel, 2021; Knutson et al., 2010), scientific outreach from ecologists to the general public becomes ever more essential. Much of this outreach typically centers around the direct dissemination of scientific findings, such as through museum exhibits, classroom visits, or scientific articles. Other forms of outreach entail engaging students in citizen science in which students use standardized protocols for collecting and submitting data. However, students often struggle with how to analyze the data (Penuel et al., 2006). In this paper, we present a model for scientific outreach that engages students in the practices of science. Rather than viewing science outreach purely through the lens of knowledge transmission or through the lens of specific practices, we instead view science outreach through the lens of using education as a bridge to bring K–12 students into ecologists' communities of practice (Lave & Wenger, 1991; Sfard, 1998). This outreach model is exemplified in the codesign process for the inquiry-based scientific curriculum *Journey to El Yunque* (McGee et al., 2023), which brings secondary students into the Luquillo Long-Term Ecological Research (LUQ LTER) community of practice.

All communities of practice share four common characteristics (Lave & Wenger, 1991). First, community members share a common domain of interest. In the case of LUQ LTER, this domain of interest is disturbance ecology in the context of the Luquillo Experimental Forest, commonly known as El Yunque. Second, community members regularly exchange information and participate in shared activities. At LUQ LTER, shared activities include gathering and analyzing longitudinal ecological data about different species following disturbance events. Third, community members have a joint repertoire of practices and problem-solving techniques. At LUQ LTER, shared practices include developing models of ecological data and engaging in scientific argumentation based on these models. Fourth, communities of practice include opportunities for newcomers to engage in "legitimate peripheral participation." Legitimate peripheral participation provides newcomers with routes to authentic participation in ways that are valued by community members. LUQ LTER offers myriad opportunities for legitimate peripheral participation, including opportunities for secondary students to engage in scientific practices of modeling and argumentation through the *Journey to El Yunque* curriculum.

Lave and Wenger (1991) argue that all learning is a form of legitimate peripheral participation in the context of communities of practice. The question becomes to which communities are students positioned as legitimate peripheral participants. In contrast to their analysis of apprenticeship practices across multiple contexts, Lave and Wenger (1991) highlight the inherent conflict that exists in school settings that are structured around teaching practices. The content of school subjects emerges from specific communities of practice. However, students are often positioned as legitimate peripheral participants with reference to the community of educated adults and not with reference to the communities where the content of the school subjects emerged.

Lave and Wenger's (1991) legitimate peripheral participation framework provides a lens through which we can examine and structure opportunities for students to be positioned as legitimate peripheral participants with respect to the scientific community. There are three key characteristics of Lave and Wenger's model of legitimate peripheral participation that are most relevant for this discussion. (1) It is not necessary for students to work directly with scientists or to contribute to the work of the community in order to be positioned as legitimate peripheral participants of the scientific community. It depends largely on the extent to which they are engaged in the scientific practices that are authentic to specific scientific communities. (2) At the outset of learning, students are not able to successfully engage in all aspects of scientific practice. Within the context of legitimate peripheral participation, students will experience the entire process of an investigation, but focus on completing specific steps independently. For example, in *Journey to El Yunque*, students are presented with a specific research question about El Yunque, provided data about organism response to disturbance, and interact with models of the influence of limiting factors on population dynamics. Students use the models to set up the post-hurricane conditions that best explain the species' responses to hurricane disturbance. (3) Lave and Wenger's concept of transparency characterizes the way in which the dialectic of using a tool and understanding the tool are central to the learning process. Lave and Wenger use the metaphor of a window to exemplify how transparency involves both invisibility and visibility. The window is invisible in that it provides visibility to what is outside of the room. The salient phenomenon is the subject matter that the window reveals. The wall on the other hand is visible and salient and does not reveal the subject matter of interest, namely what is outside the room. The tools of a community of practice move from a position of visibility and salience for legitimate peripheral participants to a position of invisibility, thus making salient the phenomena of interest to the community. In support of this community-of-practice-based model for scientific outreach, we describe a process by which ecologists and

learning scientists worked with teachers to codesign science curricula that support students to analyze real-world ecological data while developing scientific arguments about the ecosystem response to hurricane disturbance.

As hurricane frequency increases, there is an increasingly pressing need for modeling how multiple hurricanes, occurring in relatively close succession, influence the dynamics of forest ecosystems (Waide & Willig, 2012; Willig & Walker, 1999). This includes modeling the direct and indirect effects of multiple hurricane disturbances on different components of a forest ecosystem, and modeling whether a forest ecosystem will eventually return to its pre-disturbance equilibrium (resilience), or whether it will permanently change as a result of the disturbances (tipping points) (Johnstone et al., 2016). Such thinking is central to the current scientific practices of disturbance ecologists at the LUQ LTER program in Puerto Rico, who are studying the El Yunque rainforest. Studies by LUQ LTER scientists support a dynamic view of the resilience of forest ecosystems, in contrast to more static views that are often held by the general public (Zimmerman et al., 2021).

In 2017, Hurricane Maria made landfall in Puerto Rico as a category four storm. Maria's aftermath left the entire island without power, water services, or communications as well as fallen trees and stripped branches throughout the rainforest (Resnick & Barclay, 2017). In the days following the hurricane, many who saw the rainforest transformed into a landscape of fallen trees and stripped branches became concerned: there was much discussion in the media and by the general public expressing fears that the rainforest may have become damaged beyond the possibility of recovery (Ferré-Sadurní, 2017). These concerns were generally framed within a static view of the rainforest, reflecting conditions at one point in time. In contrast to this static view, disturbance ecologists in the LUQ LTER program view the rainforest as a dynamic system in a perpetual state of flux in response to disturbances, such as hurricanes, drought, or invasive species (Brokaw et al., 2012; Zimmerman et al., 2020, 2021). They find, in fact, that many species in the rainforest flourish in post-hurricane conditions, characterized by significant opening of the canopy and substantial thickening of the layer of detritus (plant debris) that covers the forest floor. These responses set the ecosystem on a trajectory to return to its pre-hurricane state—only to be interrupted by subsequent disturbances, such as drought or hurricanes.

In this paper, we describe the codesign and ongoing revision of a curriculum that offers students opportunities to engage with the LUQ LTER scientific community (https://elyunque.net/). In the *Journey to El Yunque* curriculum (McGee et al., 2006), students assume the role of ecologists exploring the long-term effect of hurricanes on the El Yunque ecosystem. Development of the initial version of *Journey to El Yunque* began in 1999 by McGee, Zimmerman, and Croft (retired). For the past two decades, the *Journey to El Yunque* curriculum has been developed and refined through long-term collaboration (McGee & Zimmerman, 2016). Middle school science teachers have also played a pivotal role in the curriculum design process, helping to optimize the curriculum's usability in science classrooms. The collaborators met both virtually and physically, with groups of teachers and learning scientists traveling to Puerto Rico, to engage in codesign sessions with LUQ LTER ecologists.

