Improving Interdisciplinary Teaching through a Complexity Lens

Sarah Neitzel[1]
Yuhao Zhao[2]
Carrie Diaz Eaton[2]

[1]Unity College, USA
[2]Bates College, USA

Correspondence: cdeaton@bates.edu

Abstract

In this article, we discuss the use of bipartite network analysis to understand and improve interdisciplinary teaching practice. We theorize mathematics and biology as part of a coevolving mutualistic ecosystem. As part of an interdisciplinary teaching initiative, we inventoried mathematics topics appearing in the marine biology classroom and their associated marine context. We then apply techniques of mutualistic bipartite networks analysis to this system to understand the use of mathematical concepts in a marine biology classroom. By analyzing the frequency and distribution of mathematics topics, we see that a variety of mathematical concepts are used across the course with most appearing only a few times. While this is an inherent trait of mutualistic coevolutionary networks, it can create a logistical challenge to supporting mathematics in the marine biology classroom. We find that marine biology topics containing the most mathematics are either close to the instructor's research area or were introduced through externally-developed educational resources. Finally, we analyze groups of topics that appear connected to each other more frequently in order to inform both interdisciplinary education development as well as disciplinary support. We also suggest ways to use network metrics to track interdisciplinary connections over time, helping us understand the impact of interventions on interdisciplinary teaching practice.

Keywords: interdisciplinary teaching, mathematics, marine biology, bipartite network, curriculum

INTRODUCTION

Disciplines as a coevolving and mutualistic complex adaptive system

As new interdisciplinary fields emerge, interdisciplinary education has become vital. Students are expected not just to know concepts in their own field, but to be able to apply them in novel situations outside one's discipline. For biology education, this expectation is clearly delineated in the Vision and Change report's description of core competencies and disciplinary practice (AAAS, 2011). This report defines expectations for students to harness the "interdisciplinary nature of science" and "collaborate and communicate with other disciplines" (p. 15). Many of the other core competencies refer to particular types of interdisciplinary collaboration such as mathematical modeling and social science.

Network analysis has been used to asses interdisciplinary research, typically through examining citation networks (e.g. Palmer, 2103; Bishop et al., 2014), and it is a fruitful avenue for understanding how synthesis centers help change research practice to become more interdisciplinary (Baron et al., 2017). Network approaches are also used within the biology community to analyze biochemical networks, protein interaction networks, and ecological networks, just to name a few (see Proulx, Promislow, & Phillips, 2005 and Ings et al., 2009, for reviews). These information network approaches are related to, but not the same as, social network approaches that are becoming more common in education research (see Grunspan et al., 2014, for overview of understanding student social networks; also Dou et al., 2016, and Buchenroth-Martin et al., 2017; see Andrews et al. 2016 for example of collegial social network analysis).

One interdisciplinary front which emerged in the sciences over the past several decades is that of mathematical biology. Some studies of disciplines as complex adaptive systems focus on one particular subject and use the tools of unimodal network analysis to examine topics and their relationships within that subject (e.g. Koponen, 2021). Here we theorize mathematical biology as a hybrid field of two mutualistic coevolving disciplines, biology and mathematics. Thus we use bipartite network analysis, common in the study of mutualistic and coevolving ecological networks, such as plant-pollinator networks (Bascompte and Jordano, 2007; Ings et al., 2009; Vázquez et al., 2009).

Mathematical biology and STEM education

Vision and Change (AAAS, 2011) called for infusion of mathematical and computational topics into biology education reform as a response to mathematical modeling and computational techniques as a rapidly growing research area. There have been a number of course reforms from infusing biology examples into calculus and to modeling in introductory biology as well as new biology or mathematical biology courses at the interface (e.g. Diaz Eaton and Callender Highlander 2017, Robeva et al 2022, Weisstein 2011, Acevedo 2020). There are also a number of funding initiatives and communities of support which support mathematics and biology

instructors to meet the demand for a more integrated education (Diaz Eaton et al 2020, Akman et al 2020). Nonetheless, it remains a challenge to help instructors who have not been cross trained in both disciplines to teach in interdisciplinary ways, for a variety of reasons including differences in epistemology and language (Redish and Kuo 2015, Diaz Eaton et al 2019).

Henderson, Beach, and Finkelstein reviewed STEM education reform strategies in 2011 with particular attention on teaching practice intervention. These interventions typically operate on two axes: intervening at the environment or the individual and using prescribed or emergent interventions. However, most of the current work on the assessment of interdisciplinary thinking is focused on undergraduate students (*e.g.* Mansilla et al. 2006; Mansilla and Draising, 2007; Spelt et al., 2009). While this is an important outcome to assess, it does not tell us explicitly about how teachers might come to their interdisciplinary teaching practice, nor the interdisciplinarity of the curriculum itself. In this article, we explore the use of bipartite network analysis to inventory and understand the evolution of interdisciplinary teaching practice between mathematics and biology, including interdisciplinary curriculum development.

