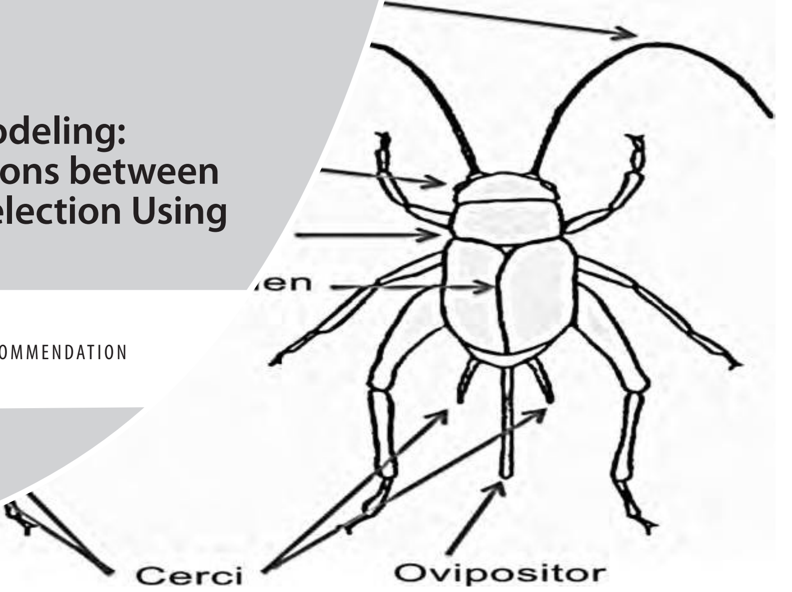
INQUIRY & INVESTIGATION

Inquiry through Modeling: Exploring the Tensions between Natural & Sexual Selection Using Crickets



NABT BioClub RECOMMENDATION

JANA BOUWMA-GEARHART,
ANDREW BOUWMA

Abstract

The Next Generation Science Standards *(NGSS Lead States, 2013) recommend that science courses engage communities of students in scientific practices that include building accurate conceptual models of phenomena central to the understanding of scientific disciplines. We offer a set of activities, implemented successfully at both the secondary and postsecondary levels, that involve students in guided inquiry toward creation and progressive revision of a robust model of selection that accounts for both natural and sexual selection and their complicated relationship to one another at the level of individuals and populations. Requiring students to progressively revise their models in light of data and previous understanding replicates scientific practice and allows for authentic assessment of students' growing content knowledge, understanding, and skills regarding scientific modeling and communication processes.*

Key Words: *Modeling-based inquiry; natural selection; sexual selection; Next Generation Science Standards.*

○ Background Research & Framework

The *Next Generation Science Standards* (NGSS Lead States, 2013) encourage student engagement in building accurate conceptual models of phenomena central to the understanding of scientific disciplines. Cartier et al. (2001, p. 2) describe a *scientific model* as "a set of ideas that describe a natural process. A 'scientific' model so conceived can be mentally run, given certain constraints, to explain or predict natural phenomena." Modeling-based inquiry encourages students to develop, critique, and revise these models, constructing a deep understanding of complex scientific phenomena through participation in genuine scientific practices. Central to this type of inquiry is that students, like scientists, actively collaborate in analyzing data toward the development, revision, use, and presentation of models. Modeling-based inquiry also encourages students to evaluate scientific models for explanatory and predictive powers and for conceptual consistency. In contrast to students' engagement in experiments that are confirmatory in nature, students engage in a more modern view of scientific practices that recognize experimentation as one part of larger model construction and revision (Nersessian, 2002; Duschl & Grandy, 2005; Windschitl et al., 2008; Schwarz et al., 2009).

Central to this type of inquiry is that students, like scientists, actively collaborate in analyzing data toward the development, revision, use, and presentation of models.

Various researchers and educators have confirmed the promise of modeling-based science curricula and instruction in fostering students' understanding of scientific knowledge and practices (Hestenes, 1987; Harrison & Treagust, 1998; White & Frederiksen, 1998; Cartier, 1999; Cartier et al., 2005; Schwarz & White, 2005; Stewart et al., 2005; Bouwma-Gearhart et al., 2009). Of notable promise is how modeling helps students build accurate causal models to account for complicated phenomena and, even, deep understanding of phenomena about which students may hold multiple misconceptions, such as natural selection and evolution (Bishop & Anderson, 1990; Jensen & Finley, 1995, 1996; Rudolph & Stewart, 1998). Various groups have promoted wider commitment to the implementation of modeling-based curriculum and instruction at the secondary and postsecondary levels, including the American Modeling Teachers Association (http://modelinginstruction.org/) and the University of Wisconsin's Modeling for Understanding in Science Education (MUSE; http://ncisla.wceruw.org/muse/).

