1-1-2020

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Recommended Citation

Eaton, C.D, LaMar, D., and McCarthy, M. 2020. "21st century reform efforts in undergraduate quantitative biology education: Conversations, initiatives, and curriculum change in the United States of America." Letters in Biomathematics. 7(1), 55–66. https://doi.org/10.30707/LiB7.1.1647875326.082928.

LETTERS IN BIOMATHEMATICS
An International Journal

Intercollegiate Biomathematics Alliance

EDUCATION ARTICLE OPEN ACCESS

21st Century Reform Efforts in Undergraduate Quantitative Biology Education: Conversations, Initiatives, and Curriculum Change in the United States of America

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ABSTRACT

In the United States, there are multiple reports from both mathematics and biology communities that address the quantitative preparation of undergraduate life science students. Many of these reports make broad recommendations for the revision of life science curriculum to incorporate more quantitative techniques. Here, we review initiatives and progress in the United States on the state of quantitative biology education in the context of the mathematics education, biology research frontiers, and the funding system and other sources of support for systemic change to meet new demands.

ARTICLE HISTORY

Received August 15, 2019
Accepted February 28, 2020

KEYWORDS

mathematical biology, quantitative biology, education, review, initiative, overview

1 Introduction

With the advent of the technological revolution, the biological sciences have seen a drastic change in the tools and processes used to conduct scientific research. Massive amounts of data are being created in all areas of our lives, including biology, from the creation of high-throughput technologies that capture the state of gene expression in the cell to the creation and launching of satellites for geographic information systems. Technology has also allowed biologists to continuously discover, at an ever-increasing rate, the biochemical players involved in biological processes in our bodies. All of this has led the field of biology to recognize the importance of quantitative and computational approaches, for they include a myriad of tools to describe and quantify highly relevant areas including systems theory, quantitative modeling, and statistical inference.

While biological research has changed dramatically with the inclusion of more quantitative and computational approaches, the pressure on the education community has experienced a lag leading to insufficient progress. Traditional life science curricula in the US require calculus or statistics, but these courses are often taught without much regard for the applications that life scientists will encounter during their careers (AAAS, 2011). An embracing of interdisciplinarity between the two, incorporating quantitative skills directly into life science courses or life science topics into mathematics courses, has been recommended by many reports, which we review and summarize below. We also present a number of actions these reports have spurred to respond to these new education needs, the sources of support for these actions, and success of such actions. Lastly, we discuss emerging frontiers in quantitative biology education.

1.1 Reports

Many recent reports authored by United States-based funding agencies and professional societies have addressed the increased need for mathematics in biology education and the challenges of modifying our educational system to address the current and future research challenges (Table 1). The reports are focused to varying degrees on both research and education in the biological and mathematical sciences. A summary of their overarching ideas and recommendations follow:

- Biology majors must learn more concepts and obtain more skills in the **quantitative and computational sciences.**
- Quantitative and computational concepts should be **integrated** into the biology curriculum. This includes techniques beyond calculus and statistics, such as discrete mathematics, linear algebra, and mathematical modeling.

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Table 1: A table of influential reports in the United States from biology, mathematics, and interdisciplinary groups addressing education at the interface of mathematics and biology.

Report Title	Year
BIO2010: Transforming Undergraduate Education for Future Research Biologists	2003
The Curriculum Foundations Project: Voices of the partner disciplines	2004
A New Biology for the 21st Century	2009
Scientific Foundations for Future Physicians (SFFP)	2009
Vision and Change in Undergraduate Biology Education: a call to action (V&C)	2011
Engage to Excel – Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics	2012
The Mathematical Sciences in 2025	2013
Report from the Program Area Study Group (PASG) on Mathematical Biology	2015
A Common Vision for Undergraduate Mathematical Science Programs in 2025	2015
Guidelines for Assessment and Instruction in Statistics Education (GAISE) college report	2016
Guidelines for Assessment and Instruction in Mathematical modeling Education (GAIMME)	2019
NSF's 10 Big Ideas	2019d
Data Science for Undergraduates: Opportunities and Options	2018

- Instructors need **professional development programs and support**. These programs would include new ways of teaching that incorporate **evidence-based pedagogies,** such as more student-centered and active learning, and relevant content needed to make interdisciplinary shifts.
- Faculty from different disciplines should be encouraged and rewarded for working together in both research and education and for participating in professional development programs. This would require **institutional change** for successful implementation.