METHODS

From 2016 - 2018, Unity College, a small environmental liberal arts college, was part of a ten college networked improvement community effort to revise foundational mathematics courses with partner disciplines (Beisiegel and Doree, 2020). Each college within the consortium has at least one co-PI from mathematics, a target foundational mathematics course or courses, and at least one co-PI from a partner discipline. Unity College's project was to revise the Calculus I and II sequence to meet the needs of the Marine Biology major. Calculus I and II had already adopted scientific writing which utilized the same scientific writing rubric as the Biology and Marine Biology classes (Diaz Eaton and Wade, 2014) and had revised the content to meet the needs of the two programs which required it: Wildlife Biology and Earth and Environmental Science (Diaz Eaton and Callender Highlander 2017). In Fall 2016, the Marine Biology program began requiring Calculus I as part of its major, thus its interest in a partnership between Calculus and Marine Biology.

As part of this grant, the Marine Biology program director sat in on Calculus I, and the next semester, the Calculus instructor (co-author Diaz Eaton) sat in on Marine Biology. Marine Biology met for 50 minutes on Wednesdays and Fridays for lecture and then for an additional 4 hour lab on Friday afternoons. During the lecture portions, when a math concept was recognized as being used in relation to the marine topic at hand (explicitly or implicitly), it was recorded, along with the context in which it occurred, as illustrated in Table 1. The math topics and marine biology topics form an edgelist for the bipartite network (edgelist data is in the CSV file in Supplementary Materials). Lecture data was collected by Diaz Eaton starting on the second lecture (the first was a syllabus review) and was not collected during lab periods. Instead, during the lab periods, Diaz Eaton acted as an assistant in the lab classroom.

Table 1

Excerpt of data table of math-marine concept interactions

Math Concept	Marine Biology Concept	Explanation/Context
max/min	lunar orbit	apogee and perigee and tides
ellipse	lunar orbit	apogee and perigee and tides
optimization	marine protected areas (MPAs)	MPAs should be designed to optimize effectiveness given funding

Diaz Eaton has graduate training in both mathematics and ecology, but not marine science, which may affect data collection. At the time of data analysis, Neitzel was an undergraduate in marine biology with a minor in Applied Mathematics and Statistics. As a pilot project, we were looking for emergent themes and keywords across a broad mathematics spectrum. Therefore, we did not establish an *a priori* ontology, but rather allowed it to emerge as a result of the observations. As part of data manual data cleaning and thematic analysis, Netizel, in consultation with Diaz Eaton, grouped topics if they shared word stems (e.g. graph and graphing), were subcategories of a broader topic (e.g. conservative systems were grouped under systems), or were otherwise closely related conceptually (e.g. min/max and optimization).

Observation within a single Marine Biology course is akin to plant-pollinator network observation data in which particular plant areas are observed for pollinators. The math concepts list should be considered complete, whereas the marine concepts list should be considered incomplete, as only marine concepts with clear math connections were listed. This can skew data signals from the full underlying coevolutionary network (Gibson et al., 2011).

For the bipartite network analysis, we utilize the bipartite.r package, which is commonly used in analysis of mutualistic complex adaptive systems.(Dormann et al., 2008; Dormann 2020; Saavedra et al., 2009) To distinguish the two types of nodes in the bipartite system, `bipartite.r' utilizes the terminology 'lower' and 'higher'. We define 'lower' as mathematics and 'higher' as marine biology. We utilized a variety of network analysis approaches common to ecological bipartite analysis including network visualization, degree distribution, and clustering analysis of the interaction matrix to gain insights. The CSV data file and the RMD file are uploaded to github (https://github.com/mathprofcarrie/marine-math-network).

RESULTS

Characterizing which math is in the marine biology classroom

Figure 1 is a plot of the generated bipartite network data. When we visualize these connections, we notice immediately that there is not a clean one-to-one relationship between math topics and marine biology topics. The thickness of an edge indicates the strength of the connection (number of times that particular combination was mentioned). However, in the case study, most concepts

were connected only once or twice. This is a common feature of network heterogeneity - few nodes have many connections (“generalists”) and many modes have few connections (“specialists”) (Vázquez et al., 2009).

