UNDERGRADUATE RESEARCH OPPORTUNITIES PROGRAM
PROPOSAL FORM

University of St. Thomas

Due *by 10:00 p.m.* on the posted deadline

Student Applicant:	Seoyeon Ma
Student UST ID#:	101256916
Grant	Collaborative Inquiry Grant
Grant type	Academic Year (100 hours)
Term of Research	Spring
Year of Research	2024
Title of Proposed Project	Modeling Prey-Predator Metacommunities with Delay Differential Equations
Faculty Mentor Name	Kenichi Okamoto
Additional Mentor(s)	

PART 1 – PROJECT NARRATIVE (REQUIRED)

(limit: 1,200 words – application will be discarded if violated)

290 possible points – up to 145 from each of two reviewers.

Describe your proposed research project using language that is appropriate to your field(s) and familiar to a specialist in your broad area(s) of study.

Be sure to address all of the following questions, preparing your responses in the appropriate section.

1. BACKGROUND AND/OR LITERATURE REVIEW (80 points)

What is the nature, context, or scholarly background of your topic of inquiry?

Consider discussing:

- Sources relevant to your topic that you have read so far
- Sources you plan to read, if awarded the grant
- How these sources have helped you define the scope of and need for this project

[For Community-Based Research: Who is your community partner, and what is that partner's identified need?]

Species evolve, adapting to consistently changing environment and competing within their group and interacting with other species [1]. In ecology, interaction between species includes prey and predators. This interaction may affect each other by making prey and predator evolve in response to each other; prey will develop defense abilities to better escape from predators and predators develop their attack ability to better hunt prey. These adaptations are inherited by their offspring, and the same process would be repeated over generations. In evolutionary biology, this interaction is called an "Arms Race," which is a competition between co-evolving species where their genes exhibit escalating adaptations and counter-adaptations against each other. "Arms races" are a special kind of coevolution.

Broadly, coevolution between prey and predator is driven by biotic factors and abiotic factors. Biotic factors are the factors that are caused by living organisms, whereas abiotic factors are the factors that are caused by non-living organisms. Biotic factors, for instance, include encounters, migration, mutations, etc. Encounters account for things like prey killed by predator; migration accounts for prey/predator immigration/emigration; mutations account for genetic changes happening during prey/predator reproduction. Note that under local coevolutionary selection, coevolution between two species can occur within a single local community, and thus migration isn't considered. However, studies conducted in the last few decades demonstrate that most coevolution occurs not in single local communities but in broader regions. The "Geographic Mosaic of Coevolution" theory holds that "coevolution is inherently geographically structured or coevolution between two species can progress along very different trajectories in different places, causing trait differences to evolve among different populations of the same species" [2]. The main instance of abiotic factors includes the spatial arrangements of communities.

Yet there's one more important factor that needs to be considered to develop the coevolutionary prey-predator model: time delay [3-5]. It is obvious that there are time delays in interactions between prey and predator because, for instance, predators can't give birth to their babies right after eating prey nor prey can convert nutrition they absorbed right away into its offspring. To demonstrate the importance of taking the time delay into account, imagine the time delay doesn't exist. Then predators will eat prey and turn it into their babies immediately. This condition can imply that in the absence of the time delay in the interaction between prey and predator can result in the prey population going extinct. Therefore, the time delay is a crucial factor in the prey-predator model which structures coevolution and drives the dynamics and stability of prey and predator populations.

2. RESEARCH QUESTION(S) AND OBJECTIVE (70 points)

- What will your inquiry address?
- What is your specific research question?
- How will your project respond to, engage with, or contribute to the scholarly context of the topic that you have described above?

[For Sustainability Scholars: How does your research question address sustainability?]

[For Interreligious Research Grants: How does your research question address encounter between, among, and/or within persons or communities with various religious identities (including secular, nonreligious, and spiritual worldviews and ways of life)?]

Everything described above demonstrates the need to incorporate time-delays into spatial prey-predator coevolution models. Our project will do so using time-delay differential equations, aiming at exploring how the time delay drives coevolution, how it changes prey/predator populations over time, and how species reshape each other across space within the "arms race." Furthermore, our project will address how time delays play in and impact the geographic mosaic of coevolution theory.

3. DESIGN, METHODOLOGY, AND/OR THEORETICAL APPROACH (80 points)

How will you conduct your inquiry? Consider discussing any of the items below that apply to your work:

Tools	Skills	Methodologies	Theories	Creative techniques
Processes	Materials and resources	Compositional frameworks	Forms of analysis	Data collection and management

Why are the methods you have described relevant and appropriate to address the research question you have identified?

[For Sustainability Scholars: What are the interdisciplinary elements of your research design?]