In one of the earlier reports in 2003, BIO2010 gave very specific recommendations on quantitative content to include in the training of biology majors, including specific topics in the aggregate categories of calculus, linear algebra, dynamical systems, discrete mathematics, probability and statistics, and computation, among others (National Research Council, 2003). Another widely discussed report was the Vision & Change report in 2011, which gave specific biological concepts and competencies for biology majors (AAAS, 2011). Many of these core competencies are highly quantitative and interdisciplinary in nature, including (1) the development of quantitative reasoning, (2) the ability to partake in the modeling and simulation enterprise, and (3) the recognition of the interdisciplinary nature of science. These core competencies also address one of the Vision & Change report's core concepts: that life is complex and interconnected, thus requiring a deep understanding of the emergent properties of systems (AAAS, 2011).

Many of these concerns and recommendations are echoed in the mathematical community. For example, the Common Vision report from 2015 stresses the importance of gaining skills in handling the deluge of data coming from many sources, therefore emphasizing the importance of taking an interdisciplinary approach to teaching statistics and data analysis (Saxe et al., 2015). The first edition of the GAIMME report from 2016 gives educational guidelines for introducing mathematical modeling early in the undergraduate curriculum, both as a standalone modeling course as well as infused into curricula in other departments (Garfunkel and Montgomery, 2019, 2nd ed.).

These reports have influenced funding towards programs designed to better advance mathematical biology (the mathematics side of this interface) and quantitative biology (the biology side of this interface). However, progress has been slow on the part of both mathematicians and biologists. On the mathematics side, we are historically unused to serving discipline needs other than engineering, physics, and mathematics. For example, statistics, whose useful reputation is established firmly in biology, is not often considered the domain of mathematics researchers. Applications commonly used in calculus instruction are almost exclusively geared towards engineering and physics. Therefore, curriculum development has been a focus of much of the mathematics community working at the interface of math and biology education over the last two decades (Ledder et al., 2013). On the biology side, some barriers include instructor time and confidence, knowledge in how to best integrate mathematics throughout the biology curriculum to further support the work of foundational mathematics courses, and support for instructors that are adopting cutting-edge curriculum (Donovan et al., 2015). As mathematics educators continue to deepen their collaborations with the life science educators, they are shaping a new field in quantitative biology education. This field has challenges because it encompasses three domains: mathematics/statistics, education, and biology. In addition, biology is so broad that each sub-discipline has their own unique needs. Each implementation of quantitative instruction is unique to the biology sub-discipline, the life science department, and the college/university context.

Knowledge and training in these multiple disciplines is one challenge, but another challenge is in communicating the relevant work being done across multiple disciplines across the United States and the world. Therefore, technology and social networks are being harnessed towards collective action to synthesize knowledge, combine resources, and move forward (Diaz Eaton et al., 2016). Below, we review some of the communities and activities that have been created to address these challenges discussed here and in the reports.

2 Review of Selected Important Efforts and Progress

To address the many quantitative education needs of biology programs, a variety of efforts are in motion. We have attempted to classify these efforts in quantitative biology education as (1) communities of practice, (2) institutions or centers, (3) curriculum development, and (4) assessment, though some initiatives overlap in more than one area. Our list contains networks which are either exclusively devoted to conversations and initiatives at the interface of math biology education or have been leading the largest such initiatives in the United States. The purpose of sharing this list is to provide readers with organizations and people to connect with and resources to utilize.

2.1 Communities of Practice: Societies, Networks, Institutes and Centers

The basis of many national initiatives is a professional society or other network of practitioners. This is extremely important as instructors implementing curricular change need the support of their peers as well as the acknowledgement of their professional community (Donovan et al., 2015). While colleges, universities, grant-funded or non-profit centers, networks, and institutes support activities, professional societies offer sustained support for long-term, national-level change, regular meeting opportunities to share educational experiments and results, professional development activities and recognition, and publishing opportunities. The definition of a network used here is a collection of individuals, institutions, or societies, that is not necessarily based on individual membership fees or dues (Diaz Eaton et al., 2016). However, these networks may have similar offerings to professional societies.

In Table 2, we have listed selected national level societies, networks, institutes, and centers that are playing a foundational role in coordinating and supporting education at the interface of mathematics and biology in the United States. To the best of our knowledge, this represents a list of the most active and influential communities of practice at the interface of undergraduate mathematics, biology, and education, with some caveats noted below. In the table, websites are provided for more information and a few exemplar models are discussed in additional detail below.