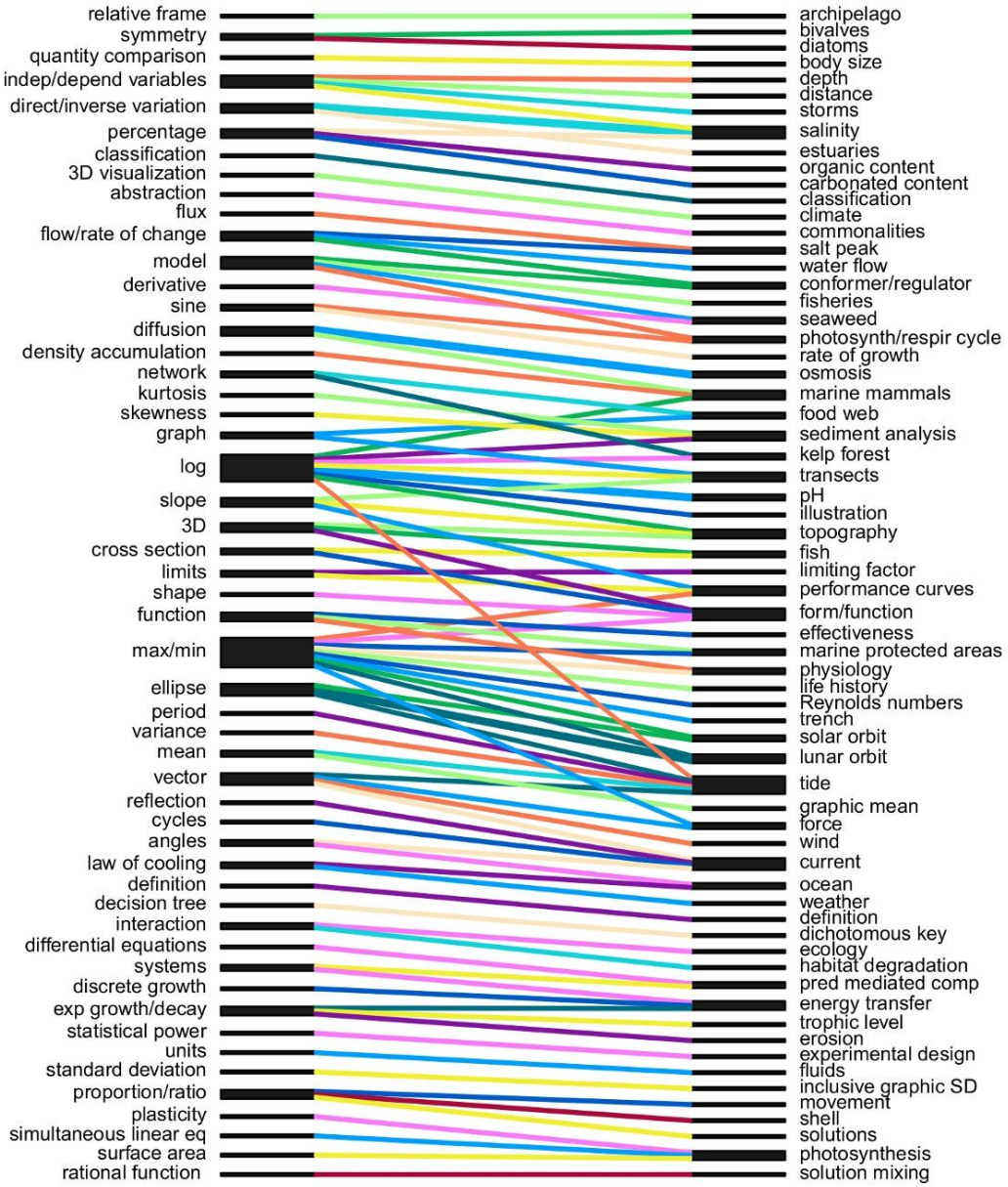

Figure 1. True web of math-marine concept network produced via ‘plotweb’. Math concepts (the ‘lower’ level) are on the right and marine concepts (the ‘higher’ level’) are on the left, utilizing ‘cca’ to group highly connected concepts together towards the center of the plot, which acts to minimize edge crossing. The black bars are nodes and the colored lines indicate co-occurring math and marine topics. The size of both indicates node or edge size respectively, with only node size varying dramatically in this web.

We can infer a few of the most common topics simply from the network graph. When we examine which mathematics topics appear most frequently, there are two topic areas that stand out. The grouping of themes related to maximum, minimum and optimization related to 10 different marine biology topics. The theme related to logarithms and scaling relate to 9 different marine biology concepts. On the other side of the web, you can see that tides are the "mathiest marine" concept. In the tail of Figure 1, there are four topics that are associated with the most mathematics: tides (6 connections), currents, salinity, and form and function (connections to 4 math topics each).

A good question to ask is whether these are inherent characteristics of marine biology, or signal something more important about the instructor and context. This study is a glimpse into a marine biology classroom in which optimization and scale are key mathematics concepts stressed. In this classroom, the instructor teaches concepts of tides, currents, salinity and form and function in ways that are connected to many math topics. After examining lecture notes for these days, we find two interesting patterns.

Multiple mathematical references (*e.g.* max/min, mathematical function, dependent/independent variables, optimization) were made related to how organisms evolve in marine environments and the physiological adaptations needed to compensate for differing levels of environmental factors such as salinity, pressure. The instructor's research area was in systematics, with an emphasis on marine invertebrate physiology. Also, the instructor had sat in on Calculus I in the previous semester, which included themes such as maximum, minimum, optimization, exponential growth, and log transformations (Eaton and Highlander, 2017). It may be that mathematics professional development took hold first in classroom topics close to the instructor's research training.

The abundance of mathematical references in the lecture on tides and currents may be intrinsic to the discussion of physical oceanography. However, the level of explicit mathematical activity was highly influenced by the instructor's choice to use an educational YouTube video to explain the tides. This video comprised a significant portion of the class and included details about the physics. This means that high quality third-party instructional materials may be a way where instructors are introducing quantitative concepts into the classroom.

These two strategies directly map onto the individual strategies proposed by Henderson, Beach, and Finkelstein (2011). The first strategy is emergent individual change, fostered by reflection and supporting new ways of thinking, which was a particular goal of the grant. The second is characterized as the use of a prescribed intervention for individuals.

Distribution of Connections

Another way of conceptualizing the structure of connections is through the use of a connectivity distribution (Figure 2). In connectivity distributions, "specialist" topics are indicated by the high bars on the left, but a long tail on the distribution, indicating that there are some "generalist" topics occurring multiple times. Both Figures 1 and 2 illustrate that, while there are some generalist topics that can be woven and reinforced into the math curriculum, there are also a number of specialist math topics which become important throughout the course.