The lynchpin in legitimate peripheral participation is optimizing the transparency of the scientific tools that students use to investigate the phenomenon of interest (Lave & Wenger, 1991). On the one hand, the tool needs to be invisible so that students can see the phenomenon through the tool. On the other hand, the tool needs to have visibility so that students have the opportunity to learn the role that the tool plays within the community of practice. In achieving this, we learned key lessons: (1) keep the design process open to revision; (2) maintain the consistency of the curriculum with emerging ecological knowledge; (3) and balance the accuracy and level of detail provided in the underlying model with the level of complexity of the student interface that optimizes student learning. In this way, one can hone the models to support usability by students, thereby ensuring that models are at an appropriate level of complexity for students. What becomes clear is while *Journey to El Yunque* is not a form of scientific outreach that can be easily obtained, the support provided by both the long-term nature of the scientific enterprise and long-term relationships with schools makes it possible. The results can arguably be considered the creation of a unique cross-disciplinary community of learning scientists, ecologists, and educators focused on making disturbance ecology accessible to students. In this paper, we describe initial versions of the simulation models that are the tools that form the core of *Journey to El Yunque*, as well as how new insights from ecology, including findings from the canopy trimming experiment (Shiels et al., 2015), and new insights from classroom enactments have shaped changes to the simulation models. The process of three-way codesign involving ecologists, learning scientists, and science teachers is of utmost pedagogical interest, as it may serve as a guide for other scientists and education researchers who are looking to engage in communities-of-practice-based outreach. The details of the simulation models described in this article may also provide useful context for interpreting other articles in this special issue.

As we reflect on our design and revision of the LUQ LTER simulation models, we address the following question: How can we design scientific models that encapsulate the complexity of emerging ecological research and provide a means for students to interact with the key components of the phenomena at the appropriate level of complexity?

METHODS

The main scientific question students are investigating in *Journey to El Yunque* is, "Organisms in El Yunque seem to be well adapted to hurricanes, but what will happen to the ecosystem if severe hurricanes strike the rainforest more frequently?" That question is derived from one of the main questions that drives the long-term research of the LUQ LTER ecologists. Organizationally, students investigate different aspects of that question across different modules focused on one or more species (see McGee & Zimmerman, 2016, for a detailed description). There is one producer module in which students directly explore how hurricane frequency influences the population dynamics of two of the most prevalent species in El Yunque: the yagrumo (*Cecropia schreberiana*) and tabonuco (*Dacroydes excelsa*). The readings provide information about the characteristics and living requirements of each species. Students then interact with a model of the effect of hurricane frequency on the population dynamics of the tree species. Students are expected to synthesize evidence from the model and information from the background readings to develop a scientific argument about how hurricane frequency affects the population dynamics of the two tree species.

The five consumer models focus on coquís, snails, anole, caterpillars, and mushrooms. The species were selected to represent different characteristic responses to hurricanes. Typically, students are divided into groups and each group completes a different consumer module. However, the goal of each consumer module is the same. Students are expected to use information from the background readings and evidence from models to develop a scientific argument about which changes to limiting factors best explain the population response to each species after the hurricane. Each consumer module follows a similar four-step investigation cycle. First, students read background information and take notes about the characteristics of the species and how different limiting factors affect a particular species' survival. Second, students draw upon the background information to draw a prediction about how the abundance of a species will change over time following a hurricane and compare their prediction to actual data collected after Hurricane Hugo (1989). Students then generate hypotheses about how changes to limiting factors may have influenced the pattern of response in the actual data. Third, students use a population model to test their hypotheses about how each limiting factor influences the long-term abundance of a species. Fourth, students draw upon their evidence of how each limiting factor affects the long-term abundance of the species to investigate which combination of limiting factor parameter settings in a disturbance model creates model output that most closely matches the population data after Hurricane Hugo. Students then use the information from the background readings and evidence from the models to develop a scientific argument about which changes to limiting factors best explain the patterns of response of their species. The website landing page for the producer module and each consumer module provides students with a visual orientation to the layout of the investigation cycle of the module (Figure 1).

The LUQ LTER simulation models show changes to different parts of the rainforest ecology following one hurricane disturbance, based on data collected by LUQ LTER. These models allow students to vary initial ecosystem conditions and then observe resulting changes in the population of an organism over time. The LUQ LTER simulations were developed using STELLA. These models were often based on general models, which were then adapted to the targeted species (Hannon & Ruth, 1999). We then developed a graphical interface that allows students to manipulate model parameters and view model output. STELLA provided a mechanism for us to develop the models. The underlying mathematical equations that STELLA generates were ported to an authoring environment to develop the graphical interface for students to manipulate select parameters. Students did not interact directly with the STELLA models. In the section that follows (and in Appendix S1), we share details regarding the development of the STELLA models in relation to the ecological dynamics they represent, as well as details regarding the informational readings that accompany each module.

MODEL DEVELOPMENT

Producers

With the Producers module, we wished to expose students to how key tree species responded to hurricanes. In selecting species, we focused on contrasting life history trade-offs, that is, rapid versus slow growth and differing abilities to survive hurricane disturbance (Willig & Presley, 2018; Zimmerman et al., 2014). We chose two tree species that are prominent in the El Yunque



FIGURE 1 (a) Website landing page for the two-step investigation cycle in that producer module. First, students read the background readings, and then students explore the Luquillo Long Term Ecological Research simulation model. (b) Example of website landing page for the four-step investigation cycle in each consumer module.

rainforest and represent alternative life histories. One was yagrumo (*C. schreberiana*), a fast-growing, shade-intolerant pioneer species that recruits heavily following hurricanes (Brokaw, 1998). The other is the slow-growing, shade-tolerant tabonuco (*Dacryodes excelsa*; Lugo & Wadsworth, 1990; Zimmerman et al., 2014). We employed a two-patch, two-species model (Hannon & Ruth, 1999; Levin & Paine, 1974; Figure 2) in which one species is a superior competitor (i.e., tabonuco) and the other is a superior colonizer (i.e., yagrumo), following a disturbance. In the model, yagrumo grows into open patches at a faster rate than tabonuco (patch colonization). Over time tabonuco usurps