2.1.1 PSALSE: Professional Society Alliance for Life Science Education

PSALSE is an effort to bring together life science professional societies around issues in education, and includes 26 of these societies and networks as members (Matyas et al., 2017a,b) and was born soon after the release of the Vision and Change report (AAAS, 2011). One of the challenges of coordinating quantitative biology education amongst biology societies is the huge proliferation of biology societies based within various sub-disciplinary niches. By one count, there are nearly 300 biology societies (and Table 2 certainly neglects to list them all). PSALSE coordinates a blog, meetings, and a listserv. Via the listserv, members routinely recruit help for education initiatives, including quantitative initiatives, which helps societies collaborate and leverage resources more easily. To foster inclusion of the mathematics community, BIO SIGMAA and QUBES (see Table 2) are represented in PSALSE by their mathematics liaisons. One example of collaboration is the use of the listserv to recruit a biology speaker to give a talk at a mathematics event. Another is that collaborative ventures are often open to the whole listserv, thereby also inviting the mathematics community representatives. A review of the impacts and progress of PSALSE is found by Matyas et al. (2017b), which found that in the "Vision and Change era" professional societies have significantly invested in undergraduate life science education.

2.1.2 QUBES: Quantitative Undergraduate Biology Education and Synthesis

QUBES (`qubeshub.org`) is a network and virtual center which supports faculty teaching at the interface of mathematics and biology (Donovan et al., 2015). Its community-oriented goals are to coordinate activities to better leverage resources and exper-

Table 2: A table of some national communities of practice supporting education at the interface of mathematics and biology.

Name	Type	Website
Biology Special Interest Group of the Mathematical Association of America (BIO SIGMAA)	Interest Group within a Professional Society	qubeshub.org/groups/biosigmaa
BioInteractive, Howard Hughes Medical Institute	Network within Institute	qubeshub.org/groups/hhmibiointeractive
BioQUEST Curriculum Consortium	Network	bioquest.org
Intercollegiate Biomathematics Alliance (IBA)	Network of Colleges and Universities	biomathalliance.org
Mathematical Biosciences Institute (MBI)	Institute	mbi.osu.edu
National Ecological Observatory Network (NEON)	Network of Observatory Centers	www.neonscience.org
National Institute for Mathematical and Biology Synthesis (NIMBioS)	Center	www.nimbios.org
Professional Society Alliance for Life Science Education (PSALSE)	Network of Professional Societies	psalse.wordpress.com
Quantitative Undergraduate Biology Education and Synthesis (QUBES)	Network and Virtual Center	qubeshub.org
Society for Mathematical Biology (SMB)	Professional Society	www.smb.org

tise and to find ways to reward faculty for pursuing an evidence-based and interdisciplinary approach to their teaching. QUBES also collaborates with over 75 Consortium collaborators and partners, such as those listed in Table 2, including BioQUEST and a number of smaller quantitative biology education projects. While the major reports mentioned above (National Research Council, 2003; AAAS, 2011) make recommendations for what the undergraduate curriculum should look like, widespread implementation of these recommendations has been the greatest challenge. QUBES targets this gap explicitly and, like PSALSE, focuses on working with a network to implement evidence-based curricular change.

Its activities include connecting biology and mathematics educators, creating peer faculty mentoring networks to support biology faculty through the awareness, adoption, adaptation, and implementation of quantitative biology materials, providing ways to access and share teaching resources online, and creating awareness among the mathematics community about the quantitative needs for biology education (Donovan et al., 2015). This is facilitated by its cyberinfrastructure (qubeshub.org), which allows for activities to occur without disciplinary or geographic boundaries. This virtual nature also makes it available for international collaboration. QUBES is funded by a number of National Science Foundation (NSF) grants. The NSF's education division has a program called Innovation in Undergraduate STEM Education (IUSE) and QUBES was the largest IUSE grant recipient as of 2017 ($3.3 million – collaborative proposals DUE 1446269, DUE 1446258, and DUE 1446284) (NSF, 2019b).