Despite the research confirming the effectiveness of modeling-based science curriculum and instruction, most students have not experienced modeling-based inquiry (Windschitl et al., 2008), including those earning science baccalaureates. Rather, during high school and their undergraduate years, students "have experienced 'doing science' only through highly scripted laboratory activities and lectures where instructors rarely discuss in explicit terms how science is done"

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(Windschitl et al., 2008, p. 311). We advocate for students' opportunities to develop, critique, and apply models via curriculum developed by instructor–facilitators with specific learning outcomes in mind, outcomes for both the models to be constructed and the specific processes that students will engage in to discover them. Of utmost importance is that students engage in modeling-based inquiry to develop deep understanding of phenomena most central to understanding the discipline – in this case, the phenomena of evolution.

Toward accurate and deep understanding of evolution as the core model underlying biology, students must develop accurate submodels concerning natural and sexual selection, concepts about which students hold multiple, deep-seated misconceptions (Bishop & Anderson, 1990; Jensen & Finley, 1995, 1996; Demastes et al., 1996; Rudolph & Stewart, 1998). In addition, they must explore how these two submodels interrelate in their contribution to the larger model of evolution. This paper presents a novel and engaging set of activities that addresses these needs.

○ An Activity for Engaging Students in Modeling-based Inquiry

Our activity stems from both authors' involvement in a project as secondary and postsecondary educators in the creation, implementation, and study of modeling-based inquiry curriculum and instruction. The curriculum described below has been taught and assessed in two high school biological science classrooms as well as in two postsecondary courses for biology majors and preservice science educators.

For those attempting to meet the *Next Generation Science Standards*, our activity engages students in the following scientific practices discussed under Dimension 1: developing and using models; analyzing and interpreting data; constructing explanations; engaging in argument from evidence; and obtaining, evaluating, and communicating information.

Specifically, our activities meet standards for grade 12, when students should be able to discuss the limitations and precision of a model and suggest ways in which the model might be improved to better fit available evidence, offer causal explanations, identify possible weaknesses in scientific arguments, and discuss them using reasoning and evidence.

○ Introducing Scientific Models

We begin our instruction by briefly detailing scientific models and scientists' role in constructing and interacting with them. Yet our students' firm understanding of models and the processes associated with modeling-based inquiry is mostly developed through the curriculum as they develop, revise, and argue the worth of them. Most important to convey to students initially is that the strongest scientific models (according to Cartier et al., 2001)

- are empirically consistent (account for all data),
- are conceptually consistent (realistic), and
- have predictive power.

Toward this introduction, we provide guidance from the Project MUSE website at http://ncisla.wceruw.org/muse/models/index.html.

Students Construct a Model of Natural Selection

It is imperative that educators begin these activities by ensuring that students have a firm basic model of natural selection, namely that if a particular genetically based trait confers greater survival to reproductive age in a particular environment, relative to individuals that lack the trait, then this trait will become more common in subsequent generations. For students with limited understanding of natural selection, we recommend taking them through a 1-week curriculum on natural selection created by Project MUSE. For postsecondary, or other students with more experience in biology, an educator can review the main premises of the model of natural selection. The ultimate goal of this review of natural selection is to launch students into the next phases of model development, (1) adding to their already constructed model to account for sexual selection (traits favored that increase the ability to obtain a mate) and (2) using/revising their model to explore the relationship between natural and sexual selection.

Students Add to Their Model to Account for Sexual Selection

We use *Acheta domesticus*, the common house cricket, as a "model" organism for this modeling-based inquiry, since it can be easily and inexpensively obtained from any local pet store. A sexually selected phenomenon that can be easily studied in a lab, or witnessed on video, is house cricket aggression. Aggression can be stimulated in adult male house crickets by housing them in isolation in small plastic "deli" containers (~10 cm diameter) for 1 to 2 days. (Crickets must be provided with a water source while in captivity, also available at your local pet store.)