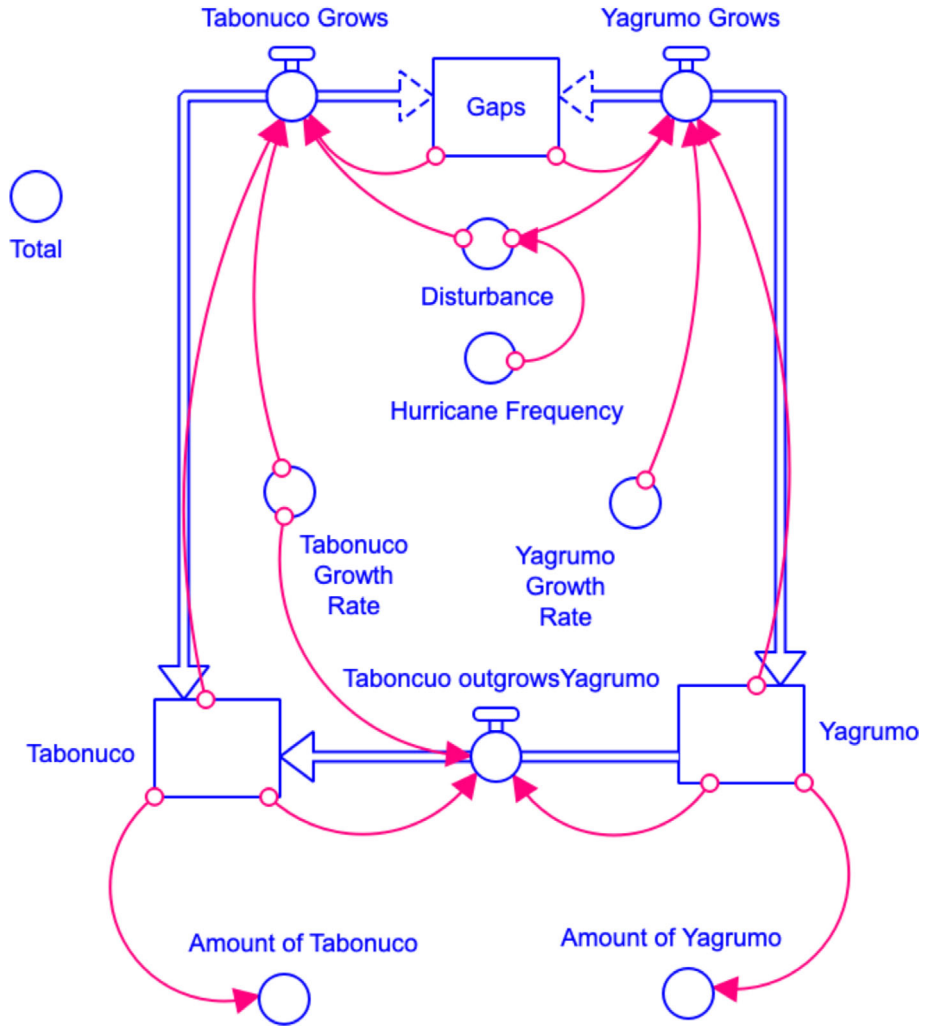


FIGURE 2 The model structure for Producers demonstrating the effect of hurricane frequency on species of contrasting life history strategies (yagrumo and tabonuco) as described in the text. Total patch space (Total) is divided into open patches created by hurricanes (Disturbance) and trees. Gap space is created by hurricanes of a given frequency (TLastHur) and intensity (HurInt). Remaining patch space is divided between tabonuco and yagrumo trees, who compete for gaps (yagrumo wins) or one another's space (tabounco wins). Biomass of each species is calculated from information provided by Scatena et al. (1993).

patch space from yagrumo (dominant interspecies competition). Thus, at intermediate disturbance frequencies, patch colonization and patch competition are balanced in a simple, dynamic system (Figure 3).

The key elements of tree characteristics and living requirements were revealed to students in the background readings authored by the fictional Ramon children. The format of the readings takes the form of a back-and-forth between the journal entries of the siblings each describing why their species of tree was the best. The Ramon children reveal in their journals the favored aspects of their trees, for example, tree relative growth rate and stature, revealing the trade-offs that underlie tree life histories. The daughter, Nicole, discusses the trade-off of the tabonuco as a superior competitor. While it grows slowly, it is stable and lives for hundreds of years. The trunk can withstand hurricanes, but many of the tabonuco limbs are knocked down by strong winds. The son, Alberto, describes the trade-off of the yagrumo as a superior colonizer. It can grow quickly to fill gaps. However, it is not strong wood, so it is susceptible to hurricanes. These ideas are represented in the model: yagrumo outcompetes tabonuco to fill gaps in the forest but tabonuco outcompetes yagrumo over time (see Appendix S1 for further details).

In exploring the model, students can set the number of years between hurricanes and the model creates graphs of tabonuco and yagrumo abundance over a 250-year period (Figure 3). Students will discover that when there is a low number of years between hurricanes, the yagrumo is most prevalent and the tabonuco will go locally extinct. When there is a high number of years

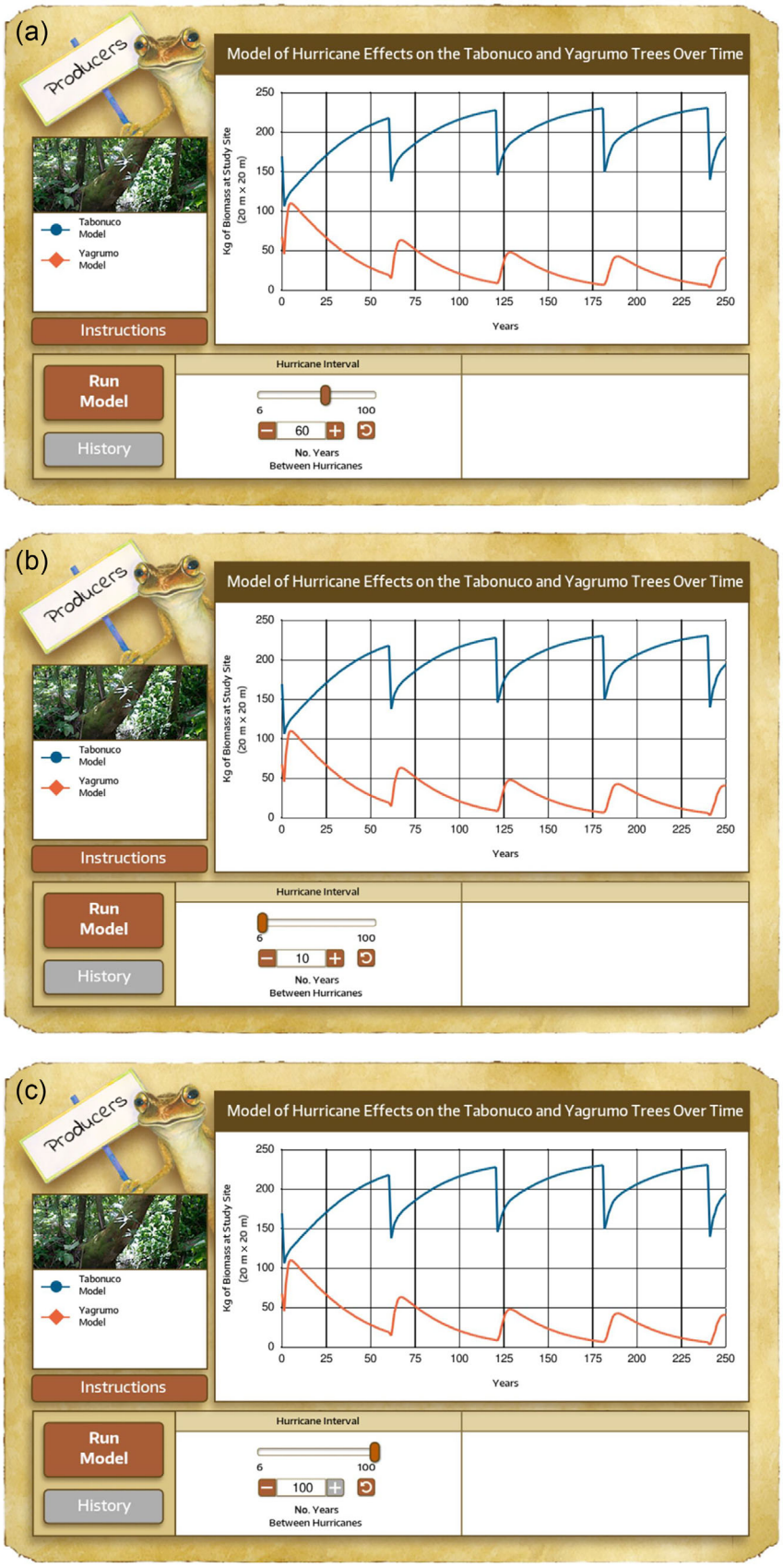


FIGURE 3 Student interface for simulations of changes in hurricane return interval on biomass of yagrumo and tabonuco trees in *Journey to El Yunque*. Results are for (a) return interval (TLastHurr) of 60 years; (b) return interval of 10 years; and (c) return interval of 100 years.