2.1.3 IBA: Intercollegiate Biomathematics Alliance

The mission of IBA is to foster collaboration across colleges and universities to provide shared brain trust, curricular, and computing resources, particularly for undergraduate student development and research (IBA, 2019). Like QUBES, IBA focuses on the implementation gap, but works as a network of colleges to foster opportunities for student and faculty research. IBA sponsors an annual conference, the International Symposium of Biomathematics and Ecology Education and Research, whose locations rotate throughout the United States and occasionally abroad. IBA also sponsors two journals: *Spora*—a student-driven mathematical biology research journal—and *Letters in Biomathematics*, which also accepts educational work. Alliance students and faculty can also participate in an early summer research conference in which faculty from all institutions showcase undergraduate research opportunities where students can pick a mentor for the summer. Therefore, students may be actively co-advised by faculty at multiple universities allowing them access to expertise and opportunities their own institution may not have. Membership in IBA is fee-based and tiered by school size, with Alliance member institutions gaining access to online, synchronous mathematical biology and statistics courses, a cloud computing cluster, publication discounts, and meeting travel support. These initiatives are promising avenues for institutions with limited resources or expertise. The virtual nature of this network also allows access to those beyond geographic proximity.

2.2 Institutes and Centers

As mentioned above, centers and institutes often support educational activities through in-house organized programs, such as public lecture series and summer research experiences for undergraduates, which are described in more detail below. The difference between a center and an institute in classification is primarily a semantic differentiation due to funding mechanism. However, some institutes and centers engage in education as part of their primary core mission. We offer some examples of such activities below.

2.2.1 MBI: Mathematical Biosciences Institute

MBI (2019) is an NSF-funded mathematics institute that opened in 2002 with the goal of furthering research in mathematical biology. They run year-long programs on specific themes in mathematical biology. With components such as postdoctoral training, graduate and undergraduate summer research programs and sabbatical programs, they emphasize traditional forms of training programs. Additionally, their Visiting Lecturer Program provides support for speakers to visit institutions that have large numbers of undergraduate students who are members of groups that are under-represented in the mathematical sciences community. MBI also provides workshops organized by interdisciplinary experts in alignment with the theme and open to all researchers by application, including postdoctoral students and graduate students. They also hold a Young Investigators Symposium, where senior graduate students and postdoctoral students can share research and learn about a variety of career paths, as well as an undergraduate research conference. In recent years, they have expanded their invited lecture series from in-person public to online streaming, so that participants from all over the world can join in the conversation.

2.2.2 NIMBioS: National Institute for Mathematical Biology and Synthesis

Since its inception in 2009, NIMBioS has engaged in programming to advance cross-disciplinary collaboration and research in mathematics and biology (Bishop et al., 2014). However, NIMBioS also has a dedicated Associate Director for Diversity Enhancement as well as an Associate Director for Outreach and Education. In addition, NIMBioS employs a full-time outreach and education coordinator staff position. They offer a suite of typical outreach and education activities such as undergraduate summer research opportunities, graduate assistantships, postdoctoral training opportunities and online tutorials for graduate students and faculty in mathematical biology. Like MBI, they also host a student research conference. However, the institute has expanded its education and outreach portfolio beyond these traditional activities. NIMBioS participates in local school outreach through their Biology-in-a-Box program, hosts tutorials in education, invites working group applications for educational research, and involves secondary school teachers in their summer undergraduate research program. They have also opened their research group funds to quantitative biology research projects. Their new associated evaluation center, the National Institute for STEM Evaluation and Research (NISER), also provides evaluation services for STEM projects, working extensively on STEM education projects. Although NIMBioS was funded as an NSF synthesis center, it provides an excellent example of how large institutions can go beyond traditional realms of outreach to affect education and diversity.

2.2.3 REU: Research Experiences for Undergraduates

REU programs are summer research experiences open to undergraduate students generally between their 3rd and 4th year of university. For example, in 2017, interdisciplinary offerings in mathematical biology, computational biology and bioinformatics included programs at MBI, Arizona State University, Auburn University, Boise State University, Boston College, Boston University, CUNY Herbert H. Lehman College, Clemson University, Cold Spring Harbor Laboratory, College of Charleston, Florida Institute of Technology, Georgetown University, and Indiana University (NSF, 2019a). REUs are not the only support option for summer research, but it is a well-known and long-established program supported by the NSF. REUs and other analogous programs, such as the Summer Research Experience program at NIMBioS, offer funding from private sources that can be made available to non-US citizens. Furthermore, the aforementioned MBI and NIMBioS both run undergraduate research conferences open to all undergraduates doing research in mathematical biology, often targeting these students specifically; MBI holds their conference at the end of their summer REU, while NIMBioS holds theirs in mid-autumn.

