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Bridging the Gap Between Mathematical Biology and Undergraduate Education Using Applicable Natural Resource Modeling

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ABSTRACT

Mathematical biology is a wide field of study with many venues that undergraduate students can access through research. However, the topics of study for these students can be overwhelming, and many topics of study yield either only trivial results or abstract outcomes that are nonintuitive and difficult to understand. We have used natural resource modeling, and more specifically, a partnership between academic researchers and federal scientists, as a bridge between undergraduate research and mathematical biology. Our collaboration is an interdisciplinary team that combines biology, mathematics, and statistics professors with government research scientists. As a team, we have mentored students through opportunities such as a Research Experiences for Undergraduates and other projects. In this article, we provide an overview of how we develop questions for undergraduates and outline two case studies, both of which resulted in peer reviewed journal articles. Last, we describe how we also transfer the results from these undergraduate projects to resource managers so the results may be applied to real world problems.

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1 Introduction

Mathematical biology and closely related fields such as natural resource modeling and mathematical ecology provide a wide subfield of mathematics for students and teachers seeking to apply mathematics as a tool for understanding the natural world and guiding human activities. As noted by Reed (2004, p. 341), "mathematical biology is a perfect subject for undergraduate research projects. Biology is so diverse and so little quantitative modeling has been done that it is relatively easy to find projects that use undergraduate mathematics in new biological applications." This breadth of opportunity also creates a challenge for would-be undergraduate researchers. What mathematical biology projects are accessible and interesting to undergraduates? We have observed natural resource modeling applications of mathematical biology to be a promising area of study for mentoring undergraduates through programs such as an Interdisciplinary Training for Undergraduates in Biological and Mathematical Sciences (UBM) and Research Experiences for Undergraduates (REU) programs. As part of the UBM program, student research focused on applied mathematical biology problems that were of interest to state/federal agencies and resource managers. Students from mathematics and biology were brought together as research teams to work on common overarching problems. Together, this program provided agencies and managers with a broader understanding of waterfowl disease along the Mississippi River, U.S. Moreover, it established an important research and collaborative foundation for future work on management questions in the region. Bennie et al. (2018) provides further details about an REU program that served as the basis for some of our examples. We have built upon the work completed by Bennie et al. (2018) by developing a broader perspective. In particular, we took the additional step of describing an interdisciplinary research team that included both federal and academic team members, thereby allowing the integration of mathematics and biology.

Our mathematical biology group grew from initial collaborations among biology, mathematics, and statistics faculty at the University of Wisconsin-La Crosse (UWL). These collaborations eventually expanded into a mathematics and biology (math bio) seminar/working group hosted by UWL. This seminar/working group attracted participants from multiple UWL departments including the Mathematics and Statistics, Biology, and Computer Science departments; government agencies including the U.S. Geological Survey (USGS), U.S. Fish and Wildlife Service (FWS), and Wisconsin Department of Natural Resources; and other local universities, such as Viterbo University. The group began meeting in 2012, met virtually during the pandemic, and continues to meet as of 2023. The inclusion of federal and academic scientists make our group unique compare to other research endeavors. The group's diverse perspectives strengthen our ability to investigate complex management questions using mathematical biology approaches.

Our group carried out traditional seminar style presentations and paper discussions, as well as collaborative research projects. The traditional seminars have included academic speakers who present their current research and nonacademic speakers who present applications of mathematical biology to real-world problems. The nonacademic speakers included scientists from the USGS and other agencies such as the Wisconsin Department of Natural Resources and the FWS. The non-USGS speakers provided insight from management agencies about what types of problems exist and where mathematics and biology may be combined to inform natural resource management. These interactions have led to several working research projects for the math bio working group, based on the research interests, questions, and needs of group participants. In addition to giving the participants an opportunity to answer their own questions, the math bio working group also has given rise to undergraduate research questions and collaborative mentoring experiences, something highlighted by a recent National Academies report (Invasive Carp Regional Coordinating Committee, 2022).