between hurricanes, the tabonuco is most prevalent and the yagrumo will go locally extinct. Students attempt to find the range of hurricane frequencies that maintains an equilibrium for both species to sustain in the forest. Students then use the information about the tree life histories to develop an explanation for why there is a limited range of hurricane frequencies that maintains an equilibrium.

Coquí

In the coquí (*Eleutherodactylus coquí*) module, we established a basic design for consumer modules. Students were provided background readings to learn about the life history of the target species. Next, students engage in prediction of the response of the consumer species after Hurricane Hugo and compare their prediction against either data collected by LUQ LTER scientists or estimated data based on scientists' prior research. The background reading and prediction activities were followed by modeling exercises. The coquí example was interesting because hurricanes have a positive effect on frog abundance, which is a counterintuitive result and therefore provides for intellectual curiosity in the students (Loewenstein, 1994). This positive response by coquís has a straightforward biological explanation in that the male frogs that care for the young require cover ("hidey-holes"; Stewart & Pough, 1983). The hurricanes create an abundance of hidey-holes in the debris. Other aspects of the biology of the frogs were well known, such as the responses to drought, as well as the identity of their prey and predators (Stewart & Woolbright, 1996). Finally, Woolbright (1996) had published a long-term dataset for the students to model (Woolbright, 2019).

The coquí module provided a useful case for developing a process for determining an appropriate level of complexity for students. An important element for supporting student learning involves the creation of a level of challenge that is just beyond students' current capabilities without creating so much complexity that students are not able to make progress (Collins et al., 1988). In our initial models of coquí population dynamics, we sought to include as much of the system as was known from prior research. Through our interactions with teachers and students, we learned which aspects of the system should be hidden from the student to manage the level of complexity and enhance student understanding (Figure 4). For example, we eliminated juvenile dynamics because teachers thought it introduced too much complexity to comprehend. Eventually, we completely eliminated drought as a limiting factor in all of the consumer modules (see Appendix S1).

To ensure that the background readings described the relationships of the key limiting factors represented in the model, we developed an alignment table for each species prior to the development of the model or the readings (see Table 1 for coquí table). The table described how each limiting factor would be represented in the model and the key ideas that needed to be described in the readings. To manage the complexity of the investigations, we focused the consumer models on a small set of general limiting factors: environmental conditions, prey abundance, predator abundance, and direct hurricane mortality. We wanted to ensure that the models included each of these general limiting factors for students to investigate which subset of limiting factors best explained the response of each species to a hurricane.

The key elements of how limiting factors affect the coquí population were revealed to students in the Coquí Chronicle readings (Figure 5). The reading format was a newspaper written by and for coquís, discussing different aspects of coquí daily life. Our prior research has shown that the students are able to accurately summarize scientific information presented in the narrative format of the readings (McGee et al., 2015) and that the narrative can be motivating for students (McGee et al., 2014). Different newspaper articles reveal information about different limiting factors. The coquí real estate agent discusses the important role that debris on the forest floor plays in protecting coquí from predators. The obituary section reveals multiple predators of the coquí, including hawks, snakes, birds, owls, and spiders. The recipe section reveals different coquí food sources including ants, spiders, crickets, and moths. The weather page reveals that coquí are unlikely to die because of direct effects of hurricanes, and may indeed experience population growth after a hurricane, due to the increase in debris on the forest floor, which provides shelter from predators, among other benefits.

The task for students in each of the consumer modules is to use the information from the background readings and evidence from the models to develop a scientific argument about which changes to limiting factors best explain the patterns of response of their target species. While the background readings provide an explanation for how each limiting factor influences the population of coquí, not all of the limiting factors play a significant role in explaining the significant increase and subsequent decrease in the coquí population. For example, in the Population Model exercise, students will discover that a decrease in the predator population will lead to an increase in the coquí population. However, the predator populations do not significantly change after a hurricane, so it would not be a relevant factor in explaining the increase in the coquí population after the hurricane.