A mathematical prey-predator model will be first built based on the equations described in the Appendix [6]. This model will take account of processes such as encounters, new babies/offspring born, death, and trait variation. We will also incorporate tradeoffs between X and Y into our model where X represents species' survival ability and Y represents the number of offspring. We will first explore the effects of time-delays on this model in the absence of migration between patches and mutations, and then add both migration and mutation, as they are important features in coevolution. Our finalized model will be generalizable to accommodate any number of patch types, prey genotypes, or predator genotypes.

Our analyses will be conducted using R. To explore the effect of the time delay, we will numerically integrate our prey-predator evolutionary model with time-delays using the *dde* package, and compare it to the baseline, non-time delayed model using the *deSolve* package in R. The *dde* package has the *ylag* function, which we will use to incorporate time delays into our model, and the *dopri* function to integrate our delay differential equations.

4. RESULTS/OUTCOME AND INTERPRETATION (30 points)

- What outcome do you anticipate?
- If the outcome is unclear, what are you interested in learning about and why do you think this research is meaningful?
- How will your framework allow you to interpret your results or draw meaningful conclusions from your inquiry?

We will start by taking account of a time delay in prey/predator birth. We will have to consider how much time delay is needed between resource consumption and reproduction in prey and predators. Under these conditions, we anticipate that as the time delay gets larger, it takes more time to reflect the change in prey/predator population genotypes, and thus the population would change more slowly. If the time delay between predator consumption and births is too short and thus if the predator babies are born quickly, then prey may get eaten so fast and will go extinct.

There are many other factors that we need to study along with the time delay. One example is the strength of the tradeoff between prey defense ability and its number of offspring. We anticipate that as prey defense ability gets higher, predators get worse at hunting prey and thus the predator population will decline. Similarly, predator attack ability is also one of the factors that determine population changes, and we anticipate that as higher predator attack ability evolves, predators get better at hunting prey and thus the predator population will grow faster.

I will also vary the migration and mutation rates in the full model. I am not yet sure how the time delay will interact with migrations and mutations in driving coevolution, and this is a major goal of the study.

5. **ANTICIPATED IMPACT OR IMPLICATIONS** (30 points)

What impact will your work have on your field, the wider community, and on you individually?
[For Community-Based Research: What is the anticipated impact on your community partner?]

Time delays play important roles in the interactions between prey and predator. This project will demonstrate how these time delays affect coevolution, and thus, the dynamics, stability and coexistence of prey and predator populations. This work has broader impacts to many fields such as biodiversity, human health, food security, and natural resource availability.

I participated in the Center for Applied Mathematics (CAM) research project in summer 2023 and learned the basics of ordinary differential equation (ODE) modeling and how to analyze them using the *dde* or *deSolve* packages in R by first implementing some examples. This project is a valuable opportunity to learn about biology, new programming skills, the overall research process from reading relevant papers through planning and actually analyzing results, and my passion for research. If possible, I want to learn more about delay differential equations, and this project gives me a good starting point.

PART 2 – MEDIA SUMMARY (REQUIRED)

(limit: 400 words – application will be discarded if violated)

30 possible points from one reviewer.

As a researcher, you are often called upon to describe your work to people outside your field.

A media summary is a brief description of your project for a general audience. Imagine you are describing your project to a journalist who is going to write an article about your work, or to a funding agency whose reviewers are not in your field and will not fund you if they can't understand you.

To write this summary, **avoid language that only a specialist would understand.** A non-specialist will read and evaluate your summary based on your ability to answer the three questions below. Pitch your summary to an educated, non-specialist reader – someone who is interested in what you are doing, but who hasn't formally learned anything about it yet. Show how you can communicate about your work and educate the general public on the importance of what you are doing.

Address all:

1. What is your project about? (10 points)
2. How are you going to do this? (10 points)
3. Why is it important? (10 points)

Species evolve, adapting to consistently changing environment and competing within their group and interacting with other species. In ecology, interaction between species includes prey and predators. For example, in the relationship between cheetahs and gazelles, cheetahs are predators and gazelles are prey. Cheetahs would evolve to hunt gazelles faster, and correspondingly gazelles would evolve to better escape from cheetahs. In evolutionary biology, this interaction is called an "Arms Race," which describes an antagonism between coevolving species where their genes exhibit escalating adaptations and counter-adaptations against each other. "Arms races" are a special kind of coevolution.

There are many important factors that drive coevolution such as migration and mutations, and one of them is a time delay. Intuitively thinking, it is impossible for predators to give birth to their babies right after eating prey nor for prey to convert nutrition they absorbed right away into its offspring. The time delay always exists in the interaction between prey and predator, and this demonstrates the need to incorporate time-delays into spatial prey-predator coevolution models.

Our project will address this need for incorporating time-delays into the prey-predator model by using time-delay differential equations and by aiming at exploring how the time delay drives coevolution, how it changes prey/predator populations over time, and how species reshape each other across space within the "arms race." We will do so by first developing mathematical models for the interaction between prey and predator with time delays but without evolution using the programming language R. Then, we will add evolution to the model to see how coevolution works in such contexts.