There is a great deal of evidence that undergraduate research opportunities benefit students enormously (Osborn and Karukstis, 2009). NIMBioS found that its mathematical biology summer research experiences enhanced their participants' feelings of self-efficacy in all tasks related to mathematical biology research, but most notably students felt more able to work collaboratively with other researchers and felt that they had learned more about the "nature of interdisciplinary research collaborations" (Duncan et al., 2010). This highlights the importance of all arenas, including mathematics, biology, and education, in helping students navigate the multidisciplinary challenges facing biology.

Table 3: A table of curriculum development and assessment projects at the interface of mathematics and biology. This is not a full listing, but it represents a sampling of different types of projects.

Name	Type	Reference
Biodiversity Literacy in Undergraduate Education (BLUE)	Curriculum Development	www.biodiversityliteracy.com
Interdisciplinary Training for Undergraduates in Biological and Mathematical Sciences (UBM)	Curriculum Development	www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf08510&org=NSF
A National Consortium for Synergistic Undergraduate Mathematics via Multi-institutional Interdisciplinary Teaching Partnerships (SUMMIT-P)	Curriculum Development	www.summit-p.com
Network for Integrating Bioinformatics in Life Science Education (NIBLSE)	Curriculum Development	niblse.qubeshub.org (Dinsdale et al., 2015)
HHMI BioInteractive – Statistics & Math	Curriculum Development	www.hhmi.org/biointeractive/statistics-and-math
iDigBio	Curriculum Development	www.idigbio.org
BioCalculus Assessment (BCA)	Assessment	Taylor et al., 2020
Biology Science Quantitative Reasoning Exam (BioSQuaRE)	Assessment	www.macalester.edu/hhmi/biosquare
Math Biology Values Instrument (MBVI)	Assessment	Andrews et al., 2017
Biology Undergraduate Mathematics Attitudes and Anxiety Program (BioMAAP)	Curriculum Development	biomaap.qubeshub.org

2.3 Curriculum Development

Curriculum development has been one of the earlier funding targets of the NSF when it began investing in quantitative biology education. As the research fields in biology were driven by breakthroughs in computing, data science, and modeling, education programs were set up specifically to train the next generation of mathematical biology researchers. Now, biology programs are recognizing that all students need quantitative and data literacy skills to make sense of the new landscape of biology (National Research Council, 2003; AAAS, 2011; AAMC-HHMI, 2009). At the same time, the role of mathematics as a college graduation requirement has shifted. Historically, it was positioned as part of a liberal arts training, but due to the aforementioned reports, such as the PCAST report (PCAST, 2012) and Vision and Change (AAAS, 2011), it has shifted to mathematics with utilitarian aims—a service in the mission of the new information literacy landscape. As a result, funded education efforts have expanded beyond purely interdisciplinary training programs and into foundational undergraduate mathematics courses. Some of this shift from a biological science point of view is recounted in the updated Vision and Change report: *Chronicling change, inspiring the future* (AAAS, 2015).

In Table 3, we list some selected curriculum development and assessment initiatives which are either highly influential or currently active and represent promising avenues for future research. Below, we examine a few of these initiatives in detail.

2.3.1 UBM: Interdisciplinary Training for Undergraduates in Biological and Mathematical Sciences

From 2004 to 2011, the National Science Foundation supported the Interdisciplinary Training for Undergraduates in Biological and Mathematical Sciences (UBM) (NSF, 2019c). This highly successful program focused on undergraduate education at the intersection of the biological and mathematical sciences. One goal was to improve preparation of undergraduate biology and mathematics students for interdisciplinary graduate study and careers. Programs included long-term research experiences for interdisciplinary balanced cohorts of at least four undergraduates. Universities funded under this program included primarily undergraduate institutions such as Truman State University, SUNY Geneseo, Jackson State University and Murray State University, and research institutions such as University of California Davis, and the Washington State University–University of

Idaho collaboration (NSF, 2019a). At these institutions, activities included the development of mathematical biology majors and minors and many interdisciplinary courses in mathematical biology. The UBM funding had a substantial impact on driving forward mathematical biology education in the United States. Unfortunately, the program was discontinued in 2011 due to its high cost per student. Since then, some UBM programs have continued to teach the mathematical biology curriculum (e.g. William & Mary, Harvey Mudd College) and/or conduct undergraduate research in the absence of funding (e.g. Truman State University, Murray State University).