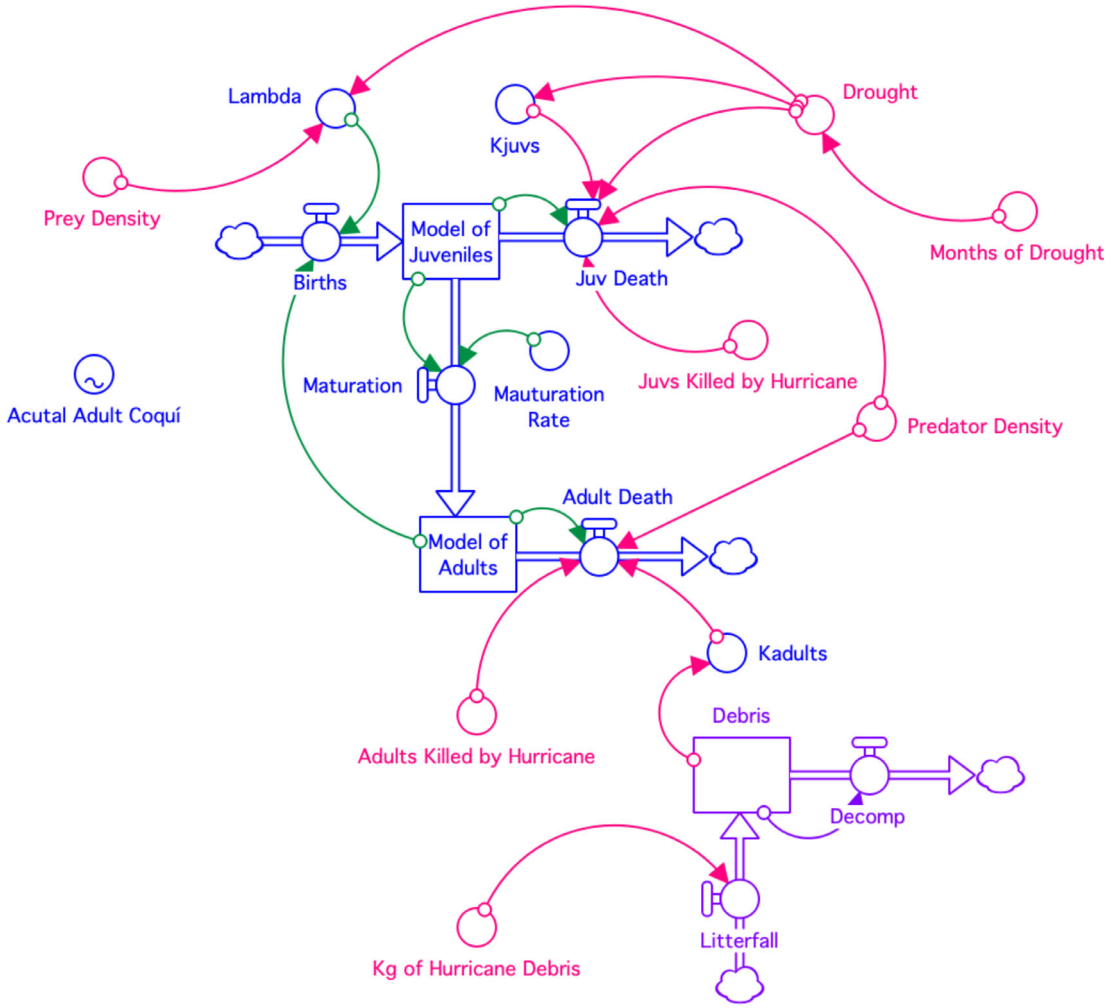


FIGURE 4 Model structure for the effect of limiting factors on the coquí abundance as described in the text. The coquí population is divided into Juveniles and Adults, although the student interface is limited to Adults (Figure 6). Limiting factors include prey abundance (prey density), predator abundance (predator density), direct hurricane mortality (adults killed by hurricane), and debris. The debris submodule includes litterfall and litter decomposition parameterized for the site (Odum, 1970; Scatena et al., 1996) and inputs from hurricanes (in kilograms of hurricane debris; Lodge et al., 1991). Note that drought effects on juveniles were originally incorporated into the modeling but were later ignored in the interface for simplicity.

To generate the best explanation—increases in debris and insects after a hurricane are the most significant factors influencing the coquí response to a hurricane—students will need to synthesize evidence from the background readings and simulation models (Figure 6).

Other consumers

As mentioned above, the species selected for *Journey to El Yunque* represent different patterns of response to a hurricane as well as how different combinations of limiting factors best explain the response to a hurricane. Below we describe the development of the remaining consumer species models and highlight the unique modeling challenges that each species presented.

Snails and walking sticks

Many of the other consumer models were derived from the coquí model. Snails (*Caracolus caracola*) were modeled like the coquí (Willig, 2020), with similar drought effects (hidden in the final version), but with the main (positive) effect due to the presence of a preferred habitat (the plant *Heliconia caribaea*; see Appendix S1). The snails prefer heliconias as a place to feed on algae and fungi growing on surfaces of the plant. Students were allowed originally to vary how the abundance of the preferred plant changed after the hurricane by drawing a graph. We later scaffolded the interface so that students were given a choice of graphs showing how abundance of the preferred plant changed over time as a model input to predict the response of

TABLE 1 Alignment between treatment of limiting factors in background readings and simulation model.

Species: coquí		
Requirement	**Facts to present**	**Model treatment**
Food	Food—*Juveniles*: ants; *Adults*: crickets, cockroaches.	The model allows adjustment of prey density by the students, but it does not distinguish between prey of juveniles and adults.
Habitat	"Hidey-holes," which include under logs and in large leaves like yagrumo.	The model has a submodel that controls the amount of debris on the forest floor. The debris directly determines the no. hidey-holes that adults can occupy (adult carrying capacity). Under non-hurricane conditions, litter inputs and decomposition are balanced so that debris is maintained. Students control the amount of debris that is caused by the hurricane—Hugo caused about 4800 kg to fall on the 400-m^2 coquí plot.
Predators/additional mortality factors	Predators—*Juveniles*: whip scorpions, tarantulas; adult coquís; *Adults*: snakes, red-legged thrush, Puerto Rican screech owls, lizard cuckoo. Additional factors—*Juveniles*: drought increases mortality; *Adults*: drought causes some mortality but, more importantly, it curtails reproduction.	The model does not distinguish the different predators of juveniles and adults, however, the rates are different for the two age classes, the proportion of juveniles eaten per predator being higher than adults. Students can adjust predator density. The model allows for drought effects on juvenile mortality and reproduction, but not adult mortality. Drought has two components, a regular drought cycle as well as a post-hurricane drought. The students can adjust the latter only. (Note: In subsequent versions, drought was removed as a parameter that students could manipulate.)
Hurricane effects	No purported direct mortality. If there is a drought after the hurricane, it will kill off juveniles and some adults.	Direct mortality is simulated as a pulse of juvenile and adult mortality. Students can control the size of this pulse.

the snails (Appendix S1: Figure S1). The choice of graphs represented the characteristic responses of a variety of species in El Yunque. When students selected the graph that best represented the change in abundance of the preferred plant, the model output comes closest to matching the real data (Appendix S1: Figure S2). The response shows the "bust vs. boom" pattern shown by the snails as the harsh post-hurricane conditions are replaced by favorable ones provided by the now abundant heliconia plants (Secrest et al., 1996).

We used the snail model to simulate the abundances of walking sticks (*Lamponius portoricensis*) post-hurricane, replacing the favored plants of the snails—heliconias—with the favored plant of the walking sticks—piper plants (*Piper glabrescens*) (Appendix S1) (Willig, 2020). In real life, however, the long-term data showed that the abundance of walking sticks did not quickly rebound as in the snails (Willig et al., 2011). Rather, the numbers remained low in the five years following the storm and showed no evidence of responding to the increase in the amount of favorable habitat. The result was, in the modeling exercise, students could not match model output to the long-term data and became frustrated (rather than learn the lesson that not getting the "right answer" can be meaningful). As explained by Willig et al. (2011), the reasons for the walking stick response were more complex, involving interactive effects of the fate of resting eggs (ephippia), drought, and the scale of the hurricane disturbance. Rather than address these complexities, we abandoned the walking stick model as we continued to revise *Journey to El Yunque*.