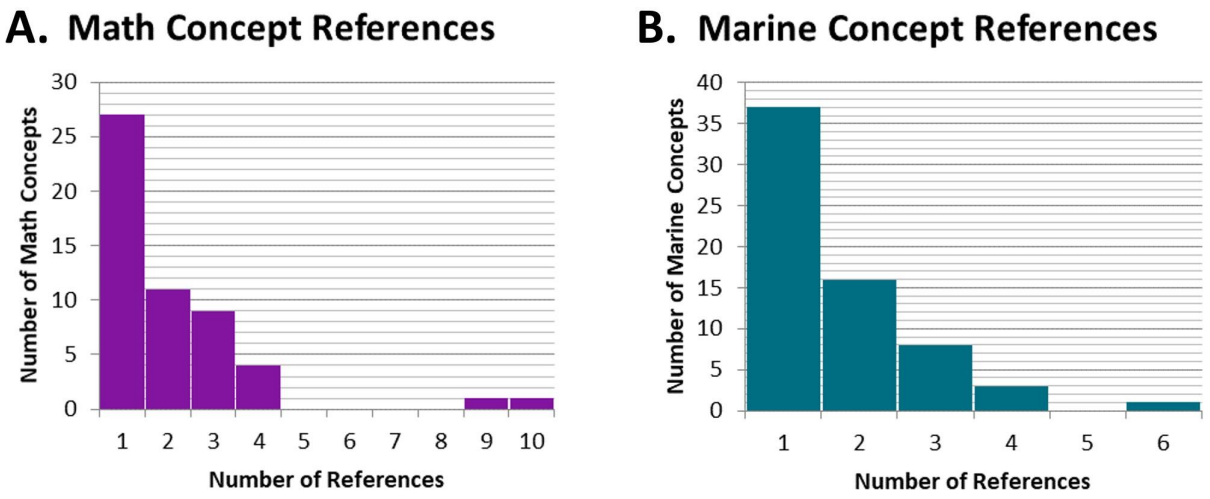

Figure 2. Histograms of the number of (A) math and (B) marine concepts referenced a given number of times during the Marine Biology course. In both cases, the majority of concepts were only referenced once (27 for math and 37 for marine) and frequency tapers off with only a select few concepts being referenced 4 or more times.

To gain insight from a student-centered perspective, we graphed the general flow of new and total math and marine concepts over the course of a semester (Figure 3). This shows that new concepts generally spike directly after an exam, then slowly taper down. The total number of concepts show a similar trend but with much more variation.

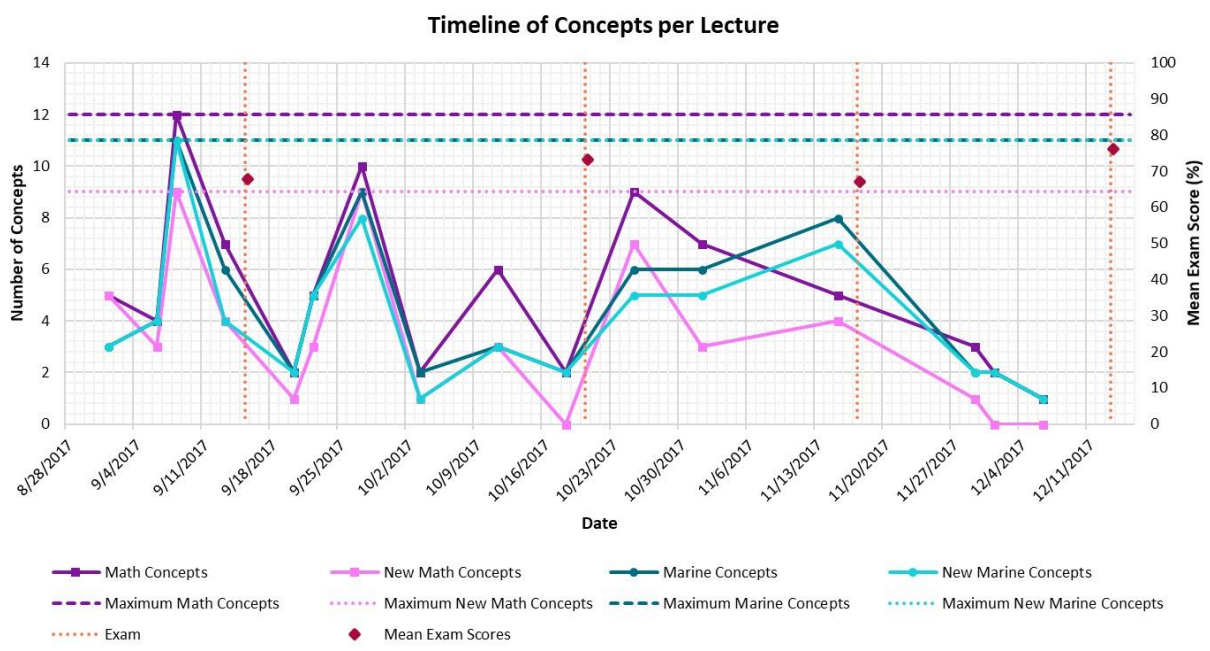

Figure 3. Timeline of Fall 2017 Marine Biology course with number of marine (teal/blue) and math (purple/pink) concepts covered per lecture along with how many were new vs. previously covered, maximum values, and exam dates (orange) and mean scores (red, as percentages).