We begin by eliciting students' thoughts about how one would go about scientifically recording animal behavior. We then have students each construct an ethogram (descriptive record of all of an organism's behavior) of solitary crickets for about 10–15 minutes (Figure 1). What students see are mostly grooming, feeding (if they have a food source), and locomotor behaviors. We charge student groups to describe what they see and to make decisions regarding behavior terminology. We provide Figure 2 to help them speak with a common language about cricket morphology.

Next, we have students observe, for several minutes, 5 previously isolated male crickets together in a 10-gallon aquarium or other container, assigning each student to construct an ethogram of their assigned (and paint-pen-marked) cricket. This can also be observed as a video but is much more exciting for students to witness in person (visit http://youtu.be/TBLrH5OTCuI for a sample of what they could see). We now ask students, as a class, to describe what they see and to make decisions regarding behavior terminology; students offer terms like *antenna touching*, *head (mandible) locking*, *shaking*, *chirping*, *kicking*, *turning away*, and *avoidance* (for figures and descriptions of different agonistic behaviors in crickets, see Alexander, 1961). We then allow students to observe for another 10–15 minutes before comparing data and identifying patterns within groups, as well as determining a dominance hierarchy among the crickets. (In agonistic confrontations, we define "dominant" crickets as those that stand their ground, while subordinates eventually turn away.) We then charge students to "think like evolutionary biologists" and propose an explanatory model to account for the observed data. We ask them to explain, "Why would natural selection favor aggression in crickets?"

Cricket Ethogram

Descriptive name for behavior	Description of behavior and social context	Number of observations

Figure 1. Partial ethogram template (for five behaviors).

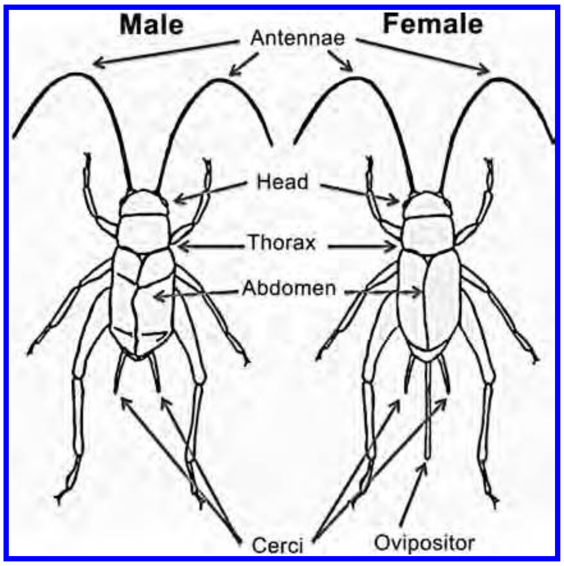


Figure 2. Cricket morphology.

A key thing happens for students at this point in the curriculum. Many students first hypothesize that the aggression witnessed is related to cricket survival and fighting to defend against predators or gain access to food, water, or space resources. At this point, we briefly review with students what makes for a legitimate scientific model, namely that it is realistic and empirically consistent with the data at hand. We ask them if the natural selection–based model that many offer to explain male cricket aggression meets these criteria (it does). This is an important juncture for students regarding the other criteria used to judge a model's strength, that being its predictive power. We remind them of this critical scientific model criterion and ask them to consider how they can test their natural selection–based explanatory model concerning cricket aggression. For if the natural selection–based model that many offer to explain the male cricket aggression is an accurate one, then we can predict that the same aggression will be exhibited by previously isolated female crickets as well. It has never failed that multiple students make this inference and request to observe previously isolated female crickets interacting. We are happy to oblige.

Students Use/Revise Their Model of Selection to Account for Both Natural & Sexual Selection

We then allow students about 10–15 minutes, in class or via video, to observe five previously isolated female crickets together in a 10-gallon aquarium. Once again, each cricket is marked and assigned to a student, and students add any new observed behaviors to ethograms. Again they compare data as a group and as a class. What they note is that the female crickets groom, feed, walk, but mostly ignore one another. We again challenge them to think like evolutionary biologists, having them consider why there is a difference in behavior between the crickets by sex and, again, why would natural selection favor male aggression in crickets? Students easily conclude that enhanced male aggression may allow for better access to a resource that goes beyond a need for mere survival (water, food, space, predators) and is, instead, meeting a need for something else. Students usually hypothesize at this point that male crickets' aggression enhances their reproductive success by allowing access to, or attracting the preference of, females.