The mentoring experiences allow undergraduate students to address important and novel mathematical biology problems. The problems are accessible to undergraduate students and are unique because of the natural resource management context. For example, model applications that might otherwise be mathematically trivial or biologically unimportant gain meaning and context when answering a natural resource management question. Furthermore, our examples illustrate how even mathematically simple models can produces results that affect resource managers decisions. For undergraduates, these opportunities have emerged as summer or semester research projects and included funded and for-credit research opportunities. Examples of these mentoring opportunities include programs created to directly fund undergraduate research (such as National Science Foundation [NSF] UBM and REU grants) and other smaller sources of funding (including small grants or research contracts such as the formal cooperative agreement between the UWL and the USGS or UWL summer research funding for students). These smaller projects often dovetail from existing faculty-researcher collaborations within the math bio working group and allow students to work directly with USGS researchers on their projects and apply mathematical biology to real-world problems.

The UWL and the USGS Upper Midwest Environmental Sciences Center (UMESC) have a long history of formal and informal cooperation. As a comprehensive research university, UWL has undergraduate students looking for opportunities for research and job experience, master's students looking for projects, and faculty looking for research collaborators. UWL also hosts the River Studies Center which provides students with hands-on experiences in studying and understanding important challenges facing the Mississippi River region. Similarly, the UMESC completes research to support natural resource management on a global level but with a focus on the Great Lakes and the Upper Midwest, including the upper Mississippi River Basin. Thus, the UMESC and UWL have overlap in their research interests, and opportunities for cooperation readily exist within and beyond the math bio working group. This cooperation between the UWL and UMESC includes research internships, graduate student projects, hosting faculty sabbaticals, guest lectures, and joint research projects. For unfamiliar readers, the USGS serves as the science agency for the Department of the Interior, with the motto "Science for a changing world." The USGS consists of multiple science mission areas such as the Water Resources Mission Area and the Ecosystems Mission Area. Hence, many different scientists such as ecologists and hydrologists work for a "geological" agency (see Wagner 1999 for more history on the moves).

Throughout this paper, we describe how we have leveraged our unique partnerships between the UWL and UMESC to capitalize on the plethora of research questions in mathematical biology that are accessible to undergraduate research. First, we describe our approach for building a strong collaboration of interdisciplinary researchers. Then, we describe two case studies from REU projects that emerged from our math bio working group and led to published research. The first case study applied mathematical modeling to assess the effects of wind energy on wildlife. The second case study applied mathematical modeling to aid in understanding movement of invasive carp in response to movement deterrent technologies.

2 Recipe for Success

Strong partnerships and teams form the foundation of our math bio working group. These partnerships help us, as mentors, to see what challenges natural resource managers currently face and how models may be used to help these resource managers make decisions. Likewise, these strong partnerships give our group access to practitioners in the field who understand the current issues that natural resource managers face. We encourage people seeking to build these relationships to reach out to venues they might not usually consider. For example, a mathematician might branch out by attending biology-focused meetings such as a fisheries or wildlife seminar series or conference. Unlike large national or international meetings, regional or state meetings often provide smaller, more personal settings and better facilitate one-on-one interactions. Conversely, a biologist or natural resource manager might attend an applied mathematics or statistics seminar series or conference. A mathematician or statistician seeking to break into natural resource modeling could contact a natural resources professional to request an informational meeting and learn about the individual's quantitative problems and questions.