We present this data as a cautionary tale for biology instructors who are wondering why their students have so much trouble with the mathematics in their classroom. In addition to issues of transference of mathematics out of the math classroom and into the marine biology classroom, we are expecting the transference of a wide array of mathematical concepts. In one semester of marine biology classroom lectures, we recorded 27 separate types of mathematics infused across 37 marine biology topics. Many of the topic areas were identified outside of the typical bounds for any one course or typical prerequisites. For example, vectors may be a topic relegated in some post-secondary curricula to be in Calculus III or perhaps in Physics I, and may or may not be part of program requirements or class prerequisites.

Supporting connections

By visualizing the interaction matrix between node types, we can better understand how topics support each other. In ecological networks, nested viswebs are used to examine nestedness (Bascompte and Jordano, 2007). In a highly nested network, all color in Figure 4A would be concentrated in the upper left corner and all or almost all ‘specialist’ concepts would only interact with ‘generalists’. If the web were highly nested, there would be a small number of ‘generalist’ concepts that could be easily focused on to increase interdisciplinary understanding. Our case study data were poorly nested: the interacting topics are highly dispersed, meaning that many specialist mathematical topics are scattered throughout many marine topics, a point also made above.

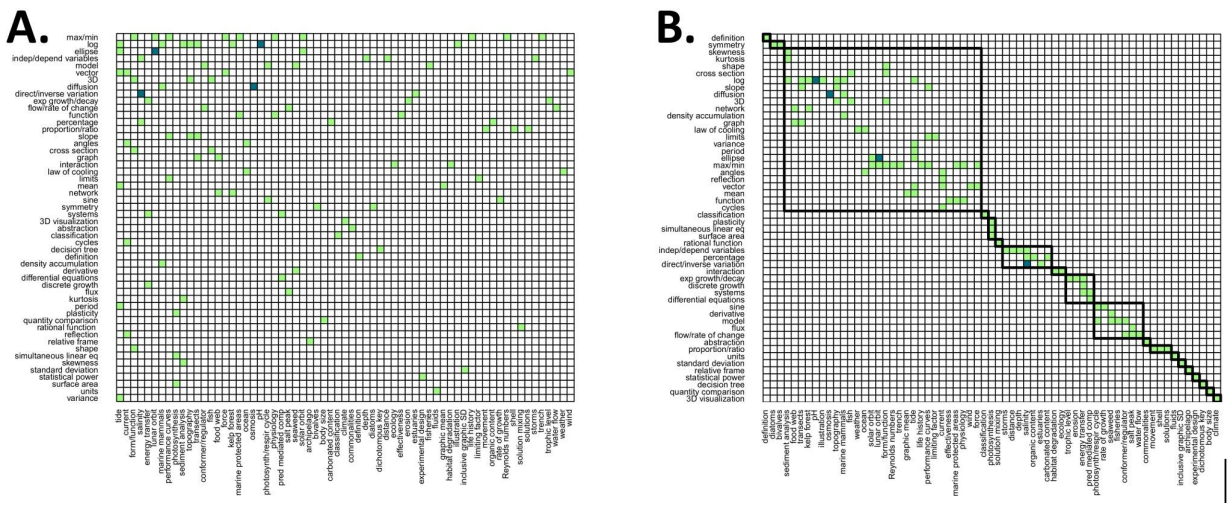

Figure 4. Grid plots of math-marine concept network produced via ‘visweb’. White squares indicate a co-occurrence count of 0, light green indicates 1, and dark teal indicates 2, which was the highest observed. There are only four pairs with an edge size of two: ellipses and [planetary/lunar] orbits; salinity and direct/indirect variation; diffusion and osmosis; and log and pH. A is plotted with ‘type=”nested”’ which sorts nodes by row and column sums, allowing for

assessment of nestedness and concept connectedness. B is plotted with ‘type=”diagonal”’ which plots the highest number of interactions along the diagonal and identifies compartments.

The compartment clustering approach in Figure 4B helps identify possible directions for an interdisciplinary module of mathematical and marine biology concepts. For example, we might create a module combining dependent/independent variables, percentages, and direct/indirect variation math concepts with solution mixing, distance, depth, and salinity. Conceptualizing the collaborative education space as a mutualistic bipartite network leads us to possible emergent directions for interdisciplinary curriculum development.

Figure 4 also indicates a relatively sparse interaction matrix. Connectance is the number of connections observed out of the number possible (Jordano, 1987) and in our case is 3.14%. While we do not know the connectance between mathematics and biology as fields, typical plant-pollinator networks average 30% connectance (Jordano, 1987). We know our sampling method falls short of seeing all connections. For example, for example it may change simply by including the laboratory component in the analysis or include multiple courses in the analysis. However, a truly co-evolving and interdisciplinary educational landscape might have on the order of ten times the references to mathematical topics. Even if we are not sure what a target connectance value should be, we could use it as a metric for measuring and tracking our success in reaching interdisciplinary teaching. One caveat is that there is likely an optimal connectance value for any mutualistic network - more edges does not necessarily mean more network stability and larger networks have smaller connectance values (Jordano, 1987).