This idea is valid in that it matches the data that students have at hand. But their data are still limited. At this point, given enough time and considerations of students' abilities and knowledge, we often ask students to consider what data would help to test their explanation. Often, students collectively propose tests akin to studies done by Nelson and Nolen (1997) that, in effect, test the actual mating success of male crickets immediately after fighting with other males; we provide students with the key data (see Figure 3).

Students easily deduce that enhanced male aggression (measured by "battles won" against other males) increases mating success by allowing more aggressive males to monopolize access to females.

At this point, we require that students speak, or write, of their explanations in terms of their developing larger model of selection. Their more basic model of selection has been revised to account for the new data at hand, that being that certain sex-specific behaviors (in this case, greater aggression in male crickets) may allow for enhanced reproductive capacities. We have achieved an important milestone of this collective set of activities in terms of students' modeling and understanding of selection. Students, using data they have analyzed, sought, and predominantly collected themselves, have been led to revise their larger model of selection, which originally consisted only of the underlying premises associated with natural selection, to a larger model of selection that accounts for sexual selection as well. At this point, we make sure that all of our students have arrived at the following set of related conclusions concerning their model: (1) survival to reproductive age (natural selection) is not the only issue for organisms and (2) there is also the need to reproduce

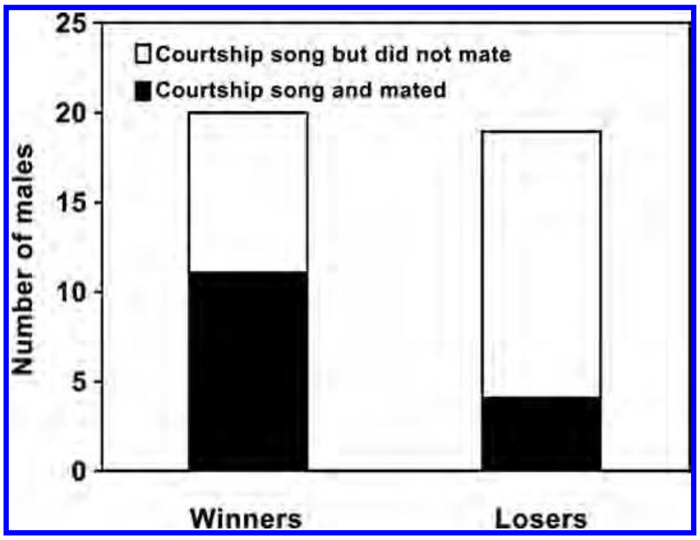
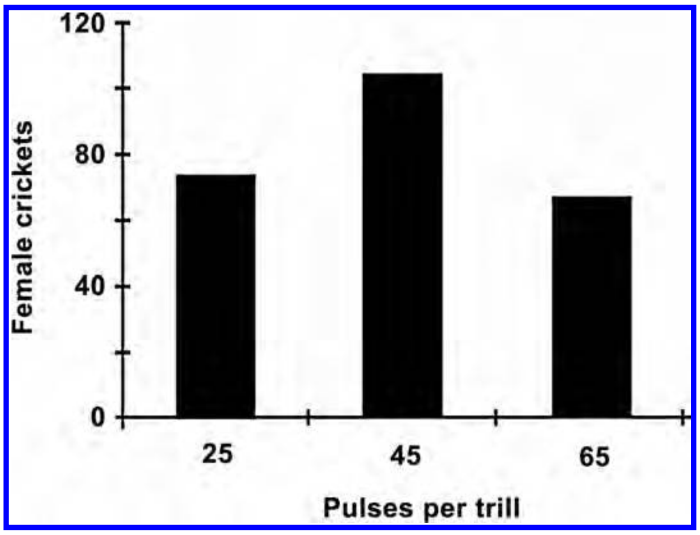


Figure 3. Matings of male winners and losers when placed together in a container with one female (adapted from Nelson and Nolen, 1997).



Figures 4. Number of visits by female crickets per pulses per trill of artificial "male" cricket calls (adapted from Gray & Cade, 1999).

(for sexual organisms, this equates to a need for access to mates and successful copulation).

We now begin to move them toward developing a model that better accounts for the nuances of the interplay of natural and sexual selection.