How to connect with scientists and land managers. Our own group emerged from a long-time collaboration and formal cooperative agreement between UWL and USGS. Furthermore, UWL has a formal liaison between the university and the USGS science center (at the time of our collaborations started, this was author RJH). This liaison connects faculty and students with USGS scientists. However, many academic scientists may not have these types of existing opportunities. There are many ways to initiate connections with government scientists. A few suggestions include:

- Identify your local federal, state, county, or tribal resource and research agencies. For example, the Wisconsin Department of Natural Resources (DNR) has an Office of Applied Science where as the Illinois DNR does not. Instead, the Illinois Natural History Survey conducts research in the state. Regardless, most agencies now have online directories.
- Many state and federal research agencies have outreach staff who may be able to connect you with scientists in their agencies.
- Look for state extension offices. Many states have these offices that help apply science to natural resource management. For example, Texas has the Texas A&M Agrilife Extension Service across much of Texas, Wisconsin has the University of Wisconsin Extension, and California has the University of California Cooperative Extension. These applied scientists often can connect with researchers at your institution and may be interested in working with them.
- Your home university may have an outreach coordinator, community engagement, marketing and communication or similar office. This type of office might be able to help you because these staff often have large professional networks in their area.
- In some regions of the U.S., large private lands will also have scientist managing their lands. For example, large ranches in Texas often have wildlife and range biologists, and large timber companies often employ foresters and wildlife biologists. Although we focus on public lands, these tools could also work for private lands.
- Last, visit your local, public natural resources. For example, go to a National Wildlife Refuge, State or National Forest, State or County Park, or other local public lands. Ask their interpretative staff if they know how science is used to manage their lands.

Using these previous mentioned approaches, we have developed a strong multidisciplinary team that includes a number of agencies and partnerships. These partnerships form the foundation of a unique undergraduate research experience. For example, over the course of our REU program, all students had at least two mentors: one subject area mentor (for example, a biologist or ecologist) and one quantitative mentor (for example, a statistician, mathematician, or computer scientist). In some years, we applied a team-based approach through which students were mentored by a group of experts in both areas without being assigned specific mentors. Hence, students could ask any team member questions during daily office hours, although "lead" mentors emerged to support students with their project write-ups based on the research problems and the mentor's expertise. During all years, we used the skills of both groups of mentors to guide the students and help them with their research. Having access to experts from different subject areas allowed students to learn from people with diverse expertise and backgrounds. We also modeled multi-disciplinary collaboration to the students and helped them to see that people have different areas of expertise and that even "experts" in subject areas do not always know the answers.

By expanding our undergraduate research experiences through guest speakers, we determined that many natural resource practitioners were willing to spend an hour or two talking with a group of enthusiastic undergraduate researchers about their own professional work and careers. During these talks, students not only learned about the practitioners' perspectives and careers but the practitioners also learned about the students' research and connected with them. An additional benefit of these talks was that the practitioners also often "bought in" to the students' research and subsequently developed a personal interest in the students' progress.

Guest speakers also assisted in bridging the gap between natural resource managers and natural resource modeling. Speakers included federal researchers, industry scientists, and state agency biologists. In later years, we had REU alumni speak about their current positions, including one former student who worked for a state agency. We also have had guest speakers participate in our programs at multiple times during a given year. For example, an FWS endangered species biologist gave an informational talk about her job and the use of models in her position at the start of one of our REUs. Later, she attended the REU to hear the students present their results and, ultimately, was able to use the students' results to inform decisions regarding the Endangered Species Act (ESA).