Anoles

Anoles were modeled as a two-species competition model (see Appendix S1) (Reagan, 2018). Anole species coexist in forests by partitioning the forest canopy spatially, both vertically and horizontally (Mahler et al., 2013). For example, *Anolis stratulus* normally occupies the forest canopy while *A. gundlachi* occupies the understory, foraging from tree trunks. By removing the canopy, hurricanes force the two species, erstwhile in separate habitats, to

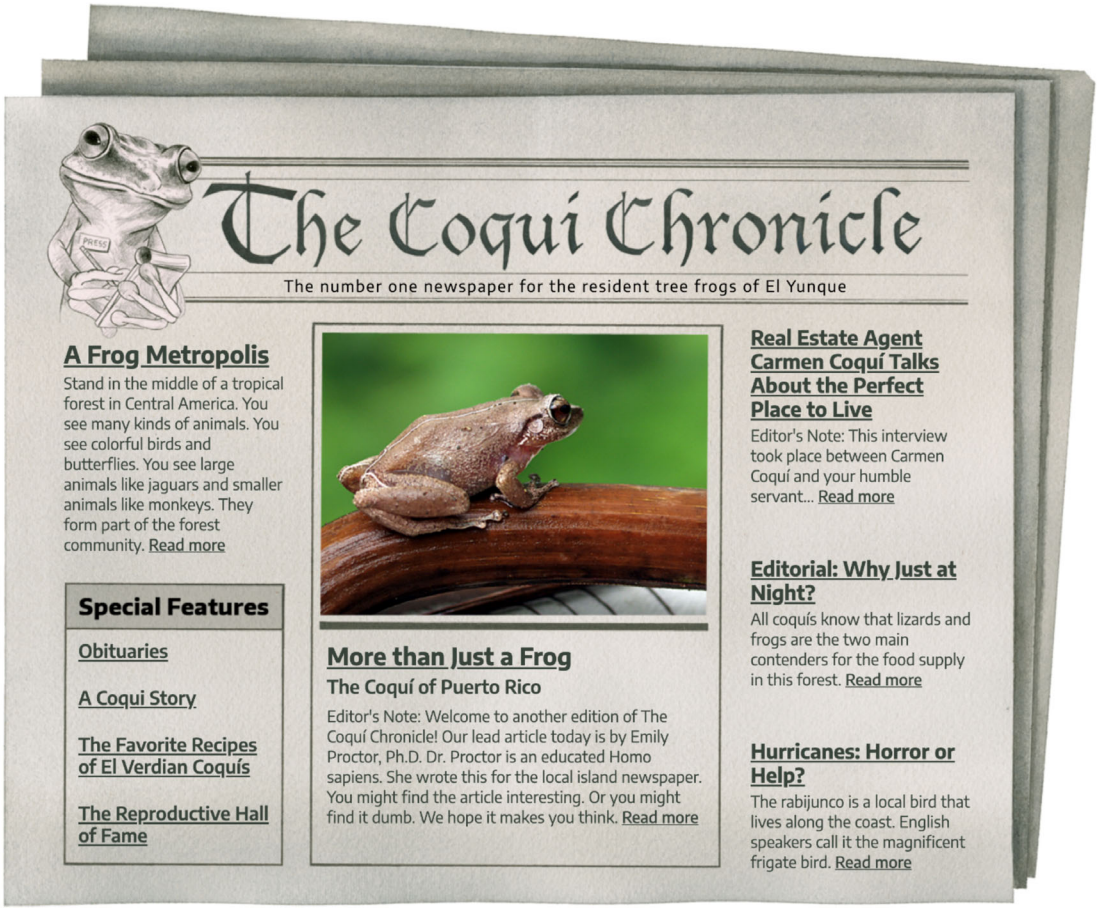


FIGURE 5 Website landing page for readings about coquí.

transiently share space and food resources (Reagan, 1991). Both species now forage in close proximity. The competition with *A. stratulus* reduces the abundance of *A. gundlachi* (Appendix S1: Figure S4). As the canopy recovers, *A. gundlachi* abundance increases. Like the heliconia in the snail model, students chose the pattern of canopy response from a series of graphs representing characteristic responses to a hurricane.

Caterpillars

Caterpillar population dynamics were modeled as an "outbreak" model. Torres (1992) observed that there were outbreaks of caterpillars on many plant species after Hurricane Hugo. Many of the caterpillars raised in the laboratory (to confirm species identification from adult characteristics) were parasitized by flies or wasps. We thought students would find this dynamic behavior interesting and therefore chose a caterpillar species, *Historis odius*, specialized to feed on yagrumo (connected to a producer species), as one of the consumer options (Appendix S1).

Mushrooms

We struggled to create a stand-alone model for the dynamics of mushroom. We found insight in a new framework, below, to resolve issues of instability in our original modeling attempt.

Forging a new approach to better support students

Studies of implementations (McGee et al., 2015, 2018) found that students had difficulty justifying the reasonableness of the parameters they set to match the model to the empirical data. They lacked experience with how the hurricanes affected the limiting factors of each species. For example, it was challenging for students studying the coquí to eliminate predators as an explanatory factor, because in the disturbance model, decreasing predators could be used to get the modeled data close to the actual data. Even though the readings indicated that the number of predators was not affected by the hurricanes, students were not



FIGURE 6 Student interface for simulations of effect of changes in limiting factors on the abundance of coquí in *Journey to El Yunque*. Results are for (a) default settings for limiting factors, and (b) configuration of limiting factors that brings the model output (blue line) closest to actual data (green line).

making a connection to use this information as counterevidence.

Consequently, we decided to expand the available models to include models of how hurricanes affected the limiting factors. In addition, research after Hurricane Georges and Hurricane Maria along with results from the canopy trimming experiment provided estimates for the way repeated hurricanes of differing Saffir–Simpson

winds scale ratings (aka category one through five strength) affect limiting factors in El Yunque. These estimates were used to develop LUQ LTER models of hurricane effects on limiting factors.

We also wanted to resolve the different approaches of the models that favored the particulars of species biology and the different timescales for producers (250 years) versus consumers (5 years). In our initial modeling approach, separate models were developed for each module: producers, coquís, snails, anoles, caterpillars, and mushrooms. Each had their own STELLA model. We are now developing a new integrated model (Figure 7) that links the producer model directly to those of the consumers, focusing on a five-year post-hurricane period. For example, canopy openness draws on the variation in patch occupancy of the two producer species, as does litter and debris deposition. Through the website interface (Figure 8), students can adjust hurricane intensity (HurInt) to different levels (roughly equivalent to differing categories on the Saffir–Simpson scale). Students can also adjust the time interval between hurricanes (TLastHur), affording the opportunity to explore interactive effects between subsequent hurricanes and the visualization of what was learned from the canopy trimming experiment.

In the new integrated model, arthropod abundance, an important prey for coquí and anoles, draws from the amount of decomposing litter and now becomes a dynamic variable, not a static one as it was previously treated. Currently, the integrated model has incorporated mushrooms and arthropods into the producer model (Figure 7), and we are currently working on also incorporating snails, coquís, anoles, and caterpillars. When completed, the new integrated model will provide consistent inputs across each of the species' modules. Thus, the integrated model will provide new ways to explore dynamic interactions between limiting factors and timing of hurricane disturbances.

DISCUSSION

We asked how we could design scientific models that both (1) encapsulate the complexity of emerging ecological research and (2) provide a means for students to interact with key components of the phenomena at an appropriate level of complexity. The revisions to the simulation models, described above, show how scientific models can be refined over time to adapt to new findings from scientific research and increase the transparency of the phenomena for students and teachers.