Not all of these transformative curricular initiatives started by NSF funds have sustained beyond the funding allotment. A recent trend in funding review emphasis is two pronged: (1) significant research on efficacy of the model proposed accompanied by rigorous evaluation and (2) attention to sustainability beyond the length of the grant. Research is one traditional way to demand products out of funding which can be shared. Assessment and evaluation of efficacy can help make the case to institutions about why such programs should be funded beyond the length of the grant, a flaw of many UBM programs. Some programs are also looking to workforce partners to address sustainability, which also matches a recent emphasis on workforce development (NSF, 2019a). However, whether these context-specific curricular solutions can be transferred and adopted to other institutions remains a challenge (Donovan et al., 2015).

2.3.2 SUMMIT-P: A National Consortium for Synergistic Undergraduate Mathematics via Multi-institutional Interdisciplinary Teaching Partnerships

SUMMIT-P is a network of 11 colleges and universities transforming their foundational math courses with the needs of partner disciplines in mind and driven by the CRAFTY partner disciplines report (Ganter and Barker, 2004; SUMMIT-P, 2019; Ganter et al., 2019). Each college and university has their own unique set of target math courses and partner disciplines, but within this network, there is a cluster devoted to projects which encompasses life science partner disciplines. In this model, curriculum development is coupled with a network so that information about developing or reforming mathematics courses with partner disciplines in mind can be shared across the entire network. In addition, there is a concurrent meta-study of the participating institutions to determine student impacts and instructor and institution impacts on implementation. This represents a shift in the interdisciplinary mathematics curriculum development from the approach under the UBM grants to development and implementation informed by education research, which represents a shift in National Science Foundation funding priorities and the post-secondary STEM education landscape. It also attempts to address the context-dependent implementation issue, to look instead at the level of methodologies for interdisciplinary collaboration that can be replicated successfully. A special issue of the *Journal of Science and Mathematics: Collaborative Explorations* is scheduled to be published in 2020 and will include case studies from several of these colleges and universities.

2.3.3 Algebraic Methods & Discrete Mathematics in Biology

When comparing quantitative biology curricula around the mathematical tools used, it becomes clear the numbers are heavily skewed towards statistics or calculus based materials, such as dynamic modeling using differential equations, discrete maps, and dynamical systems. One gap in educational materials is in the fields of discrete mathematics and abstract algebra, including techniques in network theory and algebraic topology. To address this gap, a group of educators has been developing curricula around discrete and algebraic mathematics methods in biology, covering topics such as Boolean network modeling, graph theory, knot theory, polynomial dynamical systems, discrete-time and stochastic modeling, and petri nets, to name a few (Robeva and Hodge, 2013; Robeva, 2015; Kondrashov, 2016). The community remains active through tutorials and workshops—for example the NIMBioS tutorial "Algebraic and Discrete Biological Models for Undergraduate Courses" (`www.nimbios.org/tutorials/TT_mathbio`) in 2014 and the NIMBioS Investigative Workshop "Algebraic Mathematical Biology" (`www.nimbios.org/workshops/WS_mathbio`) in 2016.

2.4 Assessment Projects

In part, due to the aforementioned shift in the postsecondary educational landscape towards researching evidence-based educational strategies, the major challenge has been to document student outcome changes. Most assessment tools are designed within mathematics education or biology education disciplines, but not between them. Assessment tools in undergraduate mathematics often focus on the ability to perform mathematical operations and in some cases, conceptual mathematics attainment. However, interdisciplinarity requires the transfer of quantitative skill sets to novel biological contexts. In addition, quantitative biology education researchers seek to understand barriers to learning mathematics which encompass motivation for and attitudes towards learning mathematics. Therefore, there is a movement toward the creation of mathematical assessments specifically for biology students that addresses their needs.

2.4.1 BCA: BioCalculus Assessment

The BCA is an assessment tool designed to assess students' calculus skills in a biology context (Taylor et al., 2020). It was initially designed for use in assessing foundational mathematics courses in which include interpreting graphs, rates of change and calculus topics designed for life science majors commonly a part of biocalculus courses such as those at the University of Tennessee (e.g. Bodine et al., 2014). The BCA is available for use by contacting Suzanne Lenhart (Taylor et al., 2020). This work at the University of Tennessee and NIMBioS is funded by an NSF Early-concept Grants for Exploratory Research (NSF, 2019a). Projects funded under this mechanism are expected to use new, interdisciplinary frameworks to address important questions. While this project is inspired by other concept inventories in STEM, such as the force concept inventory (Hestenes et al., 1992) or the calculus concept inventory (Epstein, 2007), it aims to again place the knowledge in a life science context, primarily related to medicine or ecology.