We can also look for disciplinary ways to support interdisciplinary teaching. In Figure 5, we introduce a competition plot, which examines nestedness with more of a concept-focus rather than a webwide-focus. This makes it useful for considering novel ways of approaching the ‘lower’ level with the specific goal of enhancing understanding of the ‘upper’ level. The network graph in Figure 1 indicates that maximums/minimums and log are vital math concepts for marine biology. However, the competition plot tells us that if we want to teach about maximum and minimums in a holistic manner with the goal of supporting and integrating with marine biology, we could support the teaching of ellipses and vectors. Ellipses, surprisingly, are not part of all precalculus courses and vectors are largely covered in the physics curriculum, so this could direct additional disciplinary conversations within mathematics. In contrast to maximum and minimums, proportions and ratios is another relatively large node, but it is entirely self-contained. It has no clustering to other math concepts through a common marine concept.

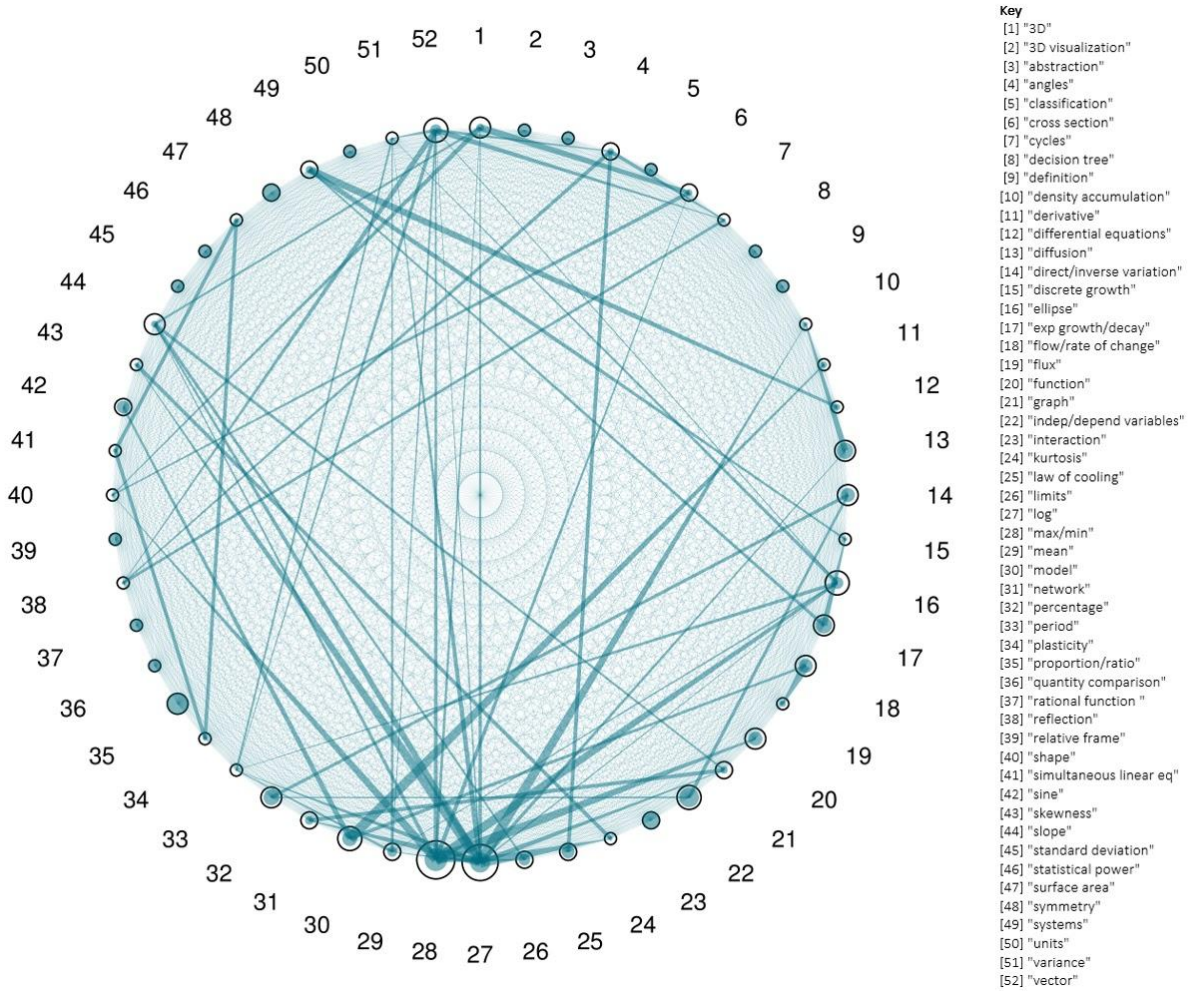

Figure 5. Competition plot with key of math (‘lower’ level) concepts produced via ‘plotPAC’.Black circles are nodes. The amount of teal fill in each circle indicates level of ‘specialization’. Teal lines indicate connections between nodes through marine (‘higher’ level) concepts.

DISCUSSION

Many of the limitations of this methodology are the same as limitations for other observing ecological bipartite networks. The way we sampled our interaction network matters (Gibson et al., 2011). A more complete web of interactions would be had, for example, if we observed every marine biology class in the curriculum or across institutions. In addition, the time at which you inventory a network matters. However, this can be viewed also as a strength of this approach. This framework understands interdisciplinary teaching practice as complex and adaptive and facilitates new approaches to explore how instructor practice might change over time as a result of interventions, conversations, and other experiences.