A key strategy for maintaining the models' ability to encapsulate the complexity of emerging ecological research was to keep the design process open to revision (Cobb et al., 2003). The models were not created once and then frozen into permanent stasis. On the contrary, ecologists and learning scientists have remained in close communication over the two decades since the creation of the initial version of the *Journey to El Yunque* curriculum (McGee et al., 2006). As new understandings have emerged within ecology (e.g., the contrasting responses to Hurricanes Hugo and Georges; Zimmerman et al., 2021), the models have been updated accordingly. When the first version of the curriculum was created, LUQ LTER only had access to data from Hurricane Hugo. Given that Hurricane Hugo was followed by a drought, drought was highlighted in early versions of the simulation models. As subsequent intense hurricanes made landfall in El Yunque and were not always followed by drought, we removed drought from the student-facing controls; instead, we provided them with the ability to control the frequency and intensity of hurricanes. Thus, the simulations continued to reflect the complexities of emerging ecological research.

Current modifications to the simulations similarly serve the purpose of keeping the curriculum consistent with emerging ecological research. The canopy trimming experiment (Shiels et al., 2015) indicates that both canopy opening and debris deposition from intense hurricanes have significant effects on many different species. Our integrated model brings these new findings to the *Journey to El Yunque* curriculum, by supporting students to explore how changes to the canopy affect the abundance of each species under study. Going forward, we will continue to update the curriculum based on advances in ecology, so that the curriculum will remain up-to-date and relevant, rather than lapsing into the status of the historical artifact.

Concurrent with revisions that keep models up to date with emerging science, we also revise the models to support the transparency of the models for the students. It is a delicate balance between seeking to accurately predict ecological variation as embodied in data gathered by LUQ LTER and providing students with a level of complexity appropriate to their novice status (Collins et al., 1988). In several cases, described previously, feedback from teachers or observations of students prompted us to realize that there were places where model complexity became overwhelming for students. Thus, the tool was most salient and the phenomenon was less visible to students. When this occurred, we worked to decrease the level of complexity presented to students, without sacrificing scientific accuracy. We did so in several different ways. First, by simplifying student-facing model controls. In the case of the coquí model, we removed student's ability to (1) differentiate between

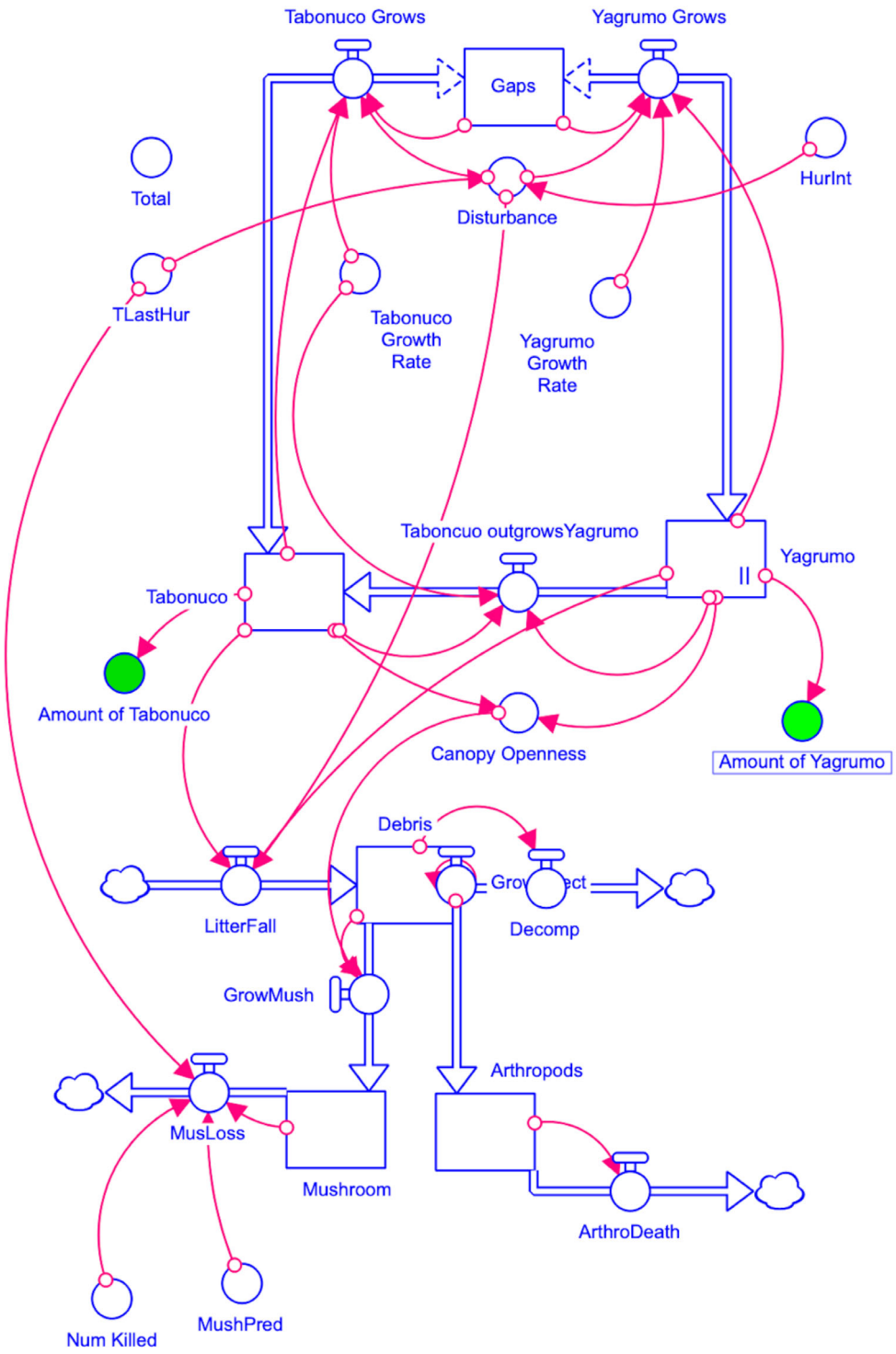


FIGURE 7 Integrated model structure that brings together the Producers model (Figure 2) and the debris/litter deposition/decomposition module from the coquí model (Figure 4) to model mushroom and arthropod abundances feeding on debris. Mushrooms are additionally limited by predator abundance (MushPred) and direct hurricane mortality (Num Killed).

adults and juveniles and (2) change drought parameters. Simplifying student-facing controls reduced cognitive overload (Sweller et al., 2011) on the part of students and allowed students to focus on the most essential components of models, thus increasing the visibility of the essential components of the phenomenon. Nevertheless, the data used to build the model remained unchanged, preserving scientific integrity. Similarly, in the snail and anole models, we simplified student controls so that students selected between multiple possible graphs