2.4.2 Mathematics Attitudes and Anxiety

Another area of particular interest is how biology students may be different from other STEM students in terms of their attitudes towards mathematics. BIOMAAP is an NSF IUSE grant to create curriculum modules for instructors of biology students that incorporate biofeedback and metacognitive activities in order to help reduce student anxiety and improve attitudes (BIOMAAP, 2019). In addition, there are efforts by researchers like Melissa Aikens to adapt and develop assessment instruments specifically to assess biology students' attitudes and perceptions of mathematics. Aikens's work uses a utility-value versus cost framework (Andrews et al., 2017), which suggests that adding a biological context to the mathematics adds value to learning the mathematics, thereby balancing the cost of learning mathematics. A recent study of biocalculus also used this framework as the basis for understanding educational gains (Diaz Eaton and Highlander, 2017).

3 Emerging Frontiers and Challenges

3.1 Data Science in a Biology Context

As mentioned above, statistics is not always considered the purview of mathematics departments in the United States. In many large schools, statistics departments are in schools separate from both mathematics and the life sciences, for example in schools of business or education. Therefore, the recent interest in "data science" provides a unique and compelling reason for mathematicians to reconnect with statistics. Data science, by some definitions, is an intertwining of computer science, mathematical modeling, and statistics in the context of a real problem with complex data (NASEM, 2018). While there are a multitude of generalist data science educational providers like DataCamp and DataONE, they lack the biological context component. However, progress has been made by more interdisciplinary groups. Data science in biology could describe some already well-defined subfields in biology, such as bioinformatics or epidemiology. An example of a curriculum project in bioinformatics which seeks to identify learning outcomes for bioinformatics and to develop materials to meet those outcomes is the Network for Integrating Bioinformatics into Life Science Education (NIBLSE) (Dinsdale et al., 2015). Biodiversity Literacy in Undergraduate Education (BLUE) also has a strong data literacy component to its curriculum development. In addition, there are emerging fields that have been spawned in the digital revolution and are simultaneously addressing emergent research and curriculum needs. For example, iDigBio (`www.iDigBio.org`) is an NSF-funded project that seeks to digitize museum collections, but has an educational branch. The National Ecological Observatory Network (NEON) is an NSF-funded national network of environmental data collection stations which works in the emerging ecoinformatics field. In addition to their work as data collectors and synthesizers, they have an active educational branch which helps to train faculty on how to use authentic data sets in the classroom.

3.2 Equity and Social Justice in Quantitative Spaces

Mathematical Biology, Data Science in Biology, and Quantitative Biology are all emerging frontiers that have the power to chart new territories in new disciplines, but who will be allowed to make these journeys? Will they be open only to those groups of principal investigators that are already successful in charting computer science and mathematics? The current disparities in the STEM workforce are staggering. For example, a recent report suggested that only 15% of data science professionals are women (Burtch, 2018). We have two choices: we can either justify that those groups are the most well-positioned, and therefore most deserving, or we can redefine the opportunities of this field to ensure an accurate representation of the broader community. Representation of marginalized and historically underrepresented communities is critically important in quantitative biology. Each of these emerging interdisciplinary fields have the potential to heavily influence, if not transform, community health, including personal, educational, environmental, and ecological (e.g. Tzoulas et al., 2007). Health disparities are well documented among marginalized groups, and the power to move community health forward is power that should be accessible to all people, particularly to members of marginalized communities (e.g. Butler and Adamowski, 2015). Indeed, these are also the emergent lessons learned from, and now core-principles of, other related emerging transdisciplinary fields, such as socio-ecological systems (Reed, 2008) and bioinformatics education (Williams et al., 2019). The National Academies Data Science Education Report devotes time to the issue of representation, justice, and equity (NASEM, 2018). The NSF (2019a) has also begun a number of initiatives in STEM broadly, including the INCLUDES program (Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science). One example of a conversation sponsored by this program is the INCLUDES Conference (`qubeshub.org/community/groups/edsin/conference_description`) "Bringing the conversation of Inclusion and Data Science to the Ecological and Environmental Science Community." Organized by NEON (`www.neonscience.org`), the conference featured both onsite conversations as well as broadcasted sessions, notes, and social media channels, opening up the conversation to those that could not attend in person. These kinds of initiatives provide the potential for the quantitative biology community to design new inclusive, equitable, and just spaces which will propel interdisciplinary science into new and innovative frontiers (Lauer et al., 2020).