When selecting problems for students, we, the mentors, looked for interesting sub-questions within our own research (such as problems emerging from the math bio working group). Specifically, we looked for questions that were (1) interesting to us, (2) interesting to the natural resource managers we work with, (3) accessible to undergraduates, and (4) focused enough for an undergraduate to make reasonable progress and feel a sense of success at the end of their project (for example, a 10-week summer REU). Although point 1 is subjective, we encourage mentors to think about how their interests fit into the broader world. For point 2, natural resource managers routinely seek to solve applied problems with concrete recommendations to their systems. Although potentially limiting compared to the scope of some academic research, we observed these constraints to be useful because they force us to pick problems that are easily accessible to people who may not have comprehensive mathematical backgrounds (for additional discussion on this topic, see commentary such as White, 2001; Ellison and Dennis, 2010). This limitation also nicely transitions to point 3: accessibility to undergraduates. Our mentees (for example, REU student participants, UWL current undergraduates) are a mix of students with quantitative majors (for example, math, statistics, computer science) and life science majors (for example, biology, ecology, wildlife management). We try to limit our initial problems to only requiring sophomore-level math courses (for example, differential equations, linear algebra) and statistics courses (for example, multiple regression). Furthermore, we do not require our students to have introductory biology, ecology, or similar coursework. The exact constraints depend on our specific project because we customize projects for our students to optimize both the mentees' and mentors' experience. Lastly, given our limited time with the students, we tend to choose narrower and more focused questions rather than broad questions when selecting projects. For example, we might have the students address the question, "How does a specific chemical treatment affect the behavior of a specific type of fish in a single pond trial?" rather than trying to generalize across treatment, species, or studies.

Through trial and error, we observed students did best when we assigned them a question for their project, but we needed to intentionally build the question to point towards open-ended questions. For example, we might have the students recreate an existing paper or run basic simulations while asking new questions as a starting place for their research. Initially during our REU, we tried giving students open-ended questions but observed most undergraduate students floundered from the lack of direction from the mentors. In contrast, we observed that structured questions worked well for all students. Less experienced students were able to have a project they could complete over the course of their internship experience, have ownership over the project, and have something to present as a result of their experience. Advanced students or students with stronger mathematical skills quickly completed their assigned question and started asking and answering their own questions based on their personal interests and ownership of the dataset.

During our mentoring experiences, student proficiency in mathematical biology was assessed through a number of scaffolding mechanisms. First, students were required to give weekly presentations about their research projects. At the end of each presentation, mentors provided students with feedback on their visuals and the delivery of information. This iterative approach ultimately allowed students to create a formal research product that could be presented in the future. Student progress was also closely monitored via the submission of weekly written materials. Once again, mentors provided students with regular feedback on these documents with the goal of generating publishable scientific papers. Although this process did not always result in a journal publication, it did teach students the process of scientific writing, incorporating feedback, and subsequently closing the scientific loop. Continued research assessment in combination with close mentorship better prepared students for their "next steps" after the program, which in many cases involved pursuing graduate degrees in mathematical biology.

3 Myotis Bats and a Dynamic System

During the first summer of our REU, one group of students focused on understanding how white-nose syndrome and wind energy affected the Indiana bat (*Myotis sodalis*) and little brown bat (*M. lucifugus*). These species of bats are important to natural resource managers because the Indiana bat was in the first group of species listed under the ESA (32FR4001, 1967); the little brown bat has been listed as an endangered in Canada (`https://species-registry.canada.ca/index-en.html#/species/1173-848`), and a listing decision is under review in the United States (`https://ecos.fws.gov/ecp/species/9051`).

The students started the summer learning about Erickson's and Eager's work with bats (e.g., Erickson et al., 2014; Russell et al., 2014, 2015; Erickson et al., 2015, 2016) and talking with a FWS endangered species biologist about her job and the use of models in issuing incidental take permits under the ESA. Part of the methodology being developed by the USGS to support the FWS and other regulatory agencies used potential biological removal (PBR) to estimate dangerous levels of wind-farm bat mortality (Diffendorfer et al., 2019). PBR is used, by statute, for setting marine fishery harvest levels, including for endangered species (59FR20599, 1994), and this application led USGS scientists to apply the model to examine the effects of wind energy on wildlife. The typical derivation of PBR assumes logistic growth but does not consider the Allee effect. The Allee effect occurs when a population becomes too small to reproduce (roughly, the model describes a system with low population sizes where too few individuals exist to find a mate; Allen, 2007).