A limitation potentially more unique to the interdisciplinary context is the ability to code the qualitative data. Recognizing when a mathematics reference has occurred in the biology classroom may be more nuanced than identifying when a plant has been visited by a pollinator. It may take some familiarity with the language across disciplines (Redish & Kou, 2015). We recommend further studies that explore the interrater reliability of this coding, particularly as it relates to disciplinary training and grounding.

Despite the limitations, our exploration of marine biology education and mathematics education as a mutualistic coevolutionary system yielded productive insights about supporting interdisciplinary teaching. Teaching practice experience may be affected by different individual interventional strategies (Henderson et al., 2011). We found two key ways that significant math was infused into this class: 1) prescribed: use of guest lectures/pre-developed resources and 2) emergent: through marine topics that were close to the instructor's area of research, training, and/or comfortability (Henderson et al., 2011). We also found that there are significant challenges marine biology instructors and students may face inherently associated with the structure of mutualistic networks i.e. heterogeneity. The variety of mathematics topics making one-time appearances in a course may make it difficult for marine biology instructors to fully prepare students for all mathematical skills necessary.

Theorizing partner disciplines as mutualistic coevolvers also helped identify ways to capture emergent points for potential intervention (Henderson et al., 2011). We were able to discern some potential areas for interdisciplinary curriculum development, both ideas for modules as well as ideas for new partner disciplines as well as identify disciplinary support opportunities. Finally, network indices, like connectance, may be helpful in evaluating the development of interdisciplinary teaching practice over time or across course networks. These opportunities fully embrace the complex adaptive nature of the mutualistic system between mathematics and biology.

ACKNOWLEDGEMENTS

This study is supported by a subaward through NSF IUSE #1625771 and #1822451, Bates College, and the William and Flora Hewlett Foundation. IRB approval UCIRB 2017-02. We thank the work of and conversations with subaward co-investigators, Dr. Perry and Dr. Wade, Unity College faculty and students, and the full SUMMIT-P collaboration team.

REFERENCES

American Association for the Advancement of Science [AAAS]. (2011). Vision and change in undergraduate biology education: a call to action. American Association for the Advancement of Science, Washington, DC. *visionandchange.org/finalreport*.

Andrews, T. C., Conaway, E. P., Zhao, J., & Dolan, E. L. (2016). Colleagues as change agents: How department networks and opinion leaders influence teaching at a single research university. *CBE-Life Sciences Education*, *15*(2), ar15.

Aviv, R., Erlich, Z., Ravid, G. and Geva, A., 2003. Network analysis of knowledge construction in asynchronous learning networks. *Journal of Asynchronous Learning Networks*, *7*(3), pp.1-23.

Bakkenes, I., De Brabander, C. and Imants, J., 1999. Teacher isolation and communication network analysis in primary schools. *Educational Administration Quarterly*, *35*(2), pp.166-202.

Baron, J.S., Specht, A., Garnier, E., Bishop, P., Campbell, C.A., Davis, F.W., Fady, B., Field, D., Gross, L.J., Guru, S.M. and Halpern, B.S., 2017. Synthesis Centers as Critical Research Infrastructure. BioScience, 67(8), pp.750-759.

Bascompte, J., & Jordano, P. (2007). Plant-animal mutualistic networks: the architecture of biodiversity. Annu. Rev. Ecol. Evol. Syst., 38, 567-593.

Bishop, P. R., Huck, S. W., Ownley, B. H., Richards, J. K., & Skolits, G. J. (2014). Impacts of an interdisciplinary research center on participant publication and collaboration patterns: A case study of the National Institute for Mathematical and Biological Synthesis. *Research Evaluation*, *23*(4), 327-340.

Brewe E, Kramer L, Sawtelle V (2012). Investigating student communities with network analysis of interactions in a physics learning center. Phys Rev Spec Top Phys Educ Res 8, 010101.

Buchenroth-Martin, C., DiMartino, T., & Martin, A. P. (2017). Measuring student interactions using networks: Insights into the learning community of a large active learning course. *Journal of College Science Teaching*, *46*(3), 90.

Christakis NA, Fowler JH (2013). Social contagion theory: examining dynamic social networks and human behavior. Stat Med 32, 556-577.

Diaz Eaton, C., & Wade, S. (2014). Collaborative learning through formative peer review with technology. *PRIMUS*, *24*(6), 529-543.

Diaz Eaton, C., & Highlander, H. C. (2017). The Case for Biocalculus: Design, Retention, and Student Performance. *CBE-Life Sciences Education*, *16*(2), ar25.

Raina Robeva, Timothy D. Comar & Carrie Diaz Eaton (2022) Can We Bridge the Gap? Mathematics and the Life Sciences, Part 1 – *Calculus-Based Modules, Programs, Curricula*, PRIMUS, 32:2, 117-123.

Weisstein, A. E. (2011). Building mathematical models and biological insight in an introductory biology course. *Mathematical Modelling of Natural Phenomena*, *6*(6), 198–214.

Acevedo, M. A. (2020). Teaching quantitative ecology online: An evidence‐based prescription of best practices. *Ecology and Evolution*, *10*(22), 12457–12464.

Diaz EatonC., LaMarM. D., & McCarthyM. (2020). 21st Century Reform Efforts in Undergraduate Quantitative Biology Education. *Letters in Biomathematics*, *7*(1), 55–66.