Students Use/Revise Their Model to Explore the Relationship between Natural & Sexual Selection: An Opportunity for Authentic Assessment

We again provide students with data they can evaluate toward further revision of their model to a more scientifically complete and robust one. The next set of data concerns the Texas field cricket (*Gryllus texensis*), an organism with a relatively large amount of diversity in its song, measured as sound pulses per trill (chirp). We point out to students that there are two kinds of sexual selection, first identified by Charles Darwin (1871). Intrasexual selection favors traits that increase success in competition for matings, such as the male–male aggression in crickets. Intersexual selection favors traits that increase success in attracting the opposite sex for mating. Male cricket "advertisement" song is such an intersexually selected trait: it attracts females for mating. In addition to attracting females with its advertisement song (intersexual selection), the Texas field cricket attracts a parasitoid fly, *Ormia ochracea*, that lays its eggs on the male crickets, eventually killing them (see Figures 4 and 5).

Educators may choose to have students continue working with others in their model revision. Alternatively, we have used the above data, and the corresponding questions below, as an individual-level written assessment to gauge students' ability to construct and revise scientific models, their understanding of how to judge the strength of models, and their ability to communicate about all of this.

○ Assessment Questions

(1) Gray and Cade observed a large amount of variability in the number of pulses per trill in song (compared with closely related species) among males in the population of *Gryllus texenis*. Assuming that there has been plenty of evolutionary time for the trait to evolve to become less variable, use your knowledge of selection (both natural and sexual selection) to construct an explanation for why cricket song has remained so variable in this population.

(2) Describe any revisions to your model of selection in terms of the *relationship* between natural and sexual selection.

(3) Think again like evolutionary biologists and predict what will happen to the song characteristics in the population over many generations, with both natural selection (the flies) and sexual selection (female crickets) present.

(4) Evaluate the "strength" of your model. To what extent does your model meet the criteria for a strong scientific model?

(5) What role(s) does the greater scientific community play in evaluating scientific models?

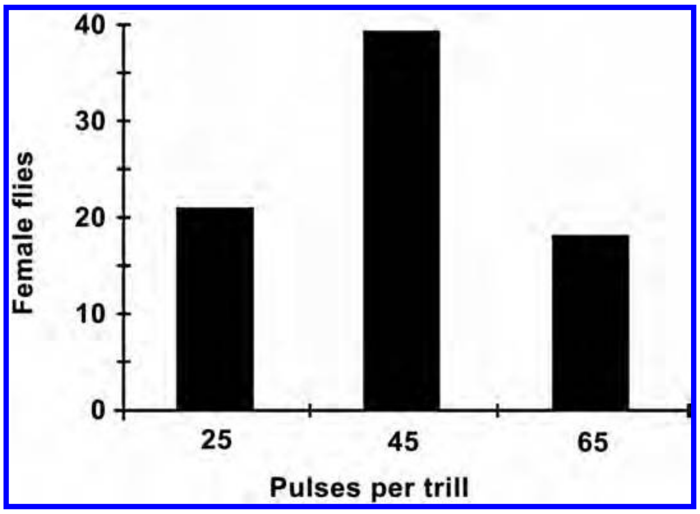


Figure 5. Number of visits by female parasitoid flies per pulses per trill of artificial "male" cricket calls (adapted from Gray & Cade, 1999).

We have again asked students to revise their model toward one with greater empirical consistency (to again account for *all* data).

The students easily observe that both the parasitoid and the female crickets appear to prefer male crickets with the same song characteristics, which means that while sexual selection favors a particular song type (45 pulses per trill), natural selection makes that song the riskiest to perform.

Students conclude that the relationship between natural and sexual selection is sometimes complicated, and that natural and sexual selection can be "at odds" with one another for particular traits. With both types of selection working at cross-purposes, students suggest that this may maintain variation in pulses per trill in the population. We sometimes challenge them to make predictions about what we might expect to observe if the parasitoid flies were extirpated from the population. Students hypothesize that if the natural selection from the parasitoid flies were to disappear from the population, then the cricket song profile favored by sexual selection would predominate, and the existing variation in pulses per trill might be lost.

Here, we provide excerpts from secondary students' work.