Again, species exist and live by interacting with other species, and so, the time delay that happens in one species would greatly affect the whole biological system that it's involved in. Modeling the effect of delays on coevolution is thus key to understanding on the effects of time delays for "coevolutionary arms races." This modeling will further help maintain the dynamics, stability and coexistence of prey and predator populations. This work also has broader impacts to many fields such as biodiversity, human health, food security, natural resource availability, etc.

Review your work. Did you explain:

- ***What?***
- ***How?***
- ***Why?***

PART 3 – PROJECT LOGISTICS (REQUIRED) – 0 points

1. TIMELINE

Outline your work plan for the duration of the grant period.
{Recommended: a week by week schedule of tasks and milestones.]

Week 1-3: Set up and analyze the mathematical model for the prey-predator interaction with time delays and without evolution.

Weeks 4-6: Set up and analyze the mathematical model for the prey-predator interaction with time delays and evolution.
Week 5-7: Write R scripts for the models that we came up with so far.
Weeks 8: Visualize or plot the results.
Week 9-10: Write final report to summarize findings.
Post-grant period: Develop poster for Inquiry session; present at Inquiry event.
Post-grant period: Develop and submit manuscript for publication.
Post-grant period: Present findings at a conference.

2. FINAL PRODUCT

Please briefly describe the final product that will be the result of your research/inquiry. This is the product that must be approved by your mentor and submitted to UROP to complete the requirements of your grant, if awarded.

My final product will have the mathematical models and visualizations for the prey-predator interaction with time delays and with/without evolution.

3. DISSEMINATION PLAN

Include a brief dissemination plan for sharing your results after your work is completed (e.g. poster and conference presentations, opportunities for publication, etc.)

My work will be shared at the Inquiry poster session. If my work has the value of publication, then I will work with my advisor and maybe will even think about participating in a conference. The R scripts developed will be stored and shared in an open-access repository though GitHub for other modelers to use, reference, or modify.

PART 4 – ADDITIONAL APPENDICES

Attach or paste any necessary appendices, figures, etc. to support your proposal. Include any citations used in your proposal. Make sure all appendices are clearly labeled and revised.

1. Abrams, Peter. (2000). The Evolution of Predator-Prey Interactions: Theory and Evidence. Annual Review of Ecology and Systematics. 31. 79-105. 10.1146/annurev.ecolsys.31.1.79.
2. Hoeksema, 2012 Geographic Mosaics of Coevolution, Nature Education Knowledge 3(10):19
3. Moujahid, Abdelmalik, and Fernando Vadillo. "Impact of Delay on Predator-Prey Models." ArXiv.org, 22 Mar. 2022, arxiv.org/abs/2203.13192.
4. Yongkun Li, Yang Kuang, Periodic Solutions of Periodic Delay Lotka–Volterra Equations and Systems, Journal of Mathematical Analysis and Applications, Volume 255, Issue 1, 2001, Pages 260-280, ISSN 0022-247X, https://doi.org/10.1006/jmaa.2000.7248. (https://www.sciencedirect.com/science/article/pii/S0022247X00972482)
5. Van Der Laan, J. D., & Hogeweg, P. (1995). Predator-Prey Coevolution: Interactions across Different Timescales. Proceedings: Biological Sciences, 259(1354), 35–42. http://www.jstor.org/stable/50231

6. **Equation 1**. The change in the prey population over time in the prey-predator model without time-delays, migration, and mutations. R(t) represents the prey population at time t, so dR(t)/dt represents the change in the prey population over time. r(φ) is the tradeoff function which represents (individual birth rate – individual death rate) where death in this case happens randomly. k is the carrying capacity or the population at which the per-individual reproductive rate is zero. χ is the predator attack ability. φ is the prey defense ability. C(t) is the predator population at time t. The first term, r(φ)R(t)(1-R(t)/k), represents the prey birth and death rate where death in this case happens randomly. The second term, χ/φ*C(t)R(t), represents the prey death rate due to predation. So, it is expected that as χ gets higher, the prey death rate due to predation will get higher, which will eventually lead to the prey population decreasing. By contrast, it is expected that as φ gets higher, the prey death rate due to predation will get lower, which will eventually lead to the prey population increasing.

$$\frac{dR(t)}{dt} = r(\varphi)R(t)\left(1 - \frac{R(t)}{k}\right) - \frac{\chi}{\varphi}C(t)R(t)$$

.

Equation 2. The change in the predator population over time in the prey-predator model without time-delays, migration, and mutations. Again, C(t) represents the predator population at time t, so dC(t)/dt represents the change in the predator population over time. γ is the conversion efficiency or the efficiency of a predator converting prey eaten into its baby. δ is the predator death rate. The first term, γ*χ/φ*C(t)R(t), represents the predator birth rate, and the second term, δ*C(t), represents the predator death rate.

$$\frac{dC(t)}{dt} = \gamma\frac{\chi}{\varphi}C(t)R(t) - \delta C(t)$$