Akman, O., Eaton, C. D., Hrozencik, D., Jenkins, K. P., & Thompson, K. V. (2020). Building Community-Based Approaches to Systemic Reform in Mathematical Biology Education. *Bulletin of Mathematical Biology*, *82*(8).

Redish, E. F., & Kuo, E. (2015). Language of Physics, Language of Math: Disciplinary Culture and Dynamic Epistemology. *Science & Education*, *24*(5–6), 561–590.

C. Diaz Eaton, H. C. Highlander, K. D. Dahlquist, G. Ledder, M. D. LaMar & R.C. Schugart (2019) A “Rule-of-Five” Framework for Models and Modeling to Unify Mathematicians and Biologists and Improve Student Learning, PRIMUS, 29:8, 799-829.

Beisiegel, Mary D.R. and Dorée, Suzanne I. (2020) "Curricular Change in Institutional Context: A Profile of the SUMMIT-P Institutions," *Journal of Mathematics and Science: Collaborative Explorations*: Vol. 16 : No. 1 , Article 17.

Dou, R., Brewe, E., Zwolak, J. P., Potvin, G., Williams, E. A., & Kramer, L. H. (2016). Beyond performance metrics: Examining a decrease in students’ physics self-efficacy through a social networks lens. *Physical Review Physics Education Research*, *12*(2), 020124.

Dormann, C.F., Gruber B. & Fruend, J. (2008). Introducing the bipartite Package: Analysing Ecological Networks. R news Vol 8/2, 8 - 11.

Gibson, R. H., Knott, B., Eberlein, T., & Memmott, J. (2011). Sampling method influences the structure of plant–pollinator networks. *Oikos*, *120*(6), 822-831.

Grunspan, D. Z., Wiggins, B. L., & Goodreau, S. M. (2014). Understanding classrooms through social network analysis: A primer for social network analysis in education research. *CBE-Life Sciences Education*, *13*(2), 167-178.

Henderson, C., Beach, A., & Finkelstein, N. (2011). Facilitating change in undergraduate STEM instructional practices: An analytic review of the literature. *Journal of research in science teaching*, *48*(8), 952-984.

Ings, T.C., Montoya, J.M., Bascompte, J., Blüthgen, N., Brown, L., Dormann, C.F., Edwards, F., Figueroa, D., Jacob, U., Jones, J.I. and Lauridsen, R.B., 2009. Ecological networks–beyond food webs. *Journal of Animal Ecology*, *78*(1), pp.253-269.

Jesus, R., Schwartz, M., & Lehmann, S. (2009, October). Bipartite networks of Wikipedia's articles and authors: a meso-level approach. In *Proceedings of the 5th international symposium on Wikis and open collaboration* (p. 5). ACM.

Luke, D.A. (2015). Affiliation Networks. In: A User’s Guide to Network Analysis in R. Use R!. Springer, Cham.

Dormann, C. F., Gruber, B., & Fründ, J. (2008). Introducing the bipartite package: analysing ecological networks. *interaction*, *1*(0.2413793).

Dormann, C. F. (2020). Using bipartite to describe and plot two-mode networks in R. *R package version*, *4*, 1-28.

Saavedra, Serguei, Felix Reed-Tsochas, and Brian Uzzi. "A simple model of bipartite cooperation for ecological and organizational networks." *Nature* 457.7228 (2009): 463-466.

Jordano, P. (1987). Patterns of mutualistic interactions in pollination and seed dispersal: connectance, dependence asymmetries, and coevolution. *The American Naturalist*, *129*(5), 657-677.

Krywinski, M. *Color Palettes for Color Blindness.* Retrieved from http://mkweb.bcgsc.ca/colorblind/

Mansilla, V. B., Feller, I., & Gardner, H. (2006). Quality assessment in interdisciplinary research and education. *Research Evaluation*, *15*(1), 69-74.

Mansilla, V. B., & Duraising, E. D. (2007). Targeted assessment of students' interdisciplinary work: An empirically grounded framework proposed. *The Journal of Higher Education*, *78*(2), 215-237.

Oshima, J., Oshima, R. and Matsuzawa, Y., 2012. Knowledge Building Discourse Explorer: a social network analysis application for knowledge building discourse. *Educational technology research and development*, *60*(5), pp.903-921.

Palmer, C. L. (2013). *Work at the boundaries of science: Information and the interdisciplinary research process*. Springer Science & Business Media.

Proulx, S. R., Promislow, D. E., & Phillips, P. C. (2005). Network thinking in ecology and evolution. *Trends in ecology & evolution*, *20*(6), 345-353.

R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from https://www.R-project.org/.

Redish, E. F., & Kuo, E. (2015). Language of physics, language of math: Disciplinary culture and dynamic epistemology. *Science & Education*, *24*(5-6), 561-590.

Spelt, E. J., Biemans, H. J., Tobi, H., Luning, P. A., & Mulder, M. (2009). Teaching and learning in interdisciplinary higher education: A systematic review. *Educational Psychology Review*, *21*(4), 365.

Uzzi, B., Amaral, L. A., & Reed‐Tsochas, F. (2007). Small‐world networks and management science research: A review. *European Management Review*, *4*(2), 77-91.

Vázquez, D. P., Blüthgen, N., Cagnolo, L., & Chacoff, N. P. (2009). Uniting pattern and process in plant–animal mutualistic networks: a review. *Annals of botany*, *103*(9), 1445-1457.