Our student, who was a rising senior and statistics/mathematics/computer science triple major, noticed that PBR does not include the Allee effect. The student used the skills he learned in his differential equations class to derive PBR that included the Allee effect. These results indicated that when the Allee effect is not included, PBR may allow take levels that are too high (or synonymously, incidental harvest), thereby not protecting populations. The student worked with us to write and document his findings (published as Haider et al., 2017). We also shared these results with the FWS biologist who used this information when deciding on modeling approaches for a future project considering harm to endangered species populations and issuing take permits. In addition to deriving the math, our student also was able to program his model using the R language and use the code as part of his online portfolio of skills (`https://github.com/haiderstats/PBR-Allee`).

This project demonstrates the take-home message of our paper. First, the project is accessible to an undergraduate student who has completed a sophomore-level course (that is, only requiring differential equations). Second, the results are useful to natural resource managers because of the specific context of the research question. Third, this usability helped our student's work to be novel enough to be successfully published (Haider et al., 2017), even if the mathematical finding in and of itself may not be novel enough to warrant publication in a math-focused journal. Thus, this example demonstrates how undergraduate research can be both accessible and beneficial.

4 Invasive Carp and Linear Algebra

Invasive carp species including bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*H. molitrix*) cause ecological and economic damage across their invaded range (Kolar, 2007). Because concerns exist that these species will spread to new locations such as the Great Lakes, resource managers are seeking to control their spread and prevent new infestations (Cuddington et al., 2014; Invasive Carp Regional Coordinating Committee, 2022). One control tool that was developed to deter the movement of these species through bottlenecks in rivers such as lock and dam structures involves injecting carbon dioxide bubbles into water (Cupp et al., 2017, 2021). As part of the barrier deterrent development process, pond studies were completed to examine how invasive carp behavior changed in pond settings (e.g., Cupp et al., 2017).

Over the course of this REU, a pair of our students recreated the results of (Cupp et al., 2017) using the publicly available data from this project (Cupp, 2020), which allowed the students to become familiar with the dataset and examine how the fish changed their locations and behavior in the ponds based on carbon dioxide levels in the treatment zone of the ponds. Additionally, we had the students compare new analytical methods to analyze the data, such as quantile regression. These new methods not only helped the students but also provided novel biological companions by giving an alternative method for understanding the data and behavioral endpoints. One of our students, then a rising senior and geography/biology double major, realized a Markov model could be used to model the movement of fish in the ponds. Specifically, she noticed that she could discretize the pond into cells and then model movement patterns with different carbon dioxide treatment levels.

For this project, the student used upper-level undergraduate coursework to teach herself a new statistical tool (quantile regression) and linear algebra (a sophomore-level course) to learn about and apply the Markov models. The students for this project taught themselves coding skills with minimal inputs from the mentors. Lastly, we, as mentors, used these results as a pilot study to support future work to study invasive carp behavior and how invasive carp respond through movement to stimuli presented by deterrent tools.

5 Conclusion

Many frontiers exist in the field of mathematical biology for undergraduate researchers to explore. Using natural resource modeling, especially in concert with managers and management agencies, can help narrow down this broad field. Specifically, natural resource modeling is a field where students can research concrete problems that address real-world applications and are readily accessible to undergraduates. We have been able to include these examples in our mentoring through developing an interdisciplinary team that includes academics and government research scientists who work closely with natural resource managers. We observed our collaborations to be fruitful for the students and the mentors. Others may wish to consider these collaborations as well.

Author Contributions

All authors mentored students through the REU, and this mentorship served as their basis for co-authorship. As mentors, we all learned together and adapted an adage: "it takes a village to mentor students in interdisciplinary projects." Barb Bennie, Eric A. Eager, James Peirce, Greg Sandland, Roger Haro, and Richard A. Erickson all served as principal investigators for the initial NSF grant to fund the REU. Molly Van Appledorn and Kathi Jo Jankowski joined as principal investigators for the renewal grant. Richard A Erickson conceived and wrote the initial draft of the paper. James Peirce assisted with major edits and direction to aid in the focus of the paper. All co-authors reviewed and approved the manuscript for submission.

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