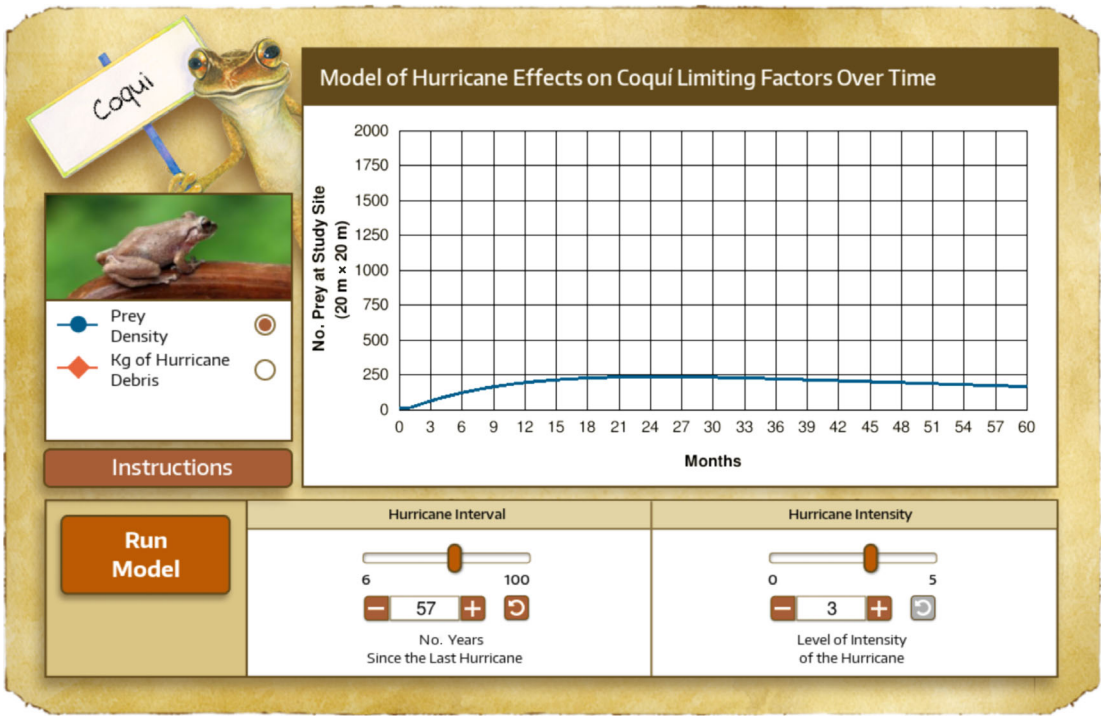


FIGURE 8 Student interface for simulation of effect of changes in hurricane frequency and intensity on the limiting factors of the coquí in Journey to Yunque. Results are for settings that simulate Hurricane Hugo.

representing variation in heliconia and canopy cover over time, rather than requiring students to draw in their own curve. By eliminating the requirement to draw a curve, it reduced the focus on the tool itself to allow the student to focus on the underlying phenomenon. Again, while this change simplified the student user experience, the underlying data remained the same.

In the case of data that currently confound ecologists, we removed the data entirely. Given that students experienced severe frustration when working with the walking stick model, we did not find value in keeping the module as part of the curriculum. As new understandings emerge (Willig et al., 2011), which suggest that the walking stick model may more accurately reflect the role of limiting factors on walking stick abundance, we may be able to reintegrate the walking stick model into the curriculum. Another strategy for supporting student understanding is building new models intentionally designed to provide additional support in areas students find challenging. Thus, in response to student challenges integrating information across models, we are developing an integrated model that will support students to make connections across all species modeled.

Representing complex and cutting-edge ecological research, while simultaneously ensuring that models are at an appropriate level for students, presents a complex design challenge. At first glance, the goals of scientific accuracy and classroom usability may seem to be at odds, competing in a zero-sum game. Nevertheless, reality is more nuanced. Several of the changes described above simultaneously increased scientific accuracy and transparency for the students. For example, putting drought "below the hood" in the coquí model both reflects the reality that hurricanes are not always followed by drought but, more importantly, decreases student cognitive overload (Sweller et al., 2011). Similarly, the new integrated models both incorporate new findings from the canopy trimming experiment (Shiels et al., 2015) and support students to more easily identify interconnections among abundance of different species. Thus, scientific accuracy and transparency are not automatically at odds.

In considering how to simultaneously support scientific accuracy and classroom usability, it is helpful to differentiate between the level of detail provided in the underlying model and the level of complexity of the student interface. In pursuit of the highest possible level of scientific accuracy, we have based the underlying model on the most recent and accurate available data. On the other hand, we have sometimes simplified the student interface based on feedback from classroom trials. We argue this simplification is appropriate, as it provides an accessible level of challenge to students who are apprenticing to new scientific practices (Nakamura & Csikszentmihalyi, 2014).

The long-term, complex, and collaborative nature of this work makes it a significant undertaking: it is not a

form of scientific outreach that can be easily or simply achieved. On the contrary, it requires ongoing communication between co-designers, cross-disciplinary coordination, and an eagerness to revise and improve. We have found the benefits to this form of scientific outreach to far outweigh the challenges. It has the transformative power of welcoming students, who might not otherwise have the opportunity to engage in real-world science, into legitimate peripheral participation as novice members of a community of scientists (Lave & Wenger, 1991). Specific benefits we have documented include supporting student motivation during science and increasing the scientific accuracy of students' work (McGee et al., 2018).

In closing, we consider what supported us to sustain our community-of-practice-based outreach model for nearly a quarter of a century. First and foremost, the long-term nature of LUQ LTER provides longevity to the outreach. The outreach is also bolstered by collaboration. From the beginning of our partnership, we have fully welcomed each other into our respective professional communities, to a degree beyond what might typically occur in cross-disciplinary interactions. In a more traditional model, the educational outreach division of a research project is often siloed off from the main project: for example, the educational outreach coordinator may not engage in frequent collaboration with the principal investigator. Similarly, the scientists who serve as expert consultants in curriculum design often play an auxiliary role, for example, reviewing for content accuracy rather than participating in design decisions. In contrast, ecologists and learning scientists in our collaboration have welcomed each other as equal and valued participants, bridging the disciplinary divide. For example, LUQ LTER scientists regularly present new findings at The Learning Partnership internal research meetings, just as The Learning Partnership regularly presents curriculum development updates at LUQ LTER internal meetings. Similarly, we jointly present at conferences in both education and ecology, and we publish in both ecology and education journals.

The success of our collaborative codesign has been made possible through long-term relationships with schools that use the *Journey to El Yunque* curriculum, as well as through long-term relationships with teachers who have been partners in the curriculum design process. Teacher design partners have traveled to Puerto Rico to engage in research with LUQ LTER ecologists (Bloch & Stock, 2014), attended ecology conferences, regularly participated in design sessions, tested revised versions of the curriculum in their classrooms, and offered ongoing feedback on how to make the curriculum more accessible to all students. School district officials support the integration of the *Journey to El Yunque* curriculum into science instruction, making it possible for students to become legitimate peripheral participants in the LUQ LTER community.

In other words, the longevity of our outreach model has been made possible by the mutual creation of a cross-disciplinary community encompassing learning scientists, ecologists, and science educators and allowing for the development and refinement of curricula supporting student legitimate peripheral participation in an authentic scientific community. For those interested in beginning similar work, we recommend embarking on cross-disciplinary conversations that stretch the boundaries of what is typically considered possible. Such conversations can provide the seeds for establishing new cross-disciplinary communities, from whom communities-of-practice-based outreach can diversify and prosper.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data are published and publicly available (Reagan, 2018; Willig, 2020; Woolbright, 2019).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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