> **Student 1:**
> The amount of variation in the population is probably due to their environment. The *Gryllus texensis* species of cricket lives in the same environment as the parasitoid fly – *Ormia ochracea*. The reason for the wide variation in number of pulses per trill in the males is probably caused by the fly who deposits her larva onto the males, which kills them shortly after. The trait for the number of pulses is heritable, and there was variation to begin with. There must be a balancing factor which keeps the number of pulses per trill from creeping closer to 45.
>
> […]If the female crickets choose these males and so do the flies, there is both an advantage (sex. sel.) and a disadvantage to the having 45 pulses. More male crickets are born with the trait for 45 pulses but an equal number die from the wound by the fly. The variation, then, will remain in the population because the trait is not more advantageous than 25 or 65 pulses[…].
>
> In other closely related cricket populations, the numbers may be closer to 45/the females may hear this the best because there are no parasitoid flies in the area.
>
> **Student 2:**
> I imagine that it is relatively rare that a trait is acted upon by two different selective processes by two relatively similar sources, i.e. natural selection working through the parasitoid flies, and sexual selection working through female crickets. I would consider the two selection factors similar especially because they have developed a very similar organ to sense the trait in male crickets.
>
> […]Furthermore, the two selection process [sic] work against each other in that one process (sex. sel.) happens to select for the trait and the other process (nat. sel.) selects against the trait. Without parasitoid flies, females' selection would cause the trait of having 45 pulses per trill to become more prevalent; but conversely, without considering the female crickets, the female parasitoid fly would cause the trait to become less prevalent through the generations[…].
>
> So in others, with both the number of pulses per trill at the same time, the variability sort of "balances out" to an apparent degree. No variation in the trait is so much more helpful or detrimental, in the end making each male just as likely to pass on his genes as any other male.

Students are overwhelmingly successful, at this point, in arguing for the strength of their model, one that has empirical and conceptual consistency and predictive power. They recognize that evaluation of a model's strength is ultimately performed by a larger scientific community that provides additional assessment per these criteria via more prediction, relevant empirical tests, and certification of model's conceptual consistency with other understandings of nature.

○ Assessment of Student Gains

Success in implementing the curriculum with secondary and postsecondary students confirms of modeling-based inquiry as a strong theoretical construct toward the creation of curriculum and instruction to meet the vast bulk of what the *Next Generation Science Standards* and other key policy documents and stakeholders continue to call for. We analyzed two classes each of students' secondary (grades 10–12) and postsecondary work, via pre- and post-activity implementation assessments (surveys and interviews) and students' class projects and presentations at the end of the course, for content and process of science knowledge. Our analysis indicated that students gained

- Ecology content knowledge
- Robust understanding of scientific models and the role they play in science
- Understanding, competence, and overall positive affect with regard to scientific modeling and associated processes as the basis of scientific inquiry and community norms
- Empowerment to engage in scientific modeling practices
- Enjoyment regarding MBI-based teaching methods and framework that they deemed unique when compared with other science courses

Students also demonstrated growth in their conceptions of how science is done. When asked to describe the process of doing science precourse, students gave typical answers, consisting of a memorized and sequential "scientific method" or a more nebulous "critical thinking about a problem." Postcourse, students were more likely to conceptualize science through modeling and stressed other key components of doing science (like communicating with a larger scientific community) in relation to modeling.

Additionally, students indicated that their engagement in scientific processes through the curriculum was novel. Precourse, most students claimed to have experienced participating in real science before, citing working through a common laboratory exercise. Postcourse, more recognized that they had not actually participated in the larger process of science, describing the course's curriculum as helping them work through and recognize more complete and nuanced processes. While constructing robust, scientifically accepted conceptual models central to scientific disciplines, this modeling-based inquiry curriculum also fostered students' understanding of the processes of inquiry, collaboration, and communication regarding crosscutting concepts in science via participation in communities akin to those of practicing scientists.

○ Conclusion

Engagement with authentic scientific practices is woefully absent from students' experiences in K–16 classrooms. Modeling-based inquiry is a promising framework through which to engage students in these practices, while ensuring their deeper understanding of concepts central to a science discipline. While the curriculum described above was specific to phenomena regarding evolution, modeling-based inquiry can be, and has been, used effectively to help students learn about various phenomena. For other examples, see the University of Wisconsin's MUSE website (http://ncisla.wceruw.org/muse/index.html) and Stewart et al. (2005).

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JANA BOUWMA-GEARHART (jana.bouwma-gearhart@oregonstate.edu) is an Associate Professor in the College of Education at Oregon State University, 304k Furman Hall, Corvallis, OR 97331. ANDREW BOUWMA (andrew.bouwma@oregonstate.edu) is an instructor in the Department of Integrative Biology at Oregon State University, 3029 Cordley Hall, Corvallis, OR 97331.