3.3 Challenges and Promising Directions

As with any curriculum innovation, challenges and opportunities arise. As outlined in Section 2, there are many different approaches to addressing the needs of quantitative biology education, with some having been more effective and sustainable than others. The UBM program has been discontinued by NSF on the grounds that it did not impact a sufficient number of students for the funds expended. That said, it did lead to a number of mathematical biology programs being created throughout the United States. MBI's support and NIMBioS's funding mechanisms will no longer be based exclusively on NSF, and they are seeking other opportunities for support for their programs. The Communities of Practice (discussed in Section 2.1) continue to be very effective ways to reach the life sciences and mathematics communities, allowing them to forge relationships that lead to innovative Curriculum Development and Assessment (see Sections 2.3 and 2.4) (e.g. Bernstein-Sierra and Kezar, 2017; Matyas et al., 2017b; Diaz Eaton et al., 2016; AAAS, 2011).

From an institutional perspective, it is imperative that quantitative skills be introduced in the biology at an early stage, and then continually be reinforced throughout the program. Many of the programs mentioned here are working towards different or all pieces of this ideal. However, it is a difficult balance to manage the expectations of reports like BIO2010 (National Research Council, 2003) with biology program credit overload (Diaz Eaton and Highlander, 2017). This requires building on institutional strengths while thinking about new strategic directions for all partner disciplines involved. The programs that have worked best are those that have incorporated key aspects of biological applications with strong support from mathematics. For example Diaz Eaton and Highlander (2017) each revamped an existing Calculus course to meet Vision and Change guidelines for modeling at their respective institutions. The two course math sequence at the University of Tennessee, which also resulted in a nationally-adopted textbook (Bodine et al., 2014), offers programming, discrete modeling, continuous modeling, statistics, Calculus 1, and Calculus 2. It is time for further discussion in the community about changes of this type to the curriculum, particularly with respect to keeping the number of course credits controlled with these changes.

Reworking and reflecting true interdisciplinary relationships should be valued by all partners and their students. In order to offer these courses, not only do mathematics departments need to listen to both the needs and constraints of biology departments, but they must preemptively address student advising, questions about transcript analysis for graduate or medical school, and other context-dependent concerns (Diaz Eaton and Highlander, 2017). In addition to having programmatic added value for students, programs should also consider redundant teaching capacity and/or leadership to deliver beyond funding and to accommodate for faculty leave and retirement. It is key to sustainability that the program is institutionalized beyond a person and that the value is demonstrated beyond the classroom to the department, school, and university levels. Even with the most constrained curriculum, if biology programs and biology students see the added value of quantitative courses, they will become the most critical champions (Diaz Eaton and Highlander, 2017).

In addition to the challenges of interdisciplinary collaboration generally, there are two rapidly changing environmental conditions which are equally as important. The first is that the landscape of technology is changing the field of biology and its research directions rapidly. Keeping up the undergraduate educational system with shifts in computing capacity and data acquisition is exciting, but will require sustained persistence. Harnessing the same technology shifts to help the community collaborate is also an opportunity (e.g. Donovan et al., 2015; Dinsdale et al., 2015). The second is to acknowledge a disproportionately educated United States with respect to these emerging fronts. In the midst of these educational pressures, the quantitative biology education community has to intentionally design educational experiences that also intentionally enhance equity.

It seems to the authors that the future of reform in quantitative life sciences education lies in the development of interdisciplinary collaborations between mathematics/statistics, education and biology. As mathematics education expands into working with the life sciences, a new field in quantitative biology education is being formed. Over the last 10-15 years, the US academic community has demonstrated that it is willing and able to bring quantitative biology education to new levels through interdisciplinary collaborations, and the education research community involved in quantitative biology education is starting to coalesce.

We envision that even more gains can be made if the US community can collaborate across the broader international community, a possibility now in the age of virtual centers, collaborative cloud-based tools, and social media. While funded programs can lead to great starting points in reform, their longevity relies on their ability to function in the absence of grant-based financial support. Providing a broader support community for education researchers could accelerate work, enhance the broader impact of interdisciplinary education research, and potentially lead to a more self-sustaining and active community.

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