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Conceptualization and Perceptions of Student Preparedness in Quantitative Reasoning Among Introductory Biology Faculty

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CONCEPTUALIZATION AND PERCEPTIONS OF STUDENT PREPAREDNESS IN QUANTITATIVE REASONING AMONG INTRODUCTORY BIOLOGY FACULTY

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A THESIS

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CONCEPTUALIZATION AND PERCEPTIONS OF STUDENT PREPAREDNESS IN QUANTITATIVE REASONING AMONG INTRODUCTORY BIOLOGY FACULTY

by Ann Cleveland
Thesis Advisor: Dr. Asli Sezen-Barrie

An Abstract of the Thesis Presented
in Partial Fulfillment of the Requirement for the
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Quantitative reasoning (QR) is a crucial competency as undergraduate biology students complete their academic program and enter a workforce increasingly reliant on analyses of vast and complex data sets. The need to prepare biology majors for the 21st century workforce was cited in *Vision and Change: a Call to Action* (American Association for the Advancement of Science [AAAS], 2011). The *Vision and Change* document also advocated for curriculum reform to incorporate QR instruction in undergraduate biology programs. Biology education researchers answered this call with a wealth of research examining undergraduate QR competencies, barriers and challenges to QR learning in students, QR assessment tools, and limited QR resources for instruction. The extent to which biology faculty are familiar with the call to include QR instruction in their courses, their conceptualization of QR, and their perception of student readiness for QR success are not well characterized, and formed the basis of this research. We examined three facets of biology faculty experience in QR, using semi-structured, in-depth interviews of fifteen biology faculty who teach in the introductory biology sequence. First, we sought to characterize how participants conceptualized QR, second, we asked participants what QR competencies were crucial for success in introductory biology, and third we asked participants how prepared they felt students were for QR success in these courses. Participant conceptualizations of QR aligned well with the competencies called for in curriculum reform, but participants also indicated they found many students unprepared for QR success in their introductory courses. These findings suggest that biology faculty would benefit from professional development in QR curricula, as well as from increased amounts and diversity of QR resources for the classroom.

DEDICATION

This work is dedicated to my students – past, present, and future. You bring purpose and meaning to my life.

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TABLE OF CONTENTS

Chapter

1. INTRODUCTION AND LITERATURE REVIEW

2. METHODS

3. RESULTS

4. DISCUSSION

5. RECOMMENDATIONS AND CONCLUSIONS

APPENDICES

A3. Additional excerpts

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction to Thesis

This thesis focuses on faculty conceptualization of quantitative reasoning (QR) and faculty expectations of students' background in QR for introductory biology courses. Quantitative reasoning is an elemental epistemic practice of scientists, i.e., a practice engaged in by scientists to construct new knowledge, claims, and theories (Kelly, 2008). Therefore, graduates in biology must possess QR competency to be successful in their careers. Despite calls for education reform in biology to focus on active learning and student-driven inquiry, challenges exist to providing authentic research and related QR experiences to undergraduates, most critically at the introductory level. The demand for STEM-educated graduates has increased, as has the number of students graduating from high school, yet enrollment in STEM majors, including biology, has stagnated (Eagan et al., 2014). Recruitment and retention in STEM begin with introductory courses, which are the gateway to success in upper-level STEM curricula (Watkins & Mazur, 2013). Students often struggle with QR preparation and competency upon matriculation to college (Sadler & Tai, 2007), with a significant relationship between QR preparation and biology performance. The purpose of this thesis is to understand how faculty in introductory biology courses conceptualize QR, and what QR background and experiences they view as critical for students to bring to the introductory undergraduate biology courses.

In this introductory chapter, my goal is to provide a rationale for why QR is critical in advancing students' learning in biology. Since QR is a critical epistemic practice of scientists, including those who work in life sciences, I will start with the theoretical and empirical underpinnings for how engaging in epistemic practices contributes to students' learning of science in general and biology more specifically. I will then review documents and guidelines that promoted epistemic practices in the form of core competencies in undergraduate biology contexts. I will describe QR terminology, definitions, and learning progressions, followed by a discussion of the pedagogical knowledge and pedagogical content knowledge requisite for teaching QR. Finally, I will provide a positionality statement for why I chose to work on epistemic practices, specifically QR, for my thesis study.

1.1.1 Epistemic Practices of Science and Science Learners

Science is best taught as science is done. The epistemic practices of scientists (i.e. knowledge construction via making observations, asking questions, designing experiments, and collecting and analyzing data) are at the root of our understanding of how the natural world works. If we are to understand the nature and development of scientific knowledge, we must understand the culture that generates the practice of scientists (Nersessian, 2008; Schultheis & Kjelvik, 2015). Science education that allows students to model these epistemic practices in their science learning increases both their engagement in and their understanding of science concepts (Berland et al., 2016; Jiménez-Aleixandre & Crujeiras, 2017). Recent studies in science education thus show a strong focus on students' sensemaking of epistemic practices (Kelly, 2008; Sezen-Barrie et al., 2020) as they construct their knowledge. Making scientific practices meaningful for students shifts science education from 'knowing' scientific and epistemic ideas to 'doing' science as an epistemic practice (Berland et al., 2016). Developing meaningful engagement in scientific practices in the learning environment aligns with the epistemic goals of scientists. Additionally, when students successfully model epistemic practices in science, their identities as scientists, even if only 'in training', may coalesce as an important sociocultural identifier (Shanahan, 2009; Shanahan et al., 2017). As they develop their epistemic practices, they enter into the community practice of investigation and application of communally developed knowledge (Aikens & Dolan, 2014; Auerbach & Andrews, 2018; Kelly, 2008).

The epistemic practices discussed above are as important to science learners at the undergraduate level as they are to student learners in K-12 (Cooper et al., 2015). Understanding how science is done, and providing student opportunities for practice, is a major thread through the Next Generation Science Standards (NGSS Lead States, 2013). Applying the epistemic practices of scientists is at the heart of the Ocean Literacy Framework (National Marine Educators Association, 2013), where classroom lessons provided by institutions such as NOAA and the Sea Education Association align with NGSS practices to encourage student engagement and understanding of seven key ocean concepts. The *Learning Progressions for Environmental Science Literacy* (Anderson et al., 2008) guides students to understand that the conceptual knowledge of science regarding carbon, water, and biodiversity cannot be separated from the practice of the disciplines that developed that knowledge.

Recent reform efforts in teaching biology at the college level mirror changes in K-12 curricula by focusing on epistemic practices as well. For example, Sadler and McKinney (2010) studied how the use of authentic research experiences that highlighted epistemic practices (such as students' active involvement in the collection, quantification, and analysis of data) impacted undergraduate science students' learning outcomes. They found that these experiences facilitated students' understanding of the nature of science (NOS) and improved attitudes towards science and self-efficacy. Similarly, Hanauer et al. (2016) found that project ownership increased students' sense of agency and achievement, resulting in increased retention in the sciences; Hanauer and Dolan (2014) subsequently developed and evaluated a Project Ownership Survey

(POS) to measure the effectiveness of student research experiences on the psychosocial and cognitive facets of this pedagogical element.

Thus was issued a call to action to the biology community – undergraduate education in biology curricula must change to reflect the epistemic practices of the discipline. This new focus on epistemic practice would distill the depth and complexity of biology into core concepts and competencies that all biology graduates should possess upon graduation, and researchers and educators launched efforts for reform.

1.1.2 Reform Based Teaching with *Vision and Change*

The call for focus on students' QR competencies in biology gained new momentum when leaders at highly recognized scientific organizations, such as the National Institutes of Health [NIH], National Science Foundation [NSF], American Association for the Advancement of Science [AAAS], and the Howard Hughes Medical Institute [HHMI], joined with a pedagogically-focused group of biologists and biology educators to examine the status of undergraduate biology education and to make recommendations for curricular change. That 2006 conversation resulted in a 2009 conference and report entitled *Vision and Change in Undergraduate Biology Education: a Call to Action* (2011) published by AAAS. The report concluded that encouraging students to think critically and actively during their learning to construct their own knowledge would be the best method to create the next generation of scientists.

The *Vision and Change* document (Table 1) advocated a shift from a vision of undergraduate biology education that relies on memorization of isolated pieces of knowledge (Roth & Tobin, 2000; Stroupe, 2015*)* to one that focuses on student-centered learning that integrates five major core concepts (e.g., evolution, structure and function) and acquiring six core competencies (e.g., ability to apply the process of science, ability to use quantitative reasoning). The wide agreement that these core concepts and competencies are necessary for developing scientifically literate students encouraged the development of innovative curricular frameworks for undergraduate biology degrees that emphasize these core concepts and competencies (Brownell et al., 2014; Clemmons et al., 2020; Laungani et al., 2018). Science education researchers have contributed a wealth of information on course design (Hester et al., 2014), pedagogy (Freeman et al., 2011), and discussions of student challenges to acquiring core concepts and competencies (Sax et al., 2015). Brownell et al. (2014) devised the BioCore Guide to help departments align their curricula with the five core concepts of *Vision and Change*. Clemmons et al. (2020) recently elaborated a set of learning outcomes, the BioSkills guide, designed to help biology faculty implement and assess the core competency recommendations of *Vision and Change*. From the call to action, the Partnership for Undergraduate Life Science Education (PULSE) was established to address barriers to the called-for curriculum change (Dolan, 2012); the partnership's efforts have continued (https://pulse-community.org/home) to assist biology departments align *Vision and Change* recommendations with their undergraduate curricula by providing workshops, trainings, and rubrics (https://pulse-community.org/rubrics) with which to assess progress.

1.1.3 *Vision and Change* Core Concepts and Competencies – with an Emphasis on Quantitative Reasoning

The "ability to use quantitative reasoning" and the "ability to use modeling and simulation" were specifically documented as two of the six core competencies in *Vision and Change* that align with the increasingly complex data nature of biology; QR is increasingly called for in students graduating with bachelor's degrees in biology. Recently, there has been an increase in data wealth and complexity in many areas of biology, including computational biology, evolutionary biology, systems ecology, climate science, and neuroscience. Biology advances thus increasingly rely on graduates who possess the ability to acquire, manage, understand, and evaluate quantitative data to support advances in our knowledge (American Association for the Advancement of Science [AAAS], 2011; Association of American Medical Colleges - Howard Hughes Medical Institute [AAMC/HHMI], 2009; National Research Council [NRC], 2003). Strasser and Hampton (2012), for example, wrote that the increasing amount and complexity of biological data has led to an increased need for data analysis and data management skills among undergraduate biology students. Forrester et al. (2022) advocate for the teaching of programming skills (e.g. the statistical and graphical program R) in undergraduate biology curricula as an increasingly valuable skill for biology graduates.

Despite the importance of these quantitative skills, students often have difficulty in performing simple calculations, representing data graphically, and articulating data-driven arguments (Speth et al., 2010). These limitations argue strongly for the need to embed such elements into course learning goals. Discipline-based education research has suggested the need to develop curricula that will attend to student learning progression in QR in the context of biology, as well as increase student self-concept (Cooper et al., 2018) and self-efficacy (Sadler & McKinney, 2010) in their QR abilities. Student self-concept is constructed when students perceive and assess their abilities (Sax et al., 2015), and their self-efficacy stems from what they believe they can accomplish with those abilities they possess (Bong & Skaalvik, 2003). Pedagogies that strengthen these attributes in QR align with calls for education reform.

1.1.4 Challenges to Education Reform in Biology

Unfortunately, despite publication of *Vision and Change* and the heroic (*sensu* Gormally et al., 2014) dissemination of evidence-based teaching practices showing marked improvement in student learning and retention (Ebert-May et al., 1997; Freeman et al., 2007; NRC, 2012; Watkins & Mazur, 2013), adoption by university faculty has been slow (Gormally et al., 2014). Stains et al. (2018) found that 75% of course observations of 2000 classes given by 500 instructors over 25 different institutions were lecture-based, with instructors focused on providing content knowledge without epistemic engagement of students. Reasons for the slow adoption of student-centered, epistemic learning are many, and are briefly summarized in *Vision and Change in Undergraduate Biology Education: Chronicling Change, Inspiring the Future* (2015), a follow up document to *Vision and Change*. The report suggested that major challenges to implementation include a shortage of faculty time to plan and implement change (83.1% of survey respondents), the need for faculty professional development (66.6%), and faculty concerns about the breadth of course coverage (62.5%). Shadle et al. (2017) described faculty efforts to switch to evidence-based instructional practices in STEM and identified eighteen faculty-identified barriers to change (Shadle et al., 2017, p. 5-6); these challenges included components of time and resource constraints, student unpreparedness and resistance, and impacts to research and other departmental obligations.

Recent research (Gardner et al., 2021; Owens et al., 2018) suggests an additional challenge to pedagogical change may be partially attributable to a lack of awareness of the *Vision and Change* documents, unfamiliarity with science education research (Harvey et al., 2016; Lund & Stains, 2015), and potentially a lack of guidance from department chairs and academic deans (Shadle et al., 2017). Recent national reports (e.g. the *President's Council of*

Advisors on Science and Technology, 2012) have indicated a need for professional development of biology faculty in order to implement pedagogical change (Addis et al., 2013). The establishment of Faculty Learning Communities (FLCs) on many campuses (Addis et al., 2013), and the hiring of biology faculty with education specialties (Bush et al., 2016), have both shown promise as agents of change in advancing the student-centered learning called for in *Vision and Change.*

1.1.4.1 Student Challenges to Teaching Quantitative Reasoning

Among the skills called for in *Vision and Change* are the ability to apply the process of science, including hypothesis testing and data interpretation, and the ability to use QR. Biologists rely on QR as a crucial epistemic practice to generate research questions, analyze and interpret data, and develop models (Speth et al., 2010). Despite clearly articulated needs for QR proficiency for biologists entering the workforce (HR Associates, 2015), instruction in these QR skills is often lacking or under-developed in undergraduate biology education (Bialek & Botstein, 2004). Students often take mathematics and biology courses in near independence (Eliassen et al., 2017; Feser et al., 2013) and rarely experience mathematics within the context of their own discipline (Hester et al., 2014). Moreover, students often do not understand the importance of integrating QR into their biology courses, a limitation that could follow them into their professional careers (Feser et al., 2013). Despite a lack of evidence that biology students are math-averse (Andrews & Aikens, 2018), some students who perceive themselves as math-weak gravitate towards biology due to the perception that biology does not rely on mathematics (Hester et al., 2014; Wachsmuth et al., 2017). Faculty sometimes shield their students from the quantitative aspects of biology (Mayes et al., 2020), although exposing students to QR at the start of their academic career is known to foster their quantitative competency in a biological context (Hester et al., 2014). Matthews et al. (2013) provided strong evidence that biology students need to see, acknowledge, and then understand how important it is for them to develop QR skills during their undergraduate studies, and points to the need to encourage biology faculty to integrate QR into all levels of student learning. Students who feel, or develop, a level of satisfaction with math early in their undergraduate training may retain that attitude; using an Attitudes toward the Subject of Mathematics Inventory (ASMI), Wachsmuth et al. (2017) found that math attitudes may be malleable if students can frame mathematical work contextually as having utility or relevance. It may also be necessary to explicitly help undergraduates put mathematics into biological contexts; Beck (2018) found that implicit teaching of statistical and quantitative concepts did not improve QR and making explicit links between mathematics and biology may be necessary, at least at introductory levels.

Despite the call to action, research has shown that many students lack fundamental QR competencies, especially upon matriculation into biology programs, e.g. they may arrive at their institutions unprepared for QR success in their introductory courses (Jackson & Kurlaender, 2014). One reason for this problem may be students' failure to view the value of QR in the context of biology (Strasser & Hampton, 2012). Once students are enrolled in their courses, biology faculty often lack the resources (Manduca et al., 2017), time (Brownell & Tanner, 2012), and pedagogical content knowledge (Corwin et al., 2019; Feser et al., 2013) to infuse their course curricula with QR instruction (Shadle et al., 2017). Therefore, faculty may be challenged when students enter their degree programs with limited experiences and background in QR.

Biology students often compartmentalize mathematics and biology early in their undergraduate education (Bao et al., 2009; Bergevin 2010; Bialek & Botstein, 2004; Texley,

2001) and thus face multiple challenges in integrating QR practice into their learning in biology. They may have successfully completed mathematics courses in high school but their mathematical content knowledge may not correlate well with scientific reasoning (Bergevin, 2010). While students may be proficient at mathematics in a math-based course (e.g. calculus); they may struggle to transfer that proficiency to biology, chemistry, and physics (Blumberg et al., 2005). Traditionally, students in the life sciences have rarely encountered mathematics in the context of biology (Hester et al., 2014) and thus they may lack the understanding that mathematics is central to the epistemic practices of life scientists, such as for analyzing and interpreting data (Andrews et al., 2017). Biology students may perhaps 'silo' mathematics as a subject to be completed, rather than applied in context to their subject learning in biology, chemistry, or physics (Tripp & Shortlidge, 2019). Students may also fail to see how QR practices are similar across these varied scientific disciplines, and lack the ability to transfer QR knowledge and experience across the breadth of their STEM curricula (Eliassen et al., 2017). For example, students may not recognize that a standard curve generated from a chemical assay is a linear representation of the relationship between concentration and absorbance, generated from a regression analysis.

Coupled with the challenge of seeing QR in the context of their discipline, students may also possess poor mathematics self-concept (Sax et al., 2015) in considering their own ratings of their skills and abilities, and interest, in mathematics. This poor self-concept can interfere with learning and the ability to see the value of QR in context; this is especially true among underrepresented students in STEM (Forrester et al., 2022; Sax et al., 2015). Math-averse students may actively seek out a biology program because of its reputation as being the least quantitative science discipline (Matthews et al., 2013). Andrews and Aikens (2018) wrote that students are motivated to engage in a task when they see value in it. Thus, students who perceive themselves as math-weak may view QR with anxiety, which may influence their interest in developing their QR competencies. Conversely, students who demonstrate strong QR skills, and interest in QR in the context of biology, often report higher math-biology task values (Andrews & Aikens, 2018) and are more likely to enroll in advanced biomodeling and biostatistics courses. Infusing biology curricula with a learning progression for QR, beginning with first year courses, that stresses the value of QR to the discipline, and scaffolding competency development to help alleviate math anxiety and elevate math self-concept, may provide a path forward to the reform called for in *Vision and Change*.

1.1.4.2 Faculty Challenges to Teaching Quantitative Reasoning

Despite *Vision and Change* calls for incorporating QR instruction in contextual ways in biology curricula, many biology courses, at all levels, remain unchanged (Feser et al., 2017). While most biology faculty are trained in and employ QR in their research (Leonelli, 2014), they face challenges to bring quantitative skills (e.g., reasoning, modeling, statistical analyses) into their teaching. The reasons for this inertia are many. The curricula of biology courses are already crowded (Matthews et al., 2013) and current curricula often emphasize content over teaching for learning (Shadle et al., 2017). Faculty may not always consider the role of data literacy in society (Kjelvik & Schultheis, 2019) and thus may not provide opportunities for students to engage with data sets in conceptual contexts. Additionally, biology faculty may not view it as their responsibility to add QR content to their courses (Eliassen et al., 2017), relying instead on mathematics curricula to provide instruction. This separation interferes with students' ability to derive discipline-specific context, and reduces student motivation to develop QR competencies they perceive to not have value (Andrews & Aikens, 2018).

Faculty also report the difficulty of maintaining mathematics/biology collaborations across departments (Bergevin, 2010) that would help all faculty provide the critical context necessary for students to engage in and appreciate QR instruction. Moreover, not all biology faculty are quantitatively trained (Matthews et al., 2013) and may lack the pedagogical content knowledge (Shulman, 1986) to teach QR effectively. Further, biology faculty often lack resources and support for providing QR instruction in their courses (Shadle et al., 2017). For example, some biology texts have dropped mathematics in favor of more figures and photographs (Crow, 2004) which both reduces student exposure to QR and also fails to provide instructor resources for teaching QR in context. Lastly, biology faculty often expect that students possess all necessary QR competencies, especially in upper level courses, and thus do not provide instruction or opportunities for practice in the necessary skills of arithmetic, percentages, graphs, estimation, elementary probability/statistics, basic geometry of measurement, and basic growth patterns (linear, exponential) (Hallett, 2003). Upper level biology faculty tend to focus on more sophisticated skills, e.g. differential equations, probability distributions (Hester et al. 2014), in context-dependent ways. Learning progressions would assist faculty in scaffolding QR exposure and practice for their students throughout the undergraduate biology curricula, while helping them be mindful of student challenges.

1.1.5 Operationalizing Quantitative Reasoning

A review of the literature suggests that faculty may struggle to conceptualize QR, and that learning progressions for teaching might be valuable resources. One of the most immediate challenges many biology faculty face when endeavoring to include QR in their curricula is in starting the conversation of what QR means (Elrod, 2014). Elrod (2014) wrote that education policy leaders were often insufficiently aware of the increasing need for QR, often situating it in general education learning outcomes and not in the context of disciplines. To design high quality instruction that integrates QR skills in context, there is a need to operationalize the meaning of QR and investigate how learners progress to the use of sophisticated QR skills (Mayes et al., 2020). Faculty need help to conceptualize QR and identify meaningful steps of progression in QR skills. One major challenge to have a common conceptualization of QR is its relationship to related, often similar sounding constructs. Elrod (2014) cited the oft-used terms of quantitative literacy (Association of American Colleges and Universities [AAC&U], 2007), quantitative fluency (Lumina Foundation), QR (Western Association of Schools and Colleges [WASC], and numeracy, when asking what these terms mean for student learning, curriculum development and accreditation. Vacher (2014) suggested a vocabulary matrix to distinguish between numeracy, quantitative literacy, and QR, finding that some researchers view those three terms as synonyms while others view them as distinct constructs. Matthews et al. (2013) used the terminology of quantitative skills, which they defined as the ability to apply mathematical and statistical thinking in context. Mayes et al. (2013) wrote that QR is a complicated construct and indicated that it is important to define QR in any work. They listed the many names by which QR is presented in the literature: numeracy, number sense, deductive reasoning, mathematical literacy, quantitative literacy, problem solving, contextualized mathematics, mathematical modeling, and, finally, QR itself. Their review of the literature found that there were some common threads among these terms' definitions; the terms all described the use of mathematics and statistics in context, and the terms suggested sophisticated reasoning with elementary mathematics. However, Mayes et al. (2013) also pointed out that there were some significant differences among the terms; some researchers emphasized the specific use of basic mathematics, while other researchers focused on the more generalized 'habit of mind'.

Compounding the existence of multiple names for QR are the multiple definitions that exist along a conceptual continuum from broad to narrowly focused. Phillips and Milo (2009) wrote that QR is the development of intuition about biological numbers. The VALUE rubrics (AAC&U, 2023), using the term quantitative literacy (including the terms numeracy and QR), described the skill as a habit of mind that demonstrates competency and comfort with numerical data; it is the ability to reason and solve quantitative problems from a wide array of authentic contexts. Further along the continuum of QR definitions is the specific "[quantitative reasoning] is a well-established and highly studied construct that encompasses not just mathematical ability but also a disposition to engage quantitative information in a reflective and systematic way and to use it to support valid inferences (Kahan et al., 2013)". Biology faculty seeking to incorporate and assess QR in the classroom would likely find it hard to measure intuition or habit of mind, and Kahan et al.'s (2013) construct might be more accessible for curriculum development. Despite the potential confusion from the array of terms and definitions of QR, Mayes et al. (2012) made an important assertion; context underlies all QR. Quantitative reasoning is not mathematics but rather it is using mathematics and statistics in context in the service of decision making (Elrod, 2014; Mayes et al., 2012; McCully, 2013).

Considering mathematics skills as part of QR in context in the sciences can be complex and it relies on the skills and experiences that students bring to their learning (Jackson et al., 2014). Many introductory biology courses do not require college mathematics as prerequisites, so faculty can only utilize high school mathematics (McCully, 2013). Faculty often face under-prepared students who need mathematics support, and faculty also face the problem of linking mathematics to science contexts. Students are exposed to using QR in context in secondary school (McClure, 2020) via crosscutting, interdisciplinary problems that integrate mathematics and science (Common Core State Standards Initiative, 2010; NRC, 2011; NGSS, 2013) but seem to struggle to bring those skill to their college learning (Hess & Kearns, 2010).

Quantitative reasoning can be developed through progressive scaffolding of exposure and practice in context through the application of learning progressions (Hester et al., 2014). Learning progressions are empirically grounded and testable hypotheses about how students learn, and how their learning becomes more sophisticated with time and practice (Corcoran et al., 2009). Mayes et al. (2014) developed a learning progression framework for QR in environmental science for middle and high school students that is also relevant at the post-secondary level. Their QR learning progression consists of three progress variables (Quantification Act QA – including Quantitative Literacy QL, Quantitative Interpretation QI, Quantitative Modeling QM) with specific elements that are tracked across achievement levels. QA, the act of quantification, is a mathematical process of attributing a measurable attribute to an object, and is the foundational component of QR. It applies elementary mathematics in sophisticated ways, via QL, to make conclusions about variables. QI is the interpretation of existing models to discover and make predictions about variables, to discover trends or make revisions. QM is the creation of representative models to explain a phenomenon. The three progress variables are embedded in a learning progression framework with four levels which move from an assessment of students' current understanding of QR to aspects desired upon completion of 12th grade (Mayes et al., 2022).

The construction and dissemination of learning progressions in QR may show promise in helping faculty 'backwards design' (Wiggins & McTighe, 2003) in the context of biology. Crucial to success of these learning progressions are faculty who have the necessary content knowledge and pedagogy to teach them. I will address pedagogical content knowledge in the next section.

1.1.6 Pedagogical Content Knowledge for Teaching Quantitative Reasoning in Undergraduate Biology Courses

There is much recognition that faculty can significantly affect student learning outcomes by the ways in which they provide instruction (Neumann et al., 2019); relatively small decisions about a teaching strategy can impact student learning (Auerbach & Andrews, 2018). Despite a wealth of evidence-based teaching strategies focused on student-centered active learning, much STEM instruction in higher education still reflects the transmission model of learning (Hill, 2013). For some, this is a reflection of the way they were trained (Cooper et al., 2015), and many STEM faculty perceive that expertise in their disciplines prepares them for teaching (Hill, 2013). Findings suggest that while faculty might be aware of student difficulties, they were more likely to see this as students' struggles with course content rather than linked to teaching styles and student learning (Hill, 2013). Professional development programs designed to help faculty change their pedagogy are increasing, but some faculty may perceive their methods as being more student-centered than they actually are (Ebert-May et al., 2011). This may suggest that faculty may not possess the pedagogical skills necessary to evaluate their own teaching.

While there is a rich history of teacher knowledge development among K-12 instructors, relatively little work has focused on how college STEM educators develop pedagogies (Auerbach & Andrews, 2018, Andrews et al., 2022). Effective teaching requires discipline-specific content knowledge (CK), a knowledge of teaching strategies and methods generalizable across disciplines (pedagogical knowledge, or PK), and an 'amalgam' of the two (Shulman, 1987; Neumann et al., 2019) termed pedagogical content knowledge (PCK). Pedagogical content knowledge, first described by Shulman (1986), is the knowledge of teaching and learning that is specific to a topic (e.g. quantitative reasoning). Those who have well-developed PCK are familiar with the most powerful illustrations, examples, and demonstrations for teaching concepts in a disciplinary context (Shulman, 1986); they are also likely to understand what discipline-specific content students are likely to struggle with and will have experience in helping students overcome them (Auerbach & Andrews, 2018).

Winberg et al. (2019) reviewed how university STEM faculty acquire pedagogical competence and found that professional development frequently targeted only PK: lesson planning, development of effective presentation skills, and reflective teaching. Professional development for STEM educators is often provided by non-STEM faculty (e.g. education and psychology faculty, [Winberg et al., 2019]) and instructional developers and thus PCK development is often omitted in training. Andrews et al. (2022) conducted a literature review examining what is known about teaching knowledge among STEM faculty; they suggested that there are few studies undertaken that examine the question of how and where STEM faculty develop PK and PCK for teaching STEM courses. These results are consistent with calls to assess adoption of *Vision and Change* principles (Vasaly et al. 2014; NSF, archived) and to determine whether faculty are using active learning and PCK to meet the reform goals. Developing PCK for teaching QR at college level can be a critical step. This study can contribute to the development of PCK by starting with conceptualizations and expectations of the biology faculty for teaching QR.

1.2 Positionality Statement

As defined by Holmes (2020), positionality describes an individual's worldview, and it is informed by ontological and epistemological assumptions, as well as by assumptions of human nature and our environment. Positionality is individual, and thus unique, and reflects a researcher's own position within a given research endeavor. As such, positionality influences how research is initiated and conducted, and will influence outcomes and results. Researchers thus should assess their position and experiences in light of how these might influence their interpretations of other's lived experiences (Scharp & Thomas, 2019). I, as primary author of this thesis, intend to locate myself in three areas (*sensu* Holmes, 2020): 1) the subject I have chosen to study, 2) the research participants interviewed, and 3) the research context and process, in order to make transparent how my identity relates to, and informs, my research interests.

My research subject concerns how faculty teaching introductory biology courses conceptualize QR and what QR competencies they see are prerequisite to introductory biology experiences. I am a professor of marine biology and have been teaching at the undergraduate level for more than twenty years. Specifically, I am a broadly trained marine ecologist with interests and expertise in quantitative biology. I have always appreciated that ecology lies at the intersection of mathematics and biology, and I have always been drawn towards studies that provide quantitative explanations for the world I see around me. I have endeavored to bring that quantitative view of the world to my students, and have been concerned that many of them have been unable to follow and appreciate the value of QR in biological contexts. This concern led to a search for pedagogies and resources that would help me bring QR to my courses (e.g. introductory biology, ecology, animal behavior, fish biology). Pedagogical strategies were numerous, and are discussed in subsequent chapters, but resources for teaching were harder to find, especially for biology faculty not familiar with discipline-based educational research. That search for resources, and conversations with colleagues like me who wanted to teach QR but were not truly certain of what that actually was, led to my pursuit of a Master of Science

Teaching degree. It is thus that my research subject is wholly a result of my positionality as an ecologist and a professor; my experiences are ‘where I am coming from’.

My research participants for this thesis are 15 faculty who teach in introductory biology courses. Eleven of the participants are ecologists/evolutionary biologists, and four of the participants are cellular/molecular biologists. I did not specifically choose this ratio of participants (selection is described in the methods sections of Chapter 2 and Chapter 3); I used the phenomenological approach of horizontalization (Moustakas, 1994) in an effort to remove my knowledge and experience from interviews and transcript analysis, but recognize that my positionality, i.e. my focus on ecology/evolutionary biology, might have influenced the recruitment process.

My research context was informed by my curiosity surrounding how QR is taught in introductory biology, especially since what I learned might inform my own teaching in QR. My research process was greatly aided by conversations with my thesis advisor, committee members, and peer STEM educators, as I am trained as a quantitative, not a qualitative, researcher. I spent time in the qualitative research literature (e.g. Rubin & Rubin, 2012) prior to coding the interview transcripts to understand how ‘to hear data’.

I am fully invested in the outcomes of this research; the primary driver of my desire to earn my Master of Science Teaching degree is to improve my own pedagogy, particularly as it relates to teaching QR in my courses. I want to be a better teacher tomorrow than I was today - every day. Thus I acknowledge that my positionality influenced this research to a significant extent, but I have endeavored throughout this process to remain as objective as possible in light of this admission.

1.3 Purpose of Study

A review of the literature suggests that research rarely has been dedicated to how biology faculty, outside of those faculty engaged in discipline-based education research, articulate QR competencies and how their interpretations inform their teaching (Vacher, 2014). Since the faculty's role is critical in the enactment of any curricular and pedagogical changes (Hachtmann, 2012), I investigated introductory biology faculty's conceptualizations of QR in the context of undergraduate biology education, and their assessment of student preparedness for success. Specifically, I interviewed faculty teaching in the introductory biology course sequence as they are potentially the first to teach QR skills to students transitioning from K-12 instruction. I intentionally chose the introductory biology focus as studies (Eliassen et al., 2017; Hester et al., 2014) suggest that success early in a student's academic career can foster motivation and retention. Assuring that students are exposed early and often to QR practice in biology may improve competency and self-efficacy (Eliasson et al., 2017; Hester et al., 2014) necessary for degree completion.

I conducted semi-structured, responsive interviews with 15 faculty teaching in the introductory biology course sequence at fourteen 14 universities and colleges in New England which represented five Carnegie classifications (n.d.). Transcripts were then coded to inform the research findings. I was assisted immeasurably in my research by my thesis advisor, thesis committee members, and external colleagues. As such, I would like switch to the use of the first person plural form of 'we' when describing the methods, results, and discussion of this work below.

1.3.1 Conceptualization of Quantitative Reasoning – Research Question 1

A comprehensive body of work has been published on 'how to' incorporate authentic QR as epistemic practice in biology courses (e.g. Massimelli et al., 2019; Mathur et al., 2019), and the challenges students face in developing QR skills (Cooper et al., 2018). Less is known about how biology faculty conceptualize QR, and how they provide instruction to their students. To that end, our first research question explored how faculty in introductory biology courses understand and conceptualize the term QR. Specifically, we asked 1) How do faculty in introductory biology courses conceptualize QR?, and 2) Do those conceptualizations vary with faculty research background, teaching experience, or institution type?

1.3.2 Quantitative Reasoning Competencies for Student Success – Research Question 2

There is a dearth of studies exploring what faculty see as critical background for biology students to successfully engage in quantitative aspects of biology curricula. In response to this need, 3) we focused on what QR competencies faculty teaching in an introductory biology course sequence viewed as critical to student success, and 4) we sought to characterize faculty perceptions of student preparedness for success in these courses.

2. METHODS

This study was a qualitative exploratory study to understand the conceptualization of QR by faculty teaching introductory biology courses. We interviewed 15 biology faculty, from 14 biology departments at New England universities and colleges (Table 2). We used phenomenology (Moustakas, 1984), which is a qualitative method that seeks to describe and understand an essence of an experience (or phenomenon) of human beings (our participants) without inserting the researcher's preconceived ideas or assumptions. Phenomenology is designed to interpret an experience without the researcher's lens of bias and specifically aims to describe what participants have in common as they experience a phenomenon. Phenomenology results in a description of an experience that protects objectivity, and is less focused on researcher interpretation and more directed to the description of the experience of the participants. Phenomenological design suggests interviews of five to twenty-five participants (Polkinghorne, 1989) to understand the essence of experience so we selected a participant pool of intermediate size.

2.1 Participant Recruitment

We identified 14 universities and colleges in New England which represented five Carnegie classifications (n.d.). We utilized a snowball sampling method (Patton, 2002) to recruit department chairs who then recruited participants for interviews. We submitted email messages to department chairs asking for referral to faculty members who most recently were assigned to teach in the introductory biology course sequence. The time limitation was included to alleviate potential selection bias of department chairs. After the faculty were identified, we sent an informed consent letter describing the research, along with the interview questions (Appendix A1). Once the participants communicated their willingness to take part in the study, an interview was scheduled at the available times provided by the faculty. Faculty were identified by their primary research interest; their primary research interest was then categorized by subject area as either cellular/molecular biology or ecology/evolutionary biology - the two major subject areas of introductory biology. Because faculty were identified by their department chairs for participation, we did not attempt to have equal numbers of faculty in each subject area category. Descriptor data were also collected on faculty rank and years of teaching. All participants were de-identified by use of a pseudonym. Three research groupings were constructed (Table 2): 1) subject area focus in biology (cellular/molecular, ecology/evolutionary), 2) years of teaching experience (0-4 yr, 5-9 yr, 10-14 yr, 20+ yr), and 3) Carnegie classification (n.d.). There are no known safety concerns with this study because it did not contain any laboratory components.

2.2 Interview Protocol

Informed by the recent literature on QR, *Vision and Change*, and discipline-based education research, we drafted the interview questions (Appendix A2) which were then revised after receiving feedback from two science education research groups and feedback from two pilot implementations. Semi-structured, responsive interviews -- a qualitative research tool of one-on-one interviews (Rubin & Rubin, 2012) -- were conducted and recorded via videoconference. All interviews were conducted by the first author. Interviews took ~45 minutes and consisted of four sections: 1) introductory questions on course content and teaching experience, 2) conceptualizing QR, 3) background and interests in QR, and 4) implementing QR. Participants were asked which QR skills they viewed as crucial for success at the introductory level of biology and where they expected students to have developed them. The interviews were recorded and transcribed for data analysis.

2.3 Data Analysis

For each interview, statements in response to questions regarding conceptualization of QR were coded (see below); where appropriate an individual statement would be assigned multiple codes. The data analysis was informed by the interview questions, QR definitions in educational research (e.g., Aikens & Dolan, 2014; Mayes et al., 2014; Stanhope et al., 2017), and the *Vision and Change* (AAAS, 2011) document. These artifacts helped deductively frame the initial and overarching codes such as ‘Meaning of Quantitative Reasoning’ and ‘Student Background in Quantitative Reasoning.’ As suggested by the phenomenological data analysis approach, we utilized ‘horizontalization’ highlighting significant statements across interviews to help us understand the essence of the teaching QR experience. We then articulated ‘clusters of meaning’ that helped us formulate codes representing the highlighting statements (e.g., Conceptual Sensemaking Through Data, Basic Math Skills). The goal of developing the codes representing such clusters of meaning was to capture participants’ experiences leading to their definition of QR in introductory biology courses. This process is called ‘bracketing’ (Moustakas, 1994) and helps researchers remove their knowledge or experience from the essence of the phenomena as much as possible. Individual statements, as opposed to entire responses to a question, were coded for each participant. In instances where two or more codes could be applied to a singular statement, co-occurrence of codes was noted. Coding analysis was done through Dedoose Ver. 7.0.23, a qualitative research analysis tool (Mauri et al., 2017).

2.3.1 Conceptualization of Quantitative Reasoning

Initially, we independently coded four of the fifteen interviews for the initial phase of establishing a reliable coding framework; we used the percent agreement (P_A) formula (Syed & Nelson, 2015) to calculate the intercoder reliability for each code. At this initial phase, the percent agreement for each code ranged between 72 - 100%. We decided to remove or collate the codes that were rated below 90% (Lombard et al., 2002), e.g., ‘using graphical models’ and ‘using mathematical models’ were collated as ‘using models’. While coding the rest of the interviews, we went through the iterative process of discussing, revising, and defining the remaining codes until we reached 100% agreement (Saldaña, 2015). The inductive codes provided in-depth qualitative accounts of how introductory biology faculty conceptualize QR. Once we determined the codes, our final step of the phenomenological approach was to see whether there were common themes in how participants explained each QR skill. Appendix A3 (Table A1, Table A2) contains all of the codes, their definitions, and extensive sample excerpts.

2.3.2 Quantitative Reasoning for Student Success

Vision and Change developed six core competencies undergraduate biology students should possess upon graduation. While the term ‘competency’ is a complex term of a higher order than ‘knowledge’ or ‘skill’, Clemmons et al. (2020) found that the term ‘skill’ was more easily recognizable to biology faculty not engaged in discipline-based education research, and they used the terms interchangeably. We followed their lead in this terminology, both in formulating our research questions (asking participants specifically about ‘skills’) and in developing our codes. We therefore report our results in terms of QR skills and not QR competencies. This convention also helps us align our data analysis with the BioSkills Guide (Clemmons et al., 2020). Additionally, we chose to use terms and definitions that came directly from participant interviews, rather than substitute terms from the literature, e.g. we employ the term ‘basic math skills’ to the list of mathematical calculations described participants because they used that term.

For each interview, statements in response to questions regarding descriptions of QR for student success were coded (see below); where appropriate an individual statement would be assigned multiple codes. As with **Conceptualization of Quantitative Reasoning** described in the section above, we used the percent agreement (P_A) formula (Syed & Nelson, 2015) to calculate the intercoder reliability for each code. This time, the percent agreement for each code ranged between 50 - 100%. We revised the coding framework where necessary to subsume most singular codes into other existing codes. As before, some codes still had percent agreement below 90% (Lombard et al., 2002) so we collated any codes below this level, e.g., ‘addition/subtraction’, ‘using exponents’, ‘understanding ratios/fractions’ were collated as ‘basic math’. Individual sentences were coded as the coherent and meaningful unit of analysis. We used deductive codes to identify the QR skills participants felt were crucial, and expected, for student success in the introductory biology course sequence. Interview transcripts revealed inductive codes characterizing what QR skills participants felt students were lacking, despite participants hoping their students possessed them. After the transcripts were coded, we created a visualization of the codes using alluvial diagrams (RAWGraphs [Mauri et al., 2017]) to understand how the QR skills clustered thematically and to probe participants' perception of QR skills necessary for student success.

3. RESULTS

3.1. Faculty Conceptualization of the Meaning of Quantitative Reasoning

Although we cannot make any generalizable claims about relationships between faculty conceptualizations of QR and their attributes due to small participant size and nature of this study, we can highlight some patterns that we noticed in our data, which can be useful for further investigation. When we asked participants to define QR in the context of their teaching, nine codes emerged. When we looked at the qualitative excerpts for these codes, we noticed that faculty's descriptions for these nine codes used keywords such as 'simple', 'easy', 'not difficult/difficult', and 'challenging'. These keywords led to two thematic areas: sophisticated and basic QR skills. The first theme included references to what participants saw as sophisticated, cognitively complex QR skills related to how students should *think about data* (Table 3, Appendix A3 Table A.1). Participants often described these skills as potentially difficult for introductory biology students. The second theme included references to what participants described as the more basic QR skills of what students should *do with data* (Table 4, Appendix A3 Table A.2), often suggesting that students should already possess these skills when they enroll in the course. Participants conceptualized *doing with data* as skills where students might work with data without recognizing the meaning or context of what they were doing. For example, participants spoke of students entering numbers into a formula to obtain a correct answer, but not knowing what that answer meant. Similarly, students might successfully generate a graph with data means and measures of variation, but not understand what the variation indicates about the data. It is important to note that these codes were generated wholly from participant comments, and do not necessarily reflect what is known from the literature. Indeed, some participants viewed certain skills as basic (e.g., 'creating/describing graphical data'), when literature (e.g., Bowen & Roth, 1998; Bowen et al., 1999) suggests they are complex.

3.1.1 First Theme: Sophisticated, Cognitively Complex Quantitative Reasoning Skills

Based on the wordings that the participants used, we identified that five QR skills were conceptualized as being sophisticated and cognitively complex. All participants emphasized at least one of these five skills in their conceptualization of QR. The following five codes of skills that were grouped under this theme are in accord with the array of critical thinking skills called for in *Vision and Change* (and others). Codes are presented in the order from most to least applied.

Conceptual Sensemaking Through Data (12 of 15 participants). This code was represented the most in the transcripts. Excerpts that were grouped under this code referred to the ability to analyze or interpret data to better understand a concept, the ability to extract evidence-based meaning from a figure, or to create a figure that graphically demonstrated a concept. For example, Paul, an ecologist/evolutionary biologist, described a lesson where he provided data on the relationship between leaf size and climate, and expected the students to be able "to look at conceptual problems and turn them into mathematical models, calculations, analysis, etc." For Paul, students should be able to draw a trend, from interpretation of global data, and to conceptually make sense of the factors affecting the leaf size across different climate zones. We saw a higher ratio of ecologists/evolutionary biologists highlighting **conceptual sensemaking through data** when compared to cellular/molecular biologists (10 of 11, 2 of 4, respectively). We also noticed that ecologists/evolutionary biologists would elaborate on conceptual sensemaking with examples from specific topics such as population growth, habitat characteristics, and prey behavior. On the other hand, cellular/molecular biologists talked about conceptual sensemaking more generally. Barbara, a cellular/molecular biologist, spoke in generalities of students being able "to look at a set of numbers and extract what it means" but she did not offer an example in context. Emphasis on **conceptual sensemaking through data** was stressed by participants across all teaching experience categories and Carnegie classifications (Appendix A4 Table A.3, Appendix A5 Table A.4).

Using Models (8 of 15 participants). This code was conceptualized as the ability to understand and/or create a model to represent data or evidence. Models that participants referred to could be conceptual, mathematical, or graphical. For example, Betsy, a cellular/molecular biologist, talked of having students employ the numerical Hardy-Weinberg model "to take a written-out series of sentences and apply the formula" to calculate gene frequencies. Paul, an ecologist/evolutionary biologist, when teaching students to use a mathematical model of the interaction between wolf and moose populations, said that QR "... involves quantitative reasoning and models…. to make quantitative predictions conceptually and qualitatively." He also spoke of using a graphical model of the intermediate disturbance hypothesis "to [have students] look at a graphical representation of it and understand the concepts behind it". It is important to note that participants viewed creating or using graphical models as a sophisticated skill, but paradoxically (see below) viewed the creation of a graph from a data set as a basic skill.

Both ecologists/evolutionary biologists (6 of 11) and cellular/molecular biologists (2 of 4) emphasized using models, but cellular/molecular biologists emphasized graphical models over numerical models, and ecologists/evolutionary biologists emphasized them equally. Emphasis on **using models** was stressed by participants across all teaching experience categories and Carnegie classifications (Appendix A4 Table A.3, Appendix A5 Table A.4).

Thinking in Numbers (7 of 15 participants). No participant employed the definitive term 'numeracy' often used in the literature, but two participants specifically spoke of **thinking in numbers;** we thus employed the term as being representative of participant experience. Under this code, we grouped excerpts in which participants referred to students' ability or inability to perform simple mathematical operations in their heads. Students who demonstrate this skill understand relative percentages, orders of magnitude, and exponential functions. Betsy, when describing how some students lack the ability to think in numbers, said "they come up with some totally unreasonable answer [on their calculator and] do [not] realize that it's an unreasonable answer." Ecologists/evolutionary biologists and cellular/molecular biologists emphasized this ability equally (5 of 11, 2 of 4, respectively). **Thinking in numbers** was coded by participants in all teaching experience categories and Carnegie classifications (Appendix A4 Table A.3, Appendix A5 Table A.4).

Applying Comparative/Inferential Statistics (7 of 15 participants). Excerpts under this code included references to the ability to go beyond the descriptive statistics (e.g., mean, standard deviation) to use comparative/inferential statistics in data analysis and interpretation and to support hypothesis testing. Jim, an ecologist/evolutionary biologist said "I tend to want students to learn how to interpret data and do hypothesis testing with statistical tests." Both ecologists/evolutionary biologists (5 of 11) and cellular/molecular biologists (2 of 4) emphasized hypothesis testing but the two cellular/molecular biologists were explicit in using hypothesis testing to specifically determine statistical significance. Barbara, a cellular/molecular biologist, teaches Mendelian genetics by having students rear fruit flies; they test the hypothesis that expected and observed frequencies align, and to determine “is it statistically what we expect?” This code was not applied to participants in the 5-9 year teaching category nor from participants in R2 institutions (Appendix A4 Table A.3, Appendix A5 Table A.4).

Using Intuition (4 of 15 participants). When used in the context of QR, intuition is the act of predicting trends in a data set, the ability to understand quantitative evidence conceptually, and the ability to draw together disparate evidence or ideas to generate claims or hypotheses. Ken, an ecologist/evolutionary biologist, spoke of the ability to intuit a pattern in nature (e.g., organisms occupy predictable areas within an intertidal zone) and to develop a testable hypothesis to verify that pattern. He indicated that students intuit the cause of zonation is due to tidal exposure because they “think about the biology first… [and then] set things up to test [a hypothesis]”. Betsy, a cellular/molecular biologist, spoke about an intuitive understanding of what one unit of pH change means: “Let's talk about how to understand this more intuitively [in terms of magnitude],” indicating that students can perceive that one unit of pH change is a 10-fold change in hydrogen ion concentration. Participants for whom this code was applied were either early (0-4 years) or late (20+ years) career educators (Appendix A4 Table A.3, Appendix A5 Table A.4) with one participant each from all Carnegie Classifications except R2.

3.1.2 Second Theme: Basic QR Skills

The second theme of QR conceptualization related to what participants described as more basic skills of how students collect, organize, and process data; the following four codes thus related to what students do with data. Codes are presented in the order from most to least applied.

Creating/Describing Graphical Data (8 of 15 participants). This code was the only basic QR code that was frequently recorded by both populations (5 of 11 ecologists/evolutionary biologists, 3 of 4 cellular/molecular biologists), and was conceptualized as the ability of students to correctly identify independent and dependent axes, units of measure, and numerical data (e.g., mean, standard deviation, regression line). Participants were clear in distinguishing this skill from **Conceptual Sensemaking through Data** and **Using Models,** although research (Bowen et al., 1999; Schultheis & Kjelvik, 2020) finds this is not uniformly a basic skill. Don, an ecologist/evolutionary biologist, gave the following example as an in-class exercise where "We pool the whole course data together [and] plot those out on scatterplots… [to produce] seven graphs and three tables." He then goes on to describe the output as "publishable-quality... meeting legibility standards in Excel and Word". Barbara, a cellular/molecular biologist, indicated that students "can read a basic graph" and describe what is being measured, and the relationship between the variables. **Creating/Describing Graphical Data** was the only basic QR skill that was frequently recorded. This code was equally emphasized by all teaching experience categories but did not appear in R2 or Baccalaureate - diverse institutions (Appendix A4 Table A.3, Appendix A5 Table A.4).

Organizing Data (5 of 15 participants). QR under this code was conceptualized as a student skill in organizing information or messy data sets into a useful or meaningful form; the importance of this QR skill is reinforced in the literature (Schultheis & Kjelvik, 2015; Schultheis & Kjelvik, 2020). Lynda, a cellular/molecular biologist spoke about the importance of organizing data to communicate information: "How are [students] going to organize that information into some useful form ... so that people can understand what it is that [they are] talking about." We noted that participants linked the importance of organizing data, either in graphical or tabular form, to communication or explanation. This code was used by both ecologists/evolutionary biologists (3 of 11) and cellular/molecular biologists (2 of 4) across most teaching experience categories but only from Masters' and Baccalaureate - arts and sciences Carnegie Classifications (Appendix A4 Table A.3, Appendix A5 Table A.4).

Using Descriptive Statistics (2 of 15 participants). This code was characterized by measures of central tendency and variation. The two participants indicated that the ability to calculate these measures, and to understand how these measures characterize data, were both important pieces of the meaning of QR. For example, Betsy, a cellular/molecular biologist (0-4 year, Master's), stressed the importance of descriptive statistics to understand data "[The students] do averages [and] standard deviations... to understand what does standard deviation mean?" David, an ecologist/evolutionary biologist (20+ years, Baccalaureate - arts and sciences), echoed the importance of descriptive statistics to communicate "measures of location, measures of variability, ... in a meaningful pictorial way that's going to tell that story." It was interesting to note that only two participants explicitly recorded using descriptive statistics as this is a QR skill that most all scientists rely on.

Making Measurements (2 of 15 participants). This code was noted as a QR skill by two of the participants, both ecologists/evolutionary biologists. As defined by Thompson (2011) making measurements can be considered as the mathematical process of attributing a unit measurement to an object. Don (20+ years, Baccalaureate - arts and sciences) stressed the importance of measurements to provide evidence for patterns that students might be seeing, "We can measure it, so that we're not just seeing what we think we see but quantifying how much."

Whitney (0-4 years, R2) stressed that students should know they are measuring attributes, and not measuring “data”. She noted, “Are you measuring the data? [no] you [are] measuring the size, the length, the circumference, the diameter.” Whitney was the only participant to mention qualitative data in her conceptualization of QR, as she pointed out “that not all data can be measured...think about the ... results in terms of numbers versus in terms of shapes or colors, or smell or texture.”

Code Co-Occurrence

To determine any relationships between the ways that the QR skills were conceptualized by participants, transcripts were analyzed for code co-occurrence within excerpts (Table 5). A code co-occurrence appears in a statement when the same participant talks about different codes in explaining the meaning of QR. Code co-occurrence among the sophisticated, cognitively complex skills was revealed in 42 transcript excerpts, whereas code co-occurrence among basic skills was only seen twice. Code co-occurrence bridging the two themes (i.e., sophisticated co-occurring with basic) was revealed 14 times. For example, this first excerpt from Melinda (ecologist/evolutionary biologist) was coded as **Creating/Describing Graphical Data** and **Conceptual Sensemaking Through Data**:

> [QR] is interpreting – actually, interpreting tables and graphs ... being able to read the table or graph, understand it, and then being able to say, "Okay, based on like the fact that, you know, this is larger than this in the graph, right, then I think that the hypothesis is supported, or I think that hypothesis is not." [to] look at an equation, and be able to kind of interpret it not just as numbers, but as kinda like what – how different variables can affect each other...

A second excerpt from Melinda was coded as **Thinking in Numbers** and **Using Models**:

> …thinking about like, well, if you increased, you know, this variable that's on one side of the equation, how would it affect, you know, your output variable. So it was kind of using – so it's, again, reasoning with numbers, right, thinking about how changes in one variable affects changes in others in kind of this numerical way."

3.1.3 Faculty Attributes and the Variation in the Meaning of Quantitative Reasoning

Our second research question examined whether QR conceptualizations varied with faculty research background, teaching experience, or institution type. We found that participants in both cellular/molecular biology and ecology/evolutionary biology similarly conceptualized QR in terms of sophisticated higher-level skills. Both groups also more heavily emphasized sophisticated higher-level skills (theme 1) over basic skills (theme 2). Participant QR conceptualization, based on years of teaching experience, similarly showed a focus on the sophisticated higher-level skills. It was interesting to note that both early career educators (0-4 yr) and those with over 20 years of teaching experience had all nine codes applied to their transcripts, suggesting strong agreement in QR conceptualization between these two groups. The four references to **intuition** (Table 2 for research focus) were made by faculty who were either in their first five years of teaching (1 participant) or those with more than 20 years of teaching experience (3 participants). While less commonly reported overall, participant conceptualization of basic QR skills did appear across all categories of teaching experience.

We found that, for the most part, all categories of Carnegie classifications stressed Theme 1 - the sophisticated higher-level skills of QR, which may suggest upon the collections of further supporting evidence that baccalaureate granting institutions conceptualize QR in much the same way as institutions with graduate level programs. Also of note is that participants at R1 and R2 institutions were less likely to use the basic-level skills codes. For example, neither Organizing Data nor Using Descriptive Statistics were applied to R1 or R2 transcripts.

3.2 Quantitative Reasoning Skills Crucial for Success in Introductory Biology

Our study design allowed for extensive semi-structured interviews with rich data, but the small sample size does not allow us to make fully generalizable claims about the QR skills biology faculty believe are necessary for student success in introductory biology. However, we highlight several patterns we noticed in our data, which can be useful for further investigation. When we asked participants what QR skills they felt were crucial for success in introductory biology courses, thirteen codes emerged. We then compared those codes to the six Core Competencies described and validated in Clemmons et al. (2020). Eleven of our codes aligned with the Core Competencies of Process of Science, Quantitative Reasoning, or Modeling (Clemmons et al., 2022); two of our codes did not readily align with any of their Core Competencies. The alignment of our codes with the Core Competencies of Clemmons et al. (2022) are visualized in an alluvial diagram (Figure 2). Participants distinguished between what students *should be able to do with data* and *how students should think about data*, which provided insight into how biology faculty might parse some QR skills into cognitively complex skill sets, and view others as more simple.

3.2.1 BioSkills Core Competency – Quantitative Reasoning

All participants spoke of the overall importance of mathematical practices to successfully engage in QR practices in introductory biology, although not all participants mentioned each practice in their response. Codes are presented in the order from most to least applied.

Basic Math Skills (15 participants) were identified as being crucial to success in introductory biology. Practices in this category referred to students’ abilities to work with numbers, including mathematical operations, an understanding of ratios, the use of exponents and powers of ten, and an understanding of algebra. Bruce indicated that “[students] should be able to do basically simple addition, subtraction. Understand how means work.” Don suggested that students “[should] understand exponents and the power of ten, understand the number line, positive and negative numbers and how to combine them and do the math with numbers on that number line.” Seven participants specifically mentioned that students should be capable of ‘simple’ or ‘basic’ algebra. That participants identified the algebra needed in introductory biology as ‘simple’ suggests the sorts of equations they expect students to be able to understand and manipulate - transcript excerpts reveal these are related to solving linear or polynomial equations. For example, Jim indicated that students should understand that the generation of a standard curve is an application of a linear equation - “they need to make a standard curve first. They need to make their dilutions of it and then make a standard curve. … you make a curve and then later when you only have one of those variables, you can calculate the value of that other variable.”

Using Descriptive Statistics (8 participants) This code was characterized by measures of central tendency and variation. Two participants specifically indicated that the ability to calculate these measures, and to understand how these measures characterize data, were both important pieces of the meaning of QR. This skill was often referred to in context of organizing, visualizing, and/or communicating data. For example, Betsy stressed the importance of descriptive statistics to understand data “[The students] do averages [and] standard deviations... to understand what does standard deviation mean?” David echoed the importance of using descriptive statistics to communicate “measures of location, measures of variability, ... in a meaningful pictorial way that's going to tell that story.”

Graphing (7 participants) Participants spoke of students' need to be able to create graphs from data, frequently that they obtained themselves, in order to communicate information. At the introductory biology level, participants viewed creating or interpreting graphs as a 'basic' skill and referenced bar graphs, pie charts, and scatterplots as the types of graphs they would expect students to encounter at this level. Don explains "I focus on the really commonly-accepted forms of data visualization... So bar graphs for ANOVA, box and whisker plots, linear regression and scatter plots, what does it mean, how can you do it by hand, things like that."

Solving Equations (5 participants) Participants distinguished solving equations from creating or interpreting models. They suggested that, at the introductory biology level, students should be able to insert numbers into an equation to solve for an unknown quantity. For example, Betsy had students employ the Hardy-Weinberg equilibrium model, a polynomial equation, to calculate gene frequencies "Okay, I know what p squared is. How do I get pq? I don't have anything about q. How do we solve for it?" Participants were clear that they did not view the more advanced subjects of calculus or differential equations as necessary for success in introductory biology. Barbara explicitly stated "I would expect only up through say algebra. Even Algebra II. I don't necessarily expect them to have a whole bunch of calculus in [introductory] bio. ... I'm not expecting them to be able to do, you know, a derivative of an equation. I am just looking for them to be able to do what I would call seventh grade math."

Using Software (5 participants) The five participants who indicated that the ability to use software is critical to success in introductory biology specifically mentioned Microsoft Excel, mostly in the context of creating graphs, although two participants also mentioned being able to use Excel for data analysis. It is noteworthy that these participants all indicated that they teach students how to use Excel in their courses, and only one participant (Barbara) expected students to know how to use Excel prior to course enrollment. She indicated “[They should] know how to graph something basic on Excel”.

Using Inferential Statistics (4 participants) Four participants were explicit in recommending that successful students were familiar with the role of inferential statistics in hypothesis testing although they distinguished between knowing the role of inferential statistics and being capable of using these methods in data analysis. Lynda described how she included inferential statistics in the laboratory component of the course: “ I tend to want students to learn how to interpret data and do hypothesis testing with statistical tests. So for me, a lot of it is learning how to manipulate data, learning how to calculate averages, variances, standard errors, and then we have them do some statistical tests – T-tests, chi-squares – this year, we’ve gone up to analysis of variance – a very simple one.”

Identifying Independent and Dependent Variables and Axes (4 participants) These participants indicated that successful introductory biology students are able to identify dependent and independent variables in a data graph or in written text, and understand the nature of dependence/independence of variables. This practice was more advanced than simply labeling axes as *x* and *y*; participants indicated that students should understand why placing an independent variable on the x-axis can make it an explanatory variable for the information in the graph. Betsy explained “Okay, tell me this is what's being shown on the x-axis. This is what's being shown on the y-axis. I pretty much expect [the students] to be able to look at a bar graph or a line graph or something and know what those mean.”

3.2.2 BioSkills Core Competency – Process of Science

All participants stressed that, for students to be successful in introductory biology, they must be able to draw meaning from, or give meaning to, data. In the context of QR in introductory biology, they asserted that students should be able to interpret data to extract meaning from a figure or a table, or to better understand a concept. Five codes were generated from the transcripts, and are presented in the order from most to least applied.

Applying Critical Thinking (10 participants) These participants reflected that successful students are those who can see connections between data and concepts. These students can solve an equation and understand and apply the solution. If their calculation returns an error, or a graph they generate using software is not appropriate to the context, they recognize and correct it. Students who can apply critical thinking are "good consumers" of data (David). Lynda said she wants "students to think critically and not just want to regurgitate information … just wanting to get the information to spit it back out on the test…".

Putting Data in Context (7 participants) This code was applied to statements that indicated successful students are able to see applicable context to data; they can give data tangible meaning. George stated that successful students "... [are] able to understand new data and what it means I guess colloquially. Like, you could look at a line but what it means in the real world. Kinda extrapolating it to the bigger picture." He further clarifies by saying "poor students just read back to me what the figure is without placing it in context of what we're going over. They're just reiterating what's written. They're not telling me what [the context] means."

Using Study Design/Scientific Methods (5 participants) Five participants suggested that successful students in introductory biology have an understanding of the nature of science and the scientific method. These students could develop testable hypotheses, suggest appropriate design and sample sizes, and describe their results. It is noteworthy that participants distinguished an understanding of the scientific method from using descriptive statistics, graphing, and applying inferential statistics. Ken suggested that successful students could

“...come up with [a] hypothesis, collect data and write a report. … they have had some experience with doing a very simple study and writing the basic kind of report.”

3.2.3 BioSkills Core Competency - Modeling

Using Models (4 participants) Models could be either mathematical or graphical. Two participants suggested that successful introductory biology students are able to use equations (e.g. Hardy-Weinberg equilibrium) as models to understand or illustrate concepts. Melinda spoke about using models in her course in this way “I'll have them … sometimes look at an equation, and they have to be able to kind of interpret it not just as numbers, but what – how different variables can affect each other … thinking about if you increased, this variable that's on one side of the equation, how would it affect your output variable?” Two other participants felt that successful students could look at graphical models and extract meaning, or draw a graph to represent a concept. Paul spoke about using a graphical model in ecology “So for example we work a little bit with what are called species area curves …, I use those that's a very simple model that allows them to sort of see what a simple model is and how to apply it especially to deforestation.”

3.2.4 Proposed Additional Core Component -- Affective Factors

Although our interview questions explicitly prompted participants to talk about experiences or backgrounds related to QR in biological contexts, emerging from transcripts was also a sense that successful students possess positive affective factors that influence learning. While affective factors are neither skills nor competencies, they deserve mention as they are part of the epistemic practices of scientists. Participants cited certain affective characteristics as critical in students’ engagement in QR practices in biology classrooms. These affective factors are not presented specifically in Clemmons et al. (2020) and review of the BioSkills guide did not find any suggestions for alignment. That participants felt affective factors were an important consideration warrants further investigation.

Demonstrating Patience (5 participants) Participants characterized successful students as those that took their time to arrive at QR understanding, demonstrating patience and tenacity. These students are capable of working toward a solution, without simply relying on memorization and recall. As George suggested "I think a lot of high school students come unprepared for intro bio in the sense that [they] don't take their time [to think]... going from that memorization to that more active learning, which requires patience." David also suggested that students have become accustomed to a "much more of an instant answer expectation like the level of inquiry just speaking in very broad general terms isn't as great as it might have been at one time."

Demonstrating Confidence (2 participants) Participants characterized confident students as those who do not withdraw from the task at hand; they remain confident in their ability to solve problems and reach understanding. Paul spoke of successful students as "those that come with confidence in their ability to reason quantitatively and a lot of practice at it so that when they're encountering these new things that they enter them without trepidation. That they're open to it, that they're confident that they can figure it out and they have a little bit of practice."

Demonstrating Curiosity (1 participant) One participant spoke to the heart of the epistemic practices of scientists; they possess curiosity. Whitney suggested that successful students in introductory biology possess it, "I think it is one of the most important skills for scientists. If [they are] not interested I think they're going to really struggle as a student in the classrooms because there's nothing that sparks some interest. It doesn't have to be everything because I certainly acknowledge that … not everyone is going to be interested in everything.

That's perfectly fine. But if you're not interested in any of it, or curious to ask questions, then the scientific process is going to be drudgery."

3.2.5 Faculty Characterization of Expected QR Skills and Student Lack of Preparedness

We asked participants what QR skills they felt were crucial for success in introductory biology courses, and where they expected students to learn them. It was to these competencies that we applied the deductive codes of **Crucial** and **Expected**. Universally, however, participants simultaneously spoke of how many of these skills were **Lacking** in many of their students. They indicated that they often **Hoped** students possessed them, but many no longer **Expected** them. The disconnect between competencies **Expected** for success and those **Hoped For** is best expressed by David, "That's [evolved, hope or expect they're different. It's taken me a long time to learn that I can't make a lot of assumptions about what people bring to the table …. I've been plagued with this idea that things that seem obvious to me I just generally assume are obvious to everybody else. And have learned over the years that that's not the case."

Figure 2 is an alluvial diagram that demonstrates how the thirteen skills mapped onto three BioSkills (Clemmons et al., 2020) core competencies and the novel category of affective factors; the figure also illustrates participants' assessments of those skills in introductory biology students. The width of each flow corresponds to the frequency with which a code was applied, and connections between the three themes and the deductive categories of **Crucial**, and **Expected**, and the inductive categories of **Lacking** and **Hoped For**, can be visualized by following the flows. The most frequently occurring component of each category (skill, BioSkills competency, participant designation) is uppermost in each section.

The faculty applied all categories of **Crucial**, **Expected**, **Lacking**, and **Hoped For** to the the BioSkill of **Quantitative Reasoning**. Therefore, the alluvial graph shows **Quantitative**

Reasoning flowing to all of the categories. **Process of Science** flowed to **Crucial**, **Expected**, and **Lacking**, but it was not **Hoped For**. Conversely, **Affective Factors** flowed to **Crucial**, **Lacking**, and **Hoped For**, but they were not **Expected**.

At a finer level, every one of the 13 child codes describing important QR competencies individually flowed, via the four categories, to **Lacking** in the diagram, indicating that participants found at least some of their students unprepared for QR success in introductory biology (Table 6). Lynda, when asked what QR skills she found lacking in introductory biology students, responded "... it's just the basic math [that] is important. But the data analysis is the other thing. They don't know an X axis from a Y axis. Or, when we use a [line] versus a bar graph. Or, when - what's a dependent or independent variable?" Barbara indicated that students lacked the ability to construct graphs "I guess one of the major things at the very first year I taught, I tried to just have them do a graph on their own. And it was pitiful. So, when I was going through and creating their lab notebooks, I was like wow, this is a disaster."

4. DISCUSSION

Our research provides insight into the QR conceptualization of biology faculty who teach introductory biology courses. This insight could suggest recommendations for curricular and pedagogical changes. Research in biology education has already indicated that students with strong QR skills feel more ready for their future careers (Matthews et al., 2013). The semi-structured nature of the responsive interviews allowed us to develop a richer understanding of QR conceptualization that can be instrumental in developing larger survey-based studies. Faculty play a pivotal role in providing experiences for biology students to improve these skills. By interviewing faculty teaching in introductory biology courses, we were able to distinguish two themes of conceptualization which can inform pedagogy at the initial stages of a biology curriculum and provide scaffolding for development of increasingly sophisticated QR skills as students move through their academic programs.

Biological scientists rely on quantitative reasoning (QR) to create meaning from increasingly complex data products. *Vision and Change* called for pedagogical change in how QR is taught at the undergraduate level, but research, resources, and assessments are often written in the language of discipline-based education research, and not in the QR 'language' used and taught by many biology faculty. This study responds to this potential language barrier by asking faculty teaching in introductory biology, potentially outside of education research, what QR skills they view as critical for student success. We discuss our results below.

4.1 Faculty Conceptualization of the Meaning of Quantitative Reasoning

Participant conceptualization of QR revealed nine codes emerging which we grouped under two themes: 1) the more frequently recorded theme of sophisticated, cognitively complex skills, and 2) the less frequently recorded theme of basic skills. This distinction between sophisticated and basic skills mirrors the QR learning progression of Mayes et al. (2013); they wrote that QR begins with the simpler Quantification Act (QA), which aligns well with the skills our participants felt were simpler, and the more sophisticated skills align with Quantitative Interpretation (QI) and Quantitative Modeling (QM). As Mayes et al. (2013) demonstrated with their table of definitions for QR (p. 3, Table 1 in Mayes et al., 2013), our participants elicited some common threads, such as using mathematics and statistics in context for sophisticated reasoning. Our participants' conceptualization of QR had the same higher level emphasis on the importance of context. However, our participants also mentioned QR specific skills (e.g. **Creating/Describing Graphical Data, Organizing Data**) that are not seen in literature definitions. This may represent participants' own experience as biological researchers with the epistemic practice of their scientific field. In research, these faculty must employ cognitively demanding QR skills as they develop research questions, conduct and analyze their data, and prepare it for dissemination to a scientific audience. While they also employ the more basic skills, e.g., organizing data and preparing graphs and tables, they are perhaps so accustomed to these practices as second nature that these skills may come less to mind when asked to conceptualize QR for undergraduate levels. Students may still possess naïve epistemologies which can impact their ability to interpret complex information and they may view certain QR practices as more cognitively demanding than their faculty do. Hoskins et al. (2011) designed the C.R.E.A.T.E. approach to primary literature as a pedagogical tool which helps students 'think like a scientist' in tasks such as graphing. DiSessa (2004) argues that some of these practices, such as graphing, are only taught as 'sanctioned representations' which simplifies how these representations are constructed by scientists. While our participants view graphing as a skill, researchers argue that graphing is more than a cognitive skill, but a practice that involves social dimensions of scientists' work when they improve, communicate, and reflect on the knowledge produced in their field (Roth & McGinn, 1997). Our participants may also possess an 'expert blind spot' (Nathan et al., 2001) where their domain-specific knowledge of how to create and/or interpret graphs makes them blind to the processes of their novice students. Participants have acquired domain-specific knowledge, they have long-term practices in their respective disciplines, and they may be able to exploit their knowledge of familiar experiences to new tasks (Nathan et al., 2001). Moreover, Shah and Freedman (2011) have shown that graph complexity can affect students' graph comprehension and participants may have been 'expert blind' to the fact that they possess greater topic familiarity and graphical literacy than do their students. Both of these factors influence top-down knowledge of graph comprehension because perceptions are heavily influenced by expectations and prior knowledge. For undergraduate students to understand how scientists in biology use graphing, we need to aim for a deeper understanding of graphing practices. For such deeper understanding, our students need to experience ‘metarepresentational’ components of graphing, including ‘critiquing and evaluating’ the adequacy of graphs and creating new ones that better represent the data and its context (diSessa, 2004).

It is interesting to note that participant conceptualization of QR was not confined to any single skill outlined in either *Vision and Change* or the Bioskills Guide (Clemmons et al., 2020); rather the conceptualizations integrated multiple skills from those documents. Specifically, *Vision and Change* defined three individual core competencies relating to QR (ability to apply the process of science, ability to use quantitative reasoning, and ability to use modeling and simulations), and the BioSkills guide provided three comprehensive learning outcomes aligned with QR (Modeling, Quantitative Reasoning, and Process of Science). Whereas *Vision and Change* did not specifically provide learning outcomes, the Bioskills guide elaborates on program- and course-level learning outcomes providing an additional tool to compare participants’ experience and conceptualization of QR, which aligns well with our study. For example, the three program-level learning outcomes under the BioSkill Modeling (Purpose of Models, Model Application, Models) align well with **Conceptual Sensemaking Through Data** and **Using Models**.

In some cases, in our classification, one BioSkill learning outcome was grouped under two themes. For example, the program-level learning outcome of Numeracy (under the BioSkill Quantitative Reasoning) has course-level learning outcomes that were grouped under both sophisticated and basic themes for our participants. One course-level learning outcome, ‘*Use* *rough estimates informed by biological knowledge to check quantitative work*', (Clemmons et al., 2020) that was classified under Numeracy, aligns with our sophisticated skill **Thinking in Numbers;** whereas '*Perform basic calculations (e.g., percentages, frequencies, rates, means)*', (Clemmons et al., 2020) another outcome under Numeracy, aligns with the basic skill of **Using Descriptive Statistics**. Similarly, the program-level learning outcome of Quantitative and Computational Data Analysis, under the BioSkill Quantitative Reasoning, has course-level learning outcomes that distribute across our two themes. The BioSkill, '*Select, carry out, and interpret statistical analyses*' (Clemmons et al., 2020), is equivalent to **Applying Comparative/Inferential Statistics;** whereas '*Record, organize, and annotate simple data sets*' (Clemmons et al., 2020) aligns with **Organizing Data.** Lastly, the BioSkill Process of Science is represented in our participants' conceptualization by **Conceptual Sensemaking Through Data** and **Applying Comparative/Inferential Statistics**, both of these sophisticated skills align well with several of the course-level learning outcomes found in the program-level outcome of Data Interpretation and Evaluation.

An important finding of this work is that conceptualization of QR by our participants, who represent diverse research areas, teaching experience, institutional backgrounds, and knowledge of discipline-based education research, does not necessarily align with the literature. While most participants were in agreement with the sophisticated skills of QR, they clearly separated understanding graphical models from creating graphical data. The weaknesses in graphing abilities at the undergraduate level, and persistence of common graphing errors among students, suggests that current curricula are ineffective at helping students access and understand graphical data (Harsh & Schmitt-Harsh, 2016). Harsh and Schmitt-Harsh (2016) assert that students are often taught graphing skills with 'clean' or 'simple' data that obscure the messiness inherent in sample variability and subtle relationships between variables. Schultheis and Kjelvik (2015) convincingly argue that students learn best the nature of science when confronted with ‘messy’ authentic data that is both engaging and realistic. Our participants, however, still conceptualized graphing those data as a basic skill. Their view contrasts with established research (Bowen & Roth, 1998; Bowen et al., 1999) that suggests that interpreting graphs is a difficult task for novice learners because of the large number of representation practices employed in graph construction (e.g., translating data from tables into averages which are then plotted). Graphing is not as much a skill as an epistemological practice (Bowen et al., 1999). This apparent disconnect between participants’ views that graphing is ‘basic’ and research indicating the opposite suggests that larger scale QR conceptualization surveys of biology faculty would be helpful in developing tools and resources that identify and ameliorate potential misunderstandings.

4.2 Faculty Attributes and the Variation in the Meaning of Quantitative Reasoning

Conceptual Sensemaking Through Data was the most recorded QR conceptualization, and was especially emphasized by participants who self-described as ecologists/evolutionary biologists, whereas **Thinking in Numbers** was somewhat less frequently recorded by this group. This contrasted with participants who self-identified as cellular/molecular biologists who recorded both skills equally. While this may be a limitation of the small number of cellular/molecular biologists in our sample, this difference in emphasis in the two sophisticated skills may reflect the nature of the two disciplines, as was hypothesized by Clemmons et al. (2020). Ecology has both strong empirical and theoretical mathematical roots (Lomnicki, 1988). Beginning in the early 1960s, mathematical models were developed to investigate predator-prey dynamics, competitive interactions, and population dynamics (Godfray & McLean, 2020).

Graduate programs in ecology often require advanced training in mathematics and statistics. In contrast, traditional cellular and molecular biology initially focused on more qualitative aspects of DNA, proteins, and other cellular processes (Short, 2009) although recent advances in technology have increasingly led to more quantitative data sets in bioinformatics and genomics (Mathur et al., 2019).

Early (0-4 yr) and late (20+) career participants were most similar to each other in their conceptualizations of QR; all nine codes were recorded for each group, despite mostly early career participants being familiar with *Vision and Change* (Table 2.1). We hypothesized that an awareness of *Vision and Change* might influence their conceptualization of QR and the need to include QR instruction in their teaching. Indeed, four of the five early career participants were aware of the five core concepts and six core skills called for in the *Vision and Change* document, including the call to increase training in QR. The participants who had been teaching the longest, although not familiar with *Vision and Change*, indicated they began incorporating QR into their introductory courses because they saw that students lacked this ability, often when they saw these students again in their upper level courses. Perhaps later career participants arrived at the need for QR instruction in an organic, experiential way from their experiences in the classroom. It was also interesting to note that early and late career participants recorded both the sophisticated and basic QR skills, whereas the middle career participants did not record **Applying Comparative/Inferential Statistics** or **Using Descriptive Statistics**. It would be interesting to investigate the role of technology in this difference. Perhaps mid-career participants found some QR skills less important as students learned to rely on technology (e.g., statistical software), but those skills became re-emphasized for the early career participants as part of their familiarity with *Vision and Change*.

Interestingly, there was no difference in sophisticated QR conceptualizations among institutions of different Carnegie classifications; for example, all institutional levels recorded **Conceptual Sensemaking Through Data** and **Thinking in Numbers**. There was more variation in the recording of basic QR skills which might reflect the more diverse nature of student preparedness among differing institutional levels.

4.3 Quantitative Reasoning Competencies Crucial for Success in Introductory Biology

Transcripts of participant interviews aligned with three BioSkills competencies necessary for student success in introductory biology: Quantitative Reasoning, Process of Science, and Modeling. Transcripts also revealed a novel category of affective factors necessary for students success. Participants identified QR as *what students do with data*. In contrast, participants identified Process of Science as *how students think about data*. Both *doing with data* and *thinking about data* represent the epistemic practices of scientists, but participants distinguished a difference in cognitive demands between these two competencies. The last theme - affective factors - described the socioemotional competencies participants felt were necessary for success, or *how students felt about data*.

4.3.1 BioSkills Core Competency – Quantitative Reasoning

Participants described mathematical skills necessary for success in introductory biology, but also they felt they should not have to teach these competencies to their students. Uniformly, they viewed mathematical practice (e.g. proportional thinking, solving algebraic equations, drawing graphs) as part of their students' K-12 curricula; their characterization agrees with the suggested practices of Hallett (2003) – arithmetic, percentages, graphs, estimation, elementary probability and statistics, linear and exponential growth patterns – as those necessary for success. Participants' expectations also align with most universities, where the only mathematics prerequisite for introductory biology is often the mathematics requirement necessary for matriculation (Agustin et al. 2012). However, no participant indicated familiarity with either the Common Core State Standards in Mathematics (National Governors' Association [NGA], 2010) or the Next Generation Science Standards (NGSS Lead States, 2013) to support their assertion that these competencies are developed in K-12 curricula. Mayes et al. (2020) point out that university faculty often make assumptions about students' abilities to apply mathematical practices to biology, which leads to student confusion and frustration, and the conclusion that 'they can't do math'. Recent studies (e.g Jackson & Kurlaender, 2014) suggest that student readiness for college is an important factor for success, but one that college faculty may not know to assess. Our participants may possess an 'expert blind spot (Nathan et al. 2001)' with regard to mathematical skills, as illustrated by one participant's assertion that the math needed for success in introductory biology is 'seventh grade math', without evidencing familiarity with seventh grade math curricula. Clinedinst et al. (2013) indicated that over 85% of higher education institutions place moderate or considerable weight on student admissions tests (ACT, SAT), but these scores often over-predict student success in STEM. High achievement in the mathematics portion of a standardized test demonstrates mathematical ability in the abstract, but does not necessarily equate to a student's ability to apply mathematics in the context of scientific reasoning (McClure, 2020). A better predictor of success in introductory STEM courses (biology, chemistry, physics) is years of mathematics instruction in high school (Sadler & Tai, 2007) as studies have demonstrated that standardized tests value geometry and trigonometry over other practices (e.g. estimation, Grawe 2011). American College Testing (ACT, 2010) suggests that only one-third of students score as 'college ready' on the ACT, and stress the need for greater understanding of mathematical practices (Er, 2018).

4.3.2 BioSkills Core Competency – Process of Science

Conceptual sensemaking is at the heart of the process of science, and forms the basis of knowledge construction; it is integral to the epistemic practices of scientists. All participants in this study possessed terminal degrees in biology and thus had first hand epistemic practice which potentially informed their pedagogy. As Hrabowski (2022) eloquently pointed out, “It takes scientists to produce scientists.” Because the participants were all experienced research scientists, they understood what conceptual sensemaking practices are necessary for success in introductory biology, and they emphasized the importance of student-driven inquiry over rote memorization of content knowledge. This emphasis on student-driven inquiry aligns with both NGSS (2013) and *Vision and Change* (2011) reform efforts; numerous studies provide evidence that active, student-driven inquiry increases both student learning (England et al., 2019; Graham et al., 2013) and also engagement (e.g. Berland et al., 2016). Participants also related they spend considerable classroom and laboratory time building conceptual sensemaking practice with their students. Their pedagogy aligns with a common goal of introductory courses, which is to stress the nature of science and scientific thinking (Upzen et al., 2019).

4.3.3 BioSkills Core Competency – Modeling

Four participants mentioned understanding models as being crucial to success in introductory biology. Three of these participants were ecologist/evolutionary biologists, and only one was a cellular/molecular biologist. This finding aligns with Clemmons et al.’s (2020) hypothesis that experience with ecology/evolutionary research might influence participants support of learning outcomes relating to modeling. While they did not find statistical differences in the support of learning outcomes related to modeling by respondents with experience with ecological/evolutionary biology research, the historical role of modeling in these fields may have led our ecologists/evolutionary biologist participants to view modeling as crucial for student success.

4.3.4 Proposed Additional Core Component -- Affective Factors

It can be difficult to predict which students will successfully complete a STEM degree. Studies have attempted to tie high school transcripts and standardized test scores to retention and graduation, but these may not be effective predictors (Thompson et al., 2018). Missing factors in predicting student success include both an assessment of how student resilience, i.e. ‘grit’, can mediate success, as well as considering the value students place on learning tasks. These affective components of learning biology are poorly understood (Cooper et al. 2018), yet were revealed in participant transcripts as important to student success in introductory biology.

Academic resilience, or ‘grit’, has been defined by Duckworth et al. (2007) as perseverance and passion for attaining a long term goal. Students with a strong ownership of learning are more likely to demonstrate persistence with complicated tasks, even in the face of obstacles (e.g. content knowledge shortcomings) (Conley & French, 2014). Also important to academic success is student self-concept; it can influence both self-efficacy and motivation (Cooper et al., 2018). Participants did not specifically refer to resilience or student self-concept as characteristics of successful students, rather they spoke of patience and confidence as necessary components for success. Those students who demonstrate patience with learning are those that are motivated sufficiently, and have the self-confidence, to know they can ‘get it’ with time. England et al. (2019) indicated that positive emotions around learning (enjoyment, interest, hope, pride) can be beneficial to student learning and motivation, and that an increased research investigating these effects is warranted.

Our participants also recognized the role of perceived task value to students. Students, especially those who may be math averse, may gravitate to biology as the STEM major that is the least quantitatively demanding (Hester et al., 2014). Varsavsky et al. (2014) surveyed students about to graduate with a science degree to determine which skills students assessed as most important to develop, and quantitative skills were perceived to be less important than science content knowledge and communication skills. Attitudes can influence learning in STEM disciplines (Uzpen et al., 2019) and thus strategies to increase math-biology task values could be beneficial (Andrews & Aikens, 2018). Andrews and Aikens (2018) described how positive attitudes towards QR were necessary for student success, and advocated for low stakes formative assessments to reduce anxiety and build positivity. They also found that students' math-biology task values were significantly related to students' preparedness in math. This is confirmed in our study as participants saw math preparedness as integral to student success. The challenge becomes one of convincing students of the value of mathematics to QR in the context of biology, and in helping them move beyond the impression that mathematics should be siloed to their math courses.

4.3.5 Faculty Assessment of Expected QR Competencies and Student Lack of Preparedness

We did not specifically ask participants to assess whether their students possessed the QR competencies necessary for success in introductory biology; rather, their assessments came spontaneously as they were describing QR competencies. Uniformly, all thirteen competencies from the three themes (**Understanding of Mathematical Practices, Conceptual Sensemaking, Affective Factors**) mapped to **Lacking** as participants felt that at least some of their students did not possess them, despite their being **Crucial** for success and mostly **Expected**. That our participants described these QR competencies as lacking in introductory biology students is supported in the literature. Research (e.g. Jackson & Kurlaeder, 2014) suggests that students' lack of these competencies, especially at the introductory level, is common to all STEM disciplines, despite significant efforts to improve them both at the K-12 and college level. Scott-Clayton (2018) reports that, as of 2009, approximately half of all college students need to take remedial courses within six years of college entry, despite college faculty often expecting students to have well developed mathematical conceptions (Williams, 2015).

At many universities, matriculation into the institution is the only prerequisite mathematics course for biology, and many biology majors obtain QR competencies through required courses in other departments (Hoffman et al., 2016). This mathematics prerequisite for matriculation would suggest that students are math capable; what appears to be missing is students' lack of context for QR in disciplines (e.g. biology, chemistry, physics) outside of their mathematics experience. McClure (2020) writes that traditional math courses may not be effective in developing the QR competencies necessary for STEM disciplines, and Gaze (2014) writes that traditional mathematics, e.g. algebra, may be over-emphasized in current math curricula, actually leading to potential math phobia among prospective STEM students. He suggests that mathematics instruction that focuses on contextual applications of algebra better prepares students to think quantitatively, and also puts mathematics in the context of other disciplines. The lack of mathematical practice competencies described by our participants stems from their experience of students not being able to apply them to learning in biology, which is not equivalent to not possessing the competencies at all. Kashyap and Mathew (2017) write that the problem is less about students' abilities to perform mathematics calculations than it is about understanding what those calculations reveal. Having the necessary mathematical background is not sufficient if students cannot use mathematical and quantitative practices in context (Feser et al. 2013). Students may achieve high marks on mathematical problems that only involve calculation compared to calculations that have a scientific context (Matthews et al., 2013). Hester et al. (2014) suggested that introductory biology students were unable to spontaneously transfer QR competencies to biological problems but, after QR instruction modules were implemented, post-assessment data demonstrated learning gains in quantitative numeracy, data interpretation, and mathematical modeling. This result would suggest that students possessed the necessary mathematical and conceptual sensemaking competencies, but lacked practice in application to learning biology. Speth et al. (2010) similarly reported that students struggled with simple calculations, graphing, and conceptualizing data-driven arguments, but that intervention proved effective in students' abilities to bring these competencies to a biological context.

Several participants also suggested that certain affective factors necessary for success in introductory biology were potentially lacking in their students. Scientific knowledge stems from inquiry, and inquiry often stems from curiosity. As such, curiosity is an important factor in the epistemic practices of scientists, as is motivation and tenacity. Chiang and Liu (2013) write that emotional resilience is one of the most important, and hard to obtain, characteristics necessary to achieve academic success, and that emotion influences curiosity and problem-solving; Villalta-Cerdas et al. (2022) assert that academic self-discipline and commitment to college are strong predictors of college retention outcomes. Participants who noted that these affective factors were potentially lacking in their students reflect an understanding of their importance. Female and underrepresented minority students tend to exhibit lower math self-concept than their male peers (Sax et al., 2015), which can influence their persistence (Flanagan & Einarson, 2017).

5. RECOMMENDATIONS AND CONCLUSIONS

5.1 Revisiting the Research Questions

This study utilized semi-structured interviews of faculty teaching in introductory biology courses to determine how they conceptualized QR, what QR practices they suggested as necessary for success in introductory biology, and how well their students had background in these QR practices. One driver of this research was the *Vision and Change Call to Action* (AAAS, 2011), a document detailing five core concepts and six core competencies all undergraduate biology students should possess upon graduation. In part, *Vision and Change* noted the data-wealthy and complex nature of modern science, and the increasing demand for biology graduates to possess QR competencies to meet these new challenges.

Numerous studies have demonstrated that outdated teaching methods in college STEM courses persist (Handelsman et al., 2022), despite prodigious efforts on the part of science education researchers to spark pedagogical change. The science education research community does a laudable job investigating pedagogical practices, developing assessment instruments, and designing effective teaching resources. However, the exchange of innovative ideas does not frequently seem to move bidirectionally. The ideas often move from practitioner biology faculty to the discipline-based biology education researchers (Penuel & Hill, 2019). For example, much less seems to be written about what faculty unfamiliar with education research think about education reform - how they learn about it, how they feel about it, how they implement it. This current work was thus an initiation of a dialogue with biology faculty not necessarily familiar with science education research to explore two competencies in the *Vision and Change* recommendations - the ability to use QR, and the ability to use modeling and simulation. Specifically, we asked 1) how do faculty in introductory biology courses conceptualize QR?, and

2) do those conceptualizations vary with faculty research background, teaching experience, or institution type? We also sought to 3) identify what QR competencies faculty teaching in an introductory biology course sequence view as critical to student success, and 4) characterize faculty perceptions of student preparedness for success in these courses. Faculty participants were identified by research discipline as either ecologists/evolutionary biologists or cellular/molecular biologists; they were also characterized by years of teaching and by institution type (Carnegie classification).

5.1.1 Research Summary 1 - Faculty Conceptualization of Quantitative Reasoning

Two themes emerged from participant conceptualization of QR. The first and more frequently reported theme consisted of five QR skills that were conceptualized as sophisticated and cognitively complex (Table 3) and can be summarized as *how students think about data*. The second theme consisted of four QR skills (Table 4) that participants viewed as basic, despite evidence in the literature (Bowen & Roth, 1998; Bowen et al., 1999) suggesting they are not and that novices, e.g. undergraduate biology students, might find them challenging. Participants characterized these basic QR skills as *what students do with data*. Participants may have possessed an 'expert blind spot' (Nathan et al. 2001) where their experience and domain-specific knowledge led them to view skills in this second theme as more accessible to introductory biology students than they actually are. Participant conceptualizations aligned well with QR skills described in the BioSkills guide (Clemmons et al. 2020), despite most (60%) participants being unfamiliar with *Vision and Change*.

We did not find differences in QR conceptualizations between ecologists/evolutionary biologists and cellular/molecular biologists; participants in both subject areas emphasized the sophisticated, cognitively complex skills over the basic skills, and there did not appear to be differences among years of teaching experience nor Carnegie classification.

5.1.2 Research Summary 2 - Faculty Perspective of Quantitative Reasoning Competencies Necessary for Student Success

Participants were asked to identify and describe the QR skills they believed were necessary for success in introductory biology, and where they expected students to have learned them. Four themes were revealed: quantitative reasoning, modeling, the process of science, and affective factors. These can be viewed as what students *should be able to do with data*, how students *make sense of data*, and how students *feel about data*. Participants identified all of these practices as critical for success in introductory biology, yet asserted students arrive diversely prepared for this success with respect to QR. The 'expert blind spot' (Nathan et al., 2001) that appeared in participant conceptualization of QR also appeared in their characterization of some mathematical practices as being 'simple', 'basic', or even 'seventh grade'. For example, participants felt students should already be, but often are not, competent in their ability to work with numbers, including mathematical operations, an understanding of ratios, the use of exponents and powers of ten, and an understanding of algebra. That some of their students appear unprepared for math in context is not surprising, studies (Blumberg et al., 2005; Nakakoji & Wilson, 2020) suggest that students struggle to apply these operations in context of biology or other scientific disciplines. Participants also noted that conceptual sensemaking and affective factors are important to student success, and that many students lacked them, but they also noted that they expect to provide instruction to build these practices.

5.2 Recommendations

Meeting the 'call to action' of *Vision and Change* to increase biology graduates' ability to use QR presents numerous challenges. Students are entering introductory biology courses under-prepared for QR in context (Jackson & Kurlaender, 2014), faculty may not see the need (Eliassen et al., 2017) nor have the pedagogical content knowledge to teach QR (Andrews et al., 2022), and colleges may not be prepared to face these challenges (Elrod, 2014). We see four critical areas for further research, and resource development: 1) a focus on providing authentic epistemic experience and QR support for students, 2) increasing the awareness of *Vision and Change* and other documents to support pedagogical change in faculty, 3) fostering the development of multidisciplinary STEM faculty groups, and 4) engaging with educators from community colleges and high schools to develop appropriate transitions for college-bound undergraduates. We will discuss each recommendation below.

5.2.1 Supporting the Quantitative Reasoning Development of Biology Undergraduates

Successful biology instruction is authentic and captures the epistemic practices of scientists (Kelly, 2008). Biology faculty may have experienced their undergraduate training as a series of courses emphasizing rote memorization (Cooper et al., 2015; Handelsman et al., 2022), or they may have been fortunate to participate in authentic research experiences. From their undergraduate degrees, they pursued advanced study and developed as practicing scientists, perhaps incorporating epistemic practice as second nature and not being metacognitive about their emerging identities and abilities. It emerges as crucial, from this and other studies (e.g. Hester et al., 2014), that biology faculty 'meet their students where they are' in terms of QR practice and development if they are to engage, excite, and educate the next generation of biological scientists (Sadler & McKinney, 2010). Aikens and Dolan (2014) found that successful development of QR skills in students can create more enjoyment of their QR work, increase confidence and self-efficacy, and provide a greater sense of the value of mathematics in context. Students who developed QR skills showed improved ability to work in interdisciplinary teams and demonstrated increased school and career persistence (Aikens & Dolan, 2014). A potential first step for faculty wishing to teach QR is to provide those faculty with means to assess their students' preparedness for the work. Many useful assessments have been developed to this end; for example, Stanhope et al. (2017) developed BioSQuaRE to assess QR in undergraduate students, and Hicks et al. (2020) developed BioVEDA to assess student understanding of variation in biological contexts. Pre- and post-assessments of student QR practices could significantly inform course learning outcomes and drive QR content incorporation. We thus recommend professional development opportunities for faculty to learn how to use these, and other, instruments to help assess and scaffold QR development in their curricula.

Science is not a 'thing', not a collection of knowledge; it is a process. It is a process that leads to new knowledge, theories, and claims which contribute, or sometimes contradict, the existing knowledge in the field. Students, especially at the introductory level, do not always recognize this distinction. Experiences that positively shift students' attitudes about science and learning, and that promote self-efficacy, should be sought (Hoskins et al., 2011). We thus recommend that students be provided a wealth of opportunities to practice authentic science. The increasing abundance and diversity of course-based undergraduate research experiences (CUREs), for example, provides extensive ideas and resources to biology faculty who wish to include epistemic practice in their courses (Dolan, 2016). We would suggest that faculty authentically model and emphasize the fact that science is 'messy' (Schultheis & Kjelvik, 2020), that QR can be hard, and that taking meaning from data requires patience and tenacity. Students often misconceive that science is ‘easy’ for practicing scientists, because often they do not see scientists struggle with the scientific process. Students may misperceive that QR comes easily and naturally to their faculty. They see what is written in textbooks and perhaps in scientific literature, but those resources do not provide an authentic view of the ‘messy data’ nature of science and its challenges and setbacks. England et al. (2019) demonstrated that student anxiety and perception of difficulty can impact performance in introductory biology. Faculty pedagogy that simultaneously finds ways to create positive emotions in students while authentically portraying their own experiences and challenges in learning and research should be effective. E.O. Wilson (1994) encouraged an entire generation of scientists when he wrote honestly about his experiences as a student and early researcher; his depictions read like those experienced by many and thus made thoughts of a career in science imaginable and attainable. Authentic research experiences have been shown to shift student attitudes toward, and ability in, science (Hoskins et al., 2011). Students should be given opportunities to work with data - collecting, organizing, analyzing - to develop QR in context, which supports increased math-biology task values (Andrews & Aikens, 2018). Successfully applying QR practices in context for conceptual sensemaking empowers students and may increase student math self-concept (Cooper et al,. 2018) and self-efficacy.

5.2.2 Developing and Supporting Quantitative Reasoning Pedagogy for Biology Faculty

A better understanding of how biology faculty conceptualize QR can lead to targeted curriculum development. For example, our study suggests that faculty may put more emphasis on sophisticated skills, and view some skills, e.g., **Creating/Describing Graphical Data**, as simpler than they actually are. This has potential implications, particularly at the introductory biology level, if faculty perceive students more ‘ready’ for QR than they actually are. Understanding that QR skills can be divided thematically into basic or sophisticated groupings can help faculty scaffold student development both within introductory courses, and as students progress through their academic program. Hester et al. (2014) and Eliassen et al. (2017) recommend putting mathematical skills into biological contexts early and focusing on a gradual buildup of quantitative skills throughout the curriculum. Introducing QR skills early in the curriculum, and starting with basic skills (e.g. QA to QI to QM of Mayes et al. 2013), could increase students’ math self-concept (Cooper et al., 2018) and encourage them to further develop more sophisticated QR skills. Experiences that positively shift students’ attitudes about science and learning, and that promote self-efficacy, should be sought.

An obvious resource for supporting QR practice would seem to be course textbooks for introductory biology. Unfortunately, many introductory texts provide little to no opportunities for QR practice; many of the mathematical principles and formulae have been supplanted by additional pictures and photographs (Crow, 2004) leaving both faculty and students without resources and pedagogies for teaching QR. While textbooks may be slow to change, other organizations and institutions, e.g. Science Education Resource Center at Carleton College (SERC, 2023), BioQUEST’s QUBES program (QUBES, 2023), National Science Teaching Association (NSTA, 2023), and Ocean Data Labs from NSF’s Ocean Observatories Initiative (OOI, 2023) are moving forward at a fast pace to provide QR opportunities and course resources for incorporating QR practice in the classroom, field, and laboratory. Many professional societies are now providing teaching resources through their websites and at professional meetings (e.g. Ecological Society of America [ESA], American Society for Microbiologists [ASM]). These, and other, resources are extensive, comprehensive, and well-vetted. Problematic, however, is lack of awareness of this resource wealth among many biology faculty who are not fully versed in science education research (Lund & Stains, 2015; Shadle et al., 2017). Additionally, locating, accessing, and adopting these resources can be extremely time consuming, especially for faculty already struggling with time constraints and inadequate resources. We recognize that knowledge of QR resource availability, and how to access and use them, should be more fully developed.

Understanding what QR skills students are bringing to their learning is a first step, one that needs to be followed by supporting faculty to develop means of teaching QR in context. Recent studies (Andrews et al., 2022; Auerbach & Andrews, 2018) suggest that little is known about how college STEM educators develop and use PK and PCK. These authors advocate for more research focused on how STEM educators develop their pedagogies, with a special emphasis on active learning. Developing faculty pedagogy (PK and PCK), with a better understanding of how biology faculty at large conceptualize QR, can lead to targeted curriculum development. A significant challenge, identified in Lund and Stains (2015), which persists today, is that many biology faculty still are not familiar with discipline-based education research and evidence-based instructional practices that foster active, student-centered learning (Gardner et al., 2021). Many faculty in introductory courses often feel pressured to cover vast amounts of material, often defaulting to teacher-centered lecture pedagogy that obscures the interdisciplinary, inquiry-based nature of science (Cooper et al., 2015). Professional development opportunities - locally within and across departments, regionally, and beyond - may hold a key to pedagogical change. For example, Frey et al. (2020) suggested professional development programs are showing promise in preparing graduate students and postdoctoral researchers for effective undergraduate STEM teaching. Dalrymple et al. (2017) advocated a grass-roots approach to change by creating a volunteer community of faculty, post docs, and students to design introductory biology curricula. Mayes et al. (2022) wrote that faculty are often challenged to know what QR skills are the most important to include in their courses. Helping faculty understand the concept of 'backward design' (Wiggins & McTighe, 1998) may inform curriculum mapping, which would allow faculty to decide upon which QR skills they believe are necessary for student success, and then allow them to identify gaps, and strengths, in their programs.

5.2.3 Enhance the Multidisciplinary Context of Quantitative Reasoning

Student-centered, active learning opportunities that provide an opportunity to use QR in context will prepare graduates for quantitatively demanding careers in STEM (AAAS, 2011). Helping students understand the interdisciplinary nature of QR, and providing opportunities for them to use QR across multiple contexts, can develop their assessment of QR value (Andrews & Aikens, 2018) and QR self-concept (Sax et al., 2015). Increasing the interdisciplinary connections between mathematics and biology has been shown to be effective for building QR in context (NRC, 2009). However, the study of how students transfer learning between mathematics and the sciences has been neglected (Nakakoji & Wilson, 2020); also, few are studies of how faculty across STEM disciplines can collaborate to create interdisciplinary QR learning opportunities. Tripp and Shortlidge (2019) provided an Interdisciplinary Science Framework to assist educators to scaffold interdisciplinary QR learning experiences across STEM classrooms; they advocated that faculty use 'backward design' to develop interdisciplinary learning opportunities for students. Jackson et al. (2014) described a co-curricular mathematics support program that partnered a mathematician as a project leader with subject coordinators in STEM disciplines; they found that collaboration between mathematics and science faculty helped students overcome learning challenges. However, opportunities for biology faculty to work across disciplines, especially with mathematics faculty, can be difficult to find (McCully, 2013). We recommend that institutions find ways to develop and support informal and formal faculty learning communities (FLC) that support co-curricular exchange of experiences, PK, and PCK (Thompson et al., 2016). Mathematics and biology faculty might benefit from sitting in on one another's courses to have a better understanding of what is being taught in their respective courses, and how they might be able to reinforce content with context. Similarly, conversations with chemistry and physics faculty, whose students must also employ QR, would be fruitful. Assessment measures of how these interdisciplinary FLCs promote pedagogical change should also be developed (Favre et al., 2021).

5.2.4 Quantitative Reasoning Bridge from High School to Higher Education

Recruitment and retention in STEM begin with introductory courses (Watkins & Mazur, 2013), frequently taken by first year students who have recently graduated from high school. Students in K-12 classrooms have been exposed to crosscutting concepts in the four domains of science (physical science, life science, earth and space science, and engineering design) which seek to develop a scientifically based view of the world (NGSS Lead States, 2013). High school students are asked to apply mathematics and computational thinking in an array of contexts (e.g. use mathematical representations to explain factors affection biodiversity) yet, as college students, seem surprised to learn that biology research requires mathematics (Hodgson et al., 2005). Estimates suggest that half of students enrolling in higher education are assigned to at least one remedial math course, with the number rising to 60% for community college students (Boatman, 2021). Thus, there appears to be a disconnect between what students learn and accomplish in high school, and what they are expected to know upon matriculation to college (Er, 2018), yet this disconnect remains largely unexplained. Hill (2013) reviewed characterizations of PCK between university professors and high school teachers, and found considerable overlap. Both groups placed similar emphasis on subject matter, knowledge of students, instructional strategies, and knowledge of the curriculum. It seems likely, therefore, that high school and college faculty share similar goals, learning outcomes, PK, and PCK. We have perhaps identified with our research that what is missing is a common understanding and a dialogue between both groups. Mayes et al. (2020) wrote that K-12 teachers often decide what to focus on based on what they perceive is necessary for student success at the next level. They suggest that preservice teachers who experience QR in their biology courses may then teach it in their own curricula. We advocate for more research centering on the transition between high school and higher education, with a focus on STEM. Creating working groups of high school and college STEM faculty who can meet and share PK and PCK could be fruitful. Additionally, classroom visitations between mathematics and biology teachers and faculty across both groups could be informative, and possibly provide a mechanism to develop transitional curricula. Community college faculty should also be included in this mix, as they enroll ~40% of undergraduates yet less than 4% of discipline-based education research in biology has focused on this group (Corwin et al., 2019)

5.3 Conclusions

The increasing wealth and complexity of data, in the sciences and in society, demand a scientifically literate citizenry (Allum et al., 2018). *Vision and Change* (2011) identified the ability to use QR, and the ability to use modeling and simulation, as two core competencies graduating biology students should possess. Calls to begin QR instruction and practice in introductory biology (AAAS, 2011) are compelling; studies demonstrate that recruitment and retention in STEM must focus on and support novice students who may struggle with math and

QR anxiety (Sax et al., 2015). That said, awareness of this need, and resources for meeting it, do not always find their way to the faculty teaching introductory courses. Education research supporting pedagogical change, QR assessment instruments, and course resources are extensive and diverse, but dissemination often has been 'top down' from science education researchers to faculty in their institutions. We need mechanisms to close the loop by bringing in biology faculty from the 'bottom up'. Our study examined how faculty teaching in the introductory biology sequence conceptualized QR, what skills they feel are critical for student success, and their perspective on student preparedness. Our results suggest that biology faculty recognize the importance of QR, and aspire to create meaningful learning, but they may lack awareness of what QR practices their students struggle with, and how to teach them. We recommend future work to close the loop; extensive surveys of faculty teaching introductory biology could determine what QR resources need to be developed and effective ways to share them. Professional development opportunities should widen the circle and actively seek participants both within and outside the science education community as a means to broaden the impact. The call for pedagogical change, as written in *Vision and Change*, can still be answered.

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Table 1. Core concepts and competencies outlined in *Vision and Change: a Call to Action* (AAAS, 2011).

Core Concepts	**Core Competencies**
Evolution	Ability to Apply the Process of Science
Structure and Function	Ability to Use Quantitative Reasoning
Information Flow, Exchange, and Storage	Ability to Use Modeling and Simulation
Pathways and Transformation of Energy and Matter	Ability to Tap Into the Interdisciplinary Nature of Science
Systems	Ability to Communicate and Collaborate with Other Disciplines
	Ability to Understand the Relationship Between Science and Society

Table 2. Participant information relating to 15 faculty who teach in the introductory biology course sequence who participated in ethnographic interviews relating to the teaching of quantitative reasoning (QR). Faculty were drawn from universities and colleges in the 6 New England States.

Participant Pseudonym	**Subject Area Focus**	**Research Area**	**Years of Teaching**	**Faculty Rank**	**Carnegie Classification***	**Familiarity with *Vision and Change***
Betsy	Cellular/molecular	Cancer Biology	2	Lecturer	M2	yes
Cindy	Cellular/molecular	Microbiology	3	Assistant Professor	Baccalaureate -- Diverse	no
Lynda	Cellular/molecular	Microbiology	9	Associate Professor	M1	no
Barbara	Cellular/molecular	Immunology	10	Assistant Professor	Baccalaureate -- Arts/Science	no
Whitney	Ecology/evolution	Environmental Science	2	Lecturer	R1	yes
Maryann	Ecology/evolution	Plant Evolution	3	Assistant Professor	M1	yes
Melinda	Ecology/evolution	Plant Ecology	3	Assistant Professor	R1	yes
George	Ecology/evolution	Plankton Ecology	5	Assistant Professor	R1	no
Bruce	Ecology/evolution	Marine Biology	5	Assistant Professor	R2	yes
Carolee	Ecology/evolution	Entomology	6	Senior Lecturer	R1	yes
David	Ecology/evolution	Plant Ecology	26	Senior Instructor	Baccalaureate -- Arts/Science	no
Jim	Ecology/evolution	Wildlife Ecology	33	Principle Lecturer	Baccalaureate -- Arts/Science	heard of it
Paul	Ecology/evolution	Plant Ecology	22	Professor	Baccalaureate -- Diverse	no
Don	Ecology/evolution	Plant Biology	33	Professor	M3	heard of it
Ken	Ecology/evolution	Marine Ecology	41	Professor	R1	no

*Carnegie Classifications: **R1** – Doctoral Universities, Very High Research Activity, **R2** – Doctoral Universities, High Research Activity, **M1** -- Master's Colleges and Universities, Larger Programs (200+ degrees), **M2** -- Master's Colleges and Universities, Medium Programs (100-199 degrees), **M3** -- Master's Colleges and Universities, Smaller Programs (50-99 degrees), **Baccalaureate Colleges – Arts and Sciences, Baccalaureate Colleges – Diverse Fields**

Table 3. Theme 1 – Sophisticated QR skills. Codes for participant conceptualization of quantitative reasoning (QR). Fifteen participants were interviewed -- 4 cellular/molecular biologists and 11 ecologists/evolutionary biologists. Numbers in parentheses in the Participant column represent the number of cellular/molecular biologists and ecologists/evolutionary biologists to which the code was reported, respectively.

Code Name	**Number of Participants**	**Brief Explanation of Code with Example Excerpts**
Conceptual Sensemaking Through Data	12 (2, 10)	Working with data to better understand a concept, to extract conceptual meaning from a figure, or create a figure that graphically demonstrates a concept "I think a little bit more broadly about quantitative reasoning as the ability of the students to be able to take some of the concepts and the concrete information that they've learned in class, and be able to apply it to some sort of problem to answer questions, analyze data." (Lynda, c/m)
Using Models	8 (2, 6)	Understanding/creating a model (conceptual, graphical, numerical) to represent data or evidence as a facet of QR "[QR is] the ability to use, and apply, and understand mathematical models to understand natural situations and the world around us" (Betsy, c/m) "so being able to understand the Hardy Weinberg Equilibrium [a mathematical model] and applying it to a problem and understand the outcome is sort of that baseline level [of understanding modelling], but then there's the higher level of being able to think numerically and understand that what's happening in the world around us can be represented in an equation, or in a formula, or change can be modeled out." (Carolee, e/e)
Thinking in Numbers	7 (2, 5)	"Doing math" in one's head, e.g., 10% of a sample of 73 trees", would be close to 7, and not 3 trees "what I'll have them do is sometimes look at an equation, and they have to be able to kind of interpret it not just as numbers, but as kinda like what – how different variables can affect each other, so I don't do this a lot 'cause there's not a lot of places to put this in. But thinking about like, well, if you increased, you know, this variable that's on one side of the equation, how would it affect, you know, your output variable. So it was kind of using – so it's, again, reasoning with numbers, right, thinking about how changes in one variable affects changes in others in kind of this numerical way." (Melinda, e/e)
Applying Comparative/Inferential Statistics	7 (2, 5)	Applying statistical tools to support hypothesis testing, including the use of tools such as t-tests, analysis of variance (ANOVA), and correlation/regression. "[I see QR as] how to interpret data and do hypothesis testing with statistical tests... and that's [descriptive statistics] not as important as understanding sampling or – and variability [in data] And understand that in science, we can falsify hypotheses, but we can't really prove hypotheses .... And how you can look at two means that are different, but that difference may not mean anything in biology." (Jim, e/e)
Using Inferential Intuition	4 (1, 3)	Drawing key scientific ideas by looking for trends or patterns in a data set, without having to do calculations "the intuition about data and numbers...So I think there's kind of like this tug of war situation where ... intuition is going to be something that lends itself to quantitative reasoning, and strong quantitative reasoning skills" (Cindy, c/m)

Table 4. Theme 2 – Basic QR skills. Codes for participant conceptualization of quantitative reasoning (QR). Fifteen participants were interviewed -- 4 cellular/molecular biologists and 11 ecologists/evolutionary biologists. Numbers in parentheses in the Participant column represent the number of cellular/molecular biologists and ecologists/evolutionary biologists to which the code was reported, respectively.

Code Name	Number of Participants	Brief Explanation of Code with Example Excerpts
Creating/Describing Graphical Data	8 (3, 5)	Identifying independent and dependent axes, units of measure, and numerical data, e.g., mean, standard deviation, regression line "So, basically it [QR] means that they [students] can look at a set of numbers and extrapolate what it means. So, you can look at a graph and you can read the graph and understand what it means…. But if you can look at a graph and you can look at in a way that - you can clearly look at it to see if the axis makes sense, and what the person is saying about the graph actually is what the data represents. That being in a major quantitative reasoning." (Barbara, c/m)
Organizing Data	5 (2, 3)	Organizing information or messy data sets into a useful or meaningful form "[QR is] the ability to understand what data means and how to organize data so that it makes sense...And then again, how are you going to organize that information into some useful form that has summarized things quickly so that people can understand what it is that you're talking about." (Lynda, c/m)
Using Descriptive Statistics	2 (1, 1)	Identifying measures of central tendency and variation "So we start out with descriptive statistics… So before they even learn what biology is, they learn that when we have to have a look at the world, we observe it, ... and we quantify what we're seeing...We're analyzing the data we got. And so they're doing descriptive statistics. What is the mean? What does that mean? The central tendency of the data. What is the standard deviation? It's a measure of variance. And it's how wide this histogram is at a certain place. So we're trying to get the idea that data are not perfect, that there's variance in the data, and that we have to make decisions based on how the mean and the standard deviation reflect each other."(Don, e/e)
Making Measurements	2 (0, 2)	Attributing a unit measurement to an object or observation "I think the [QR] skills around some of their [experimental] designs revolve around getting comfortable with both the tools and the types of measurements that are appropriate for particular experiments for what we do in the lab. So the tools being the hydrometers that they build, how did they scale things properly, what are they measuring and have they measured it properly with the appropriate equipment." (Whitney, e/e)

Table 5. Code co-occurrences between nine child codes representing participant conceptualization of quantitative reasoning (QR). Fifteen participant interviews were coded for responses; where appropriate an individual statement could be assigned multiple codes, which is represented below. The numbers in the table represent the number of times two codes co-occurred, and not the number of participants for whom co-occurrences were recorded. Shaded areas indicate where skills within the same theme are co-occurring.

		Theme 1 – Sophisticated QR Skills					Theme 2 – Basic QR Skills			
		Conceptual Sensemaking Through Data	Using Models	Thinking in Numbers	Applying Comparative Inferential Statistics	Using Intuition	Creating Describing Graphical Data	Organizing Data	Using Descriptive Statistics	Making Measurements
Theme 1	Conceptual Sensemaking Through Data		**7**	**11**	**6**	**7**	4	3	1	1
	Using Models			**2**	**1**	**4**	2	0	0	0
	Thinking in Numbers				**2**	**0**	0	0	0	1
	Applying Comparative Inferential Statistics					**2**	1	0	0	1
	Using Intuition						0	0	0	0
Theme 2	Creating Describing Graphical Data							**0**	**1**	**0**
	Organizing Data								**1**	**0**
	Using Descriptive Statistics									**0**
	Making Measurements									

Table 6. Example excerpts relating the three BioSkills competencies, and one novel category of affective factors, to thirteen codes fifteen participants indicated are crucial for success in introductory biology. *The text in italics below each code name is a program- or course-level learning objective (PLO or CLO) from BioSkills Guide (Clemmons et al., 2020) that aligns with that code)*. The number of participants to whom the code was applied is indicated in the second column of the table.

Code Name	**Number of Participants**	**Example Excerpts**
		BioSkills Competency – Quantitative Reasoning
Basic Math Practices (*CLO -perform basic calculations*)	14	Bruce: In a perfect world, my students would come to intro bio with at least being ready to take precalc and understand how rates of change work, how means work, how deviation works. I'm pausing a little bit just because I know it's going to be many, many, many years until that happens in my context. … That's just reality of who I get. I go into my semesters knowing it's going to be a pretty wide range [of student abilities]. I don't teach with the expectation that they have these skills, because then I'll set them up to fail. I do as much as I can to figure out where they are and build a pedagogy to support the progress based on how they enter. Don: I would like them to come in with much more than they do. They struggle with simple algebra. They struggle understanding exponents and powers of ten. They don't have a great idea about probability. They don't understand the number line, positive and negative numbers, and how to combine them and do the math with numbers on that number line. Cindy: I mean unfortunately, students come in and they don't have a solid understanding of algebra and we do have students … that are in remedial classes ... I would expect them to have that [basic math] but in reality, it's not always true. Carolee: And so we find that there's a proportion of students who just don't have the quantitative – the baseline quantitative skills to be able to push themselves to move forward. Jim: I'm not sure if they do have [basic math] because they've been using calculators all the time. … what I mean is being able to divide and multiply. … I do find that students are not as good in math as they used to be. Like … where instead of just moving a decimal place over a couple of places … they're taking a hundredth of something, they need to pull out their calculators. Jim: in terms of converting from one metric unit to another – the joke is, we'll go from milliliters to microliters, and they'll get out their calculators. And I'll stand at the board and say, no, just move the decimal place over. Melinda: You know, I thought they would understand ratios, to be honest. That was [a mistake] on my part. They really don't get that.

Table 6 continued

Using Descriptive Statistics (*CLO - select, carry out, and interpret statistical analysis*)	8	Jim: … we have some students who really struggle with [descriptive statistics]. I guess I would want them to know what an average means. And I guess that's about it. … I suppose I don't even expect them to know what a median means, because we really don't talk about the difference between means and medians. David: I would think that they would come in and this is really basic like knowing what an average is. Essentially the stuff you were saying you calculate and average and draw a conclusion from that. And most of them … have that concept; they have very basic descriptive statistics concept and some of them can actually put it in a graphical form. But I probably don't expect much more than that and sometimes don't get even that. And we're talking cream of the crop students here. Don: And so they're doing descriptive statistics. What is the mean? What does that mean? The central tendency of the data. What is the standard deviation? It's a measure of variance. And it's how wide this histogram is at a certain place. So we're trying to get the idea that data are not perfect, that there's variance in the data, and that we have to make decisions based on how the mean and the standard deviation reflect each other. Betsy: it's pretty basic stuff for the most part, right? They do averages. They do standard deviations. So I would ideally like them to understand: what does standard deviation mean? It's the spread in your data. And then something else I often see with students is they think you have to have a small standard deviation for it to be good data. And it's like: well, it depends on what type of data. If there is variation in the sample because you're looking at a bunch of birds and they have variation, then that doesn't make your data bad. But that's something they struggle with a lot.
Graphing (*CLO - create and interpret informative graphs and other data visualizations*)	7	Whitney: Unfortunately they don't already have that [graphing skills]. You know, to ask it would be wonderful if students all were able to [do] this, have the ability to read a basic line graph, to understand histograms. You know, just basic data skills. Lynda: But the data analysis is the other thing. They don't know an X axis from a Y axis. Or, when we use a [line graph] versus a bar graph. Or, when - what's a dependent or independent variable? Barbara: I would expect them to come in with, know what and X and Y axis is. Know how to graph something basic on Excel, which they don't come in knowing, but that's - I have learned they don't come in with that. …I've given them data and made them graph it on the exam like in hand. It's a simple graph that you can do in two seconds, and so how they make it take five minutes? Betsy: So I think it will be straightforward to them to understand: if I said, "Make a bar graph of the activity at those five different concentrations," but then this number that is – how do I wanna say this? I think it's the idea of analyzing the data in a different way than what they're used to so far. Whitney: So any kind of graph or, you know, when is a chart [table]appropriate, when is a graph appropriate, what kind of visual results are appropriate, and they have a hard time of graphs and making and labeling appropriately the graphs.

Table 6 continued

Solving Equations (*CLO - select and apply appropriate equations to solve problems*)	5	Lynda: … these kids that shut down when you see them put an equation up on the board and say, "Don't worry about this, just look at the big picture," I'm kind of like, I don't even sometimes know how to start thinking about integrating more mathematical concepts into my class. It's a balancing act that I think we all struggle with. *Note: there are two forms of the Hardy-Weinberg equation that students work with (referenced in excerpts below):* $(p+q)^2=1$ *and* $p^2+2pq+q^2=1$ Betsy: with Hardy-Weinberg, there're multiple equations. It's like you have p-squared, pq , q-squared, and the p plus q equals 1 . So I think actually maybe the fact that you have a system of multiple equations – I think that's tricky for them. Betsy: For Hardy-Weinberg it's mostly: what is p? If I look at this word problem and I see this thing, this number associated with some words, is that p? Is that p squared? What does that mean? I think that part they struggle with. And then also: even if they figure out appropriately that that is p squared, they're like, "Well, I see p squared" – so I guess they don't struggle with the algebra – how do I say this? So if they know what p squared is, they still are like, "Okay, I know what p squared is. How do I get pq? I don't have anything about q." And I'm like, "Yeah, but you have an equation." So I don't know if you count that as struggling with the algebra or not. Carolee: And of course within evolution using the Hardy Weinberg Equilibrium to understand natural flux in population shifts. Very challenging for many students. Barbara: Yeah, so I'd say all the Hardy-Weinberg stuff is in lecture. So, that's simple algebra.. You can apply this simple quadradic equation that I have learned since grade seven to do.
Using Software (*CLO - record, organize, and annotate simple data sets*)	5	Barbara: How to graph something basic on Excel, which they don't come in knowing, but that's - I have learned they don't come in with that. I tried to just have them do a graph on their own. And it was pitiful. So, when I was going through and creating their lab notebooks, I was like wow, this is a disaster. That was the first one. Then I was like okay, I need to go through and show them how to use Excel. But I think a lot of them in - maybe in high school that's just not, you just don't teach how to make a graph in Excel.
Using Inferential Statistics (*CLO - interpret the biological meaning of quantitative results*)	4	Maryann: Sometimes they think that the bar graph is the anova, rather than a representation of the data. So rather than seeing a graph as something that can enhance your readers' understanding, they think of it as the output of the analysis. David: Just the thing that I talk about in lecture that whole idea you can't draw conclusions based on small differences in the mean. And that's what they like to do, that's the skill they come in with. Betsy: Again, really basic statistics like a t-test, and understanding what a p-value is. And it's so interesting. 'Cause a lot of them can say – if you say, "Your p-value is this, do you have a significant difference or not?" they'll tell you, "Oh, no, there is not a

Table 6 continued

		significant difference." But they'll go on in the next sentence to say, "Oh, this treatment had a bigger effect – increased reaction time." And you're like: "You literally just said it's not a significant difference and now you're" – they disconnect it in their head.
Identifying Independent and Dependent Variables and Axes (*CLO - create and interpret informative graphs and other data visualizations*)	4	Barbara: I would expect them to come in with, know what and X and Y axis is. Know how to graph something basic on Excel, which they don't come in knowing, but that's - I have learned they don't come in with that. Lynda: They don't know an X axis from a Y axis. Or, when we use a line versus a bar graph. Or, when - what's a dependent or independent variable?
		BioSkills Competency – Process of Science
Applying Critical Thinking (*PLO – SCIENTIFIC THINKING*)	10	George: So if I gave them a problem and I gave them data, they can't then see the solution. They can identify the problem, and they can maybe interpret the data, but they can't put the two together. they'll just repeat what the two axes mean. …So they're describing what they see but not what's being represented?... They're just reiterating what's written. They're not telling me what it means. Cindy: Critical thinking skills. I think that it's really tough to get them out of the mindset of learn or memorize, regurgitate and forget.…I think a major challenge is showing – or having them recognize the value of understanding the concept, and then thinking critically about it in context. Carolee: I think students get bogged down in believing that we want them to memorize the details with the evidence. David: I do think that way that students gather and interpret information has changed. …And now everybody is instantly connected …. I get the sense that the students expect everything to be a quick answer. You don't have to think about it because you can just Google it. … And to what extent that has effective their ability to do this quantitative reasoning sort of thing I can't say with any certainty. I think it could have an influence and probably not for the better.
Putting Data in Context (*PLO – DATA INTERPRETATION AND EVALUATION*)	7	Cindy: I think a major challenge is showing – or having them recognize the value of understanding the concept, and then thinking critically about it in context. I think that one of the major things that I encounter with students is their ability to understand the significance of research finding. So I'm really trying to expose them more to primary literature at this very first stage in their college career, and for me, the quantitative reasoning component really becomes the forefront of my discussion with them, when we're talking about how we interpret results. First of all, how we design experiments and how we – how we get results, and then how we interpret them is something that I think that a lot of students struggle with. And so in the context of biology, I think it's important to expose them more to what actually is being done in the field, and I mean it's an incredibly diverse field, being biology, but what's being done and how we gather meaning from that data that's collected. Because again, my biggest thing is trying to connect all of these kind of abstract concepts. You know, why should students care about mitosis? Why should they care

Table 6 continued

		about miosis? How does that affect their daily life? So I think that quantitative reasoning to me is really trying to connect those dots of what's being collected out in the field, and how it's being applied in the classroom.
		Carolee: [in terms of applying this to inherited diseases and population change] you can answer that on many levels, so being able to understand the Hardy Weinberg Equilibrium and applying it to a problem and understand the outcome is sort of that baseline level, but then there's the higher level of being able to think numerically and understand that what's happening in the world around us can be represented in an equation, or in a formula, or change can be modeled out.
		Whitney: And I think sometimes what happens is students get so nervous and so bogged down in like, "I have to have numbers," and they lose the big picture of what the purpose of the topic is that we're covering…. [they can take] these finer scales, numerical values that they're getting from their measurements and be able to step back and apply it in context, and to the big picture.
Attending to Nature of Science and Epistemic Practices of Science (*PLOs – SCIENTIFIC THINKING, STUDY DESIGN*)	5	Paul: I don't really mean that that's highly exaggerated but some of the series of exercises and assignments and things like that and short lectures that I did that I hope the idea is that it teaches them why we do statistics, how to do statistics, what are appropriate statistics, how to use them, how to find them and how to interpret them in primary literature all of those sorts of things.
		Don: I think the reason we chose [the text] over the others was that it has a lot of built-in experiments and results. And they focus a lot on scientific method, experimental method, and interpretation of results. The students really needed this.
		Whitney: They want to, in their results, describe things numerically, but the way that they setup their not able to do it and they only are able to describe it qualitatively. And so when we present that quantitative ways of thinking about design, we ask them to think what is it that you're actually measuring. Are you measuring how the _____ _____ data? Are you measuring the size, the length, the circumference, the diameter? How can you think about the aspect of your results in terms of numbers versus in terms of shapes or colors, or smell or texture?
		Ken: And they're supposed to come up with hypothesis, collect data and write a report. Which means they have had some experience with doing a very simple study and writing the basic kind of report. But they have very little understanding or appreciation for the diversity in the animal kingdom and the plant kingdom and such. Because they just have to sort of memorize some stuff out of the textbook and lectures. And they don't have any exposure … to get them to reinforce that.
		Whitney: I think in terms of more qualitative skills I think healthy curiosity.
		I think is one of the most important skills for scientists. If you're not interested I think they're going to really struggle as a student in the classrooms because there's nothing that sparks some interest. It doesn't have to be everything because I certainly acknowledge that biology in the inter _____ is so _____, and not everyone is going to be interested in everything. That's perfectly fine. But if you're not interested in any of it, or curious to ask questions, then the scientific process is going to be drudgery.

Table 6 continued

BioSkills Competency -- Modeling

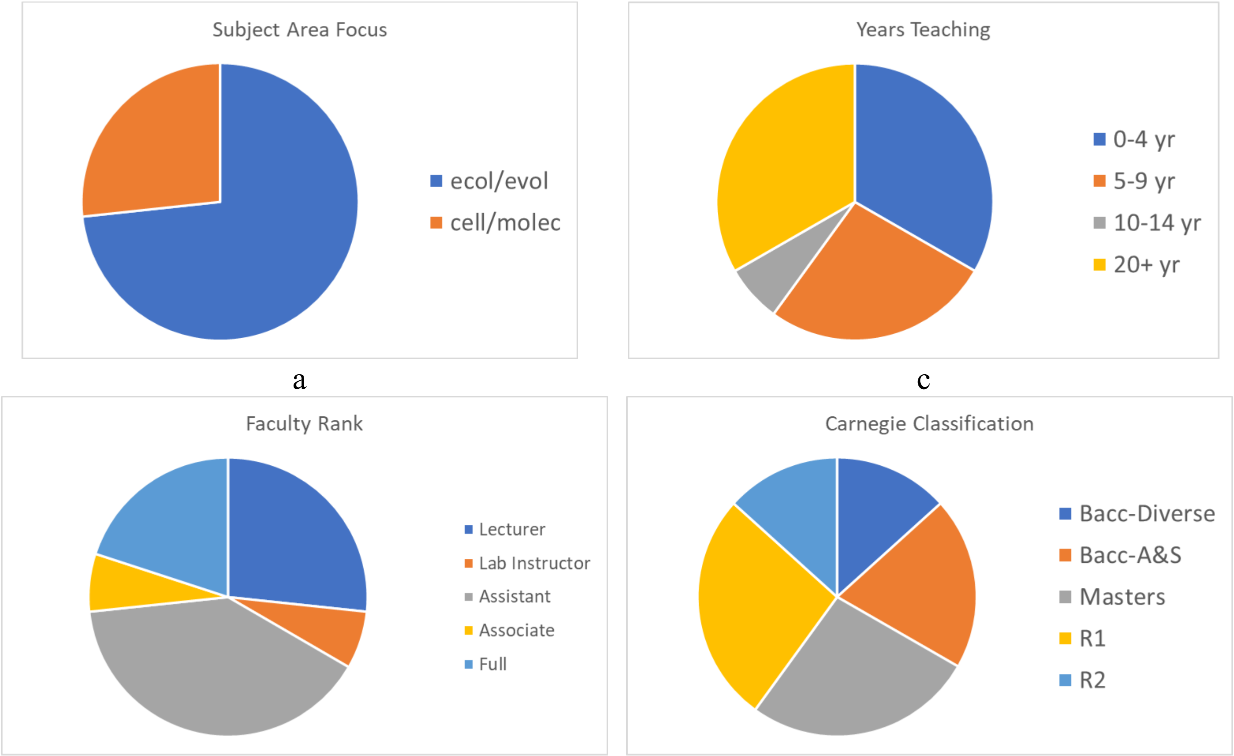
Using Models (*PLO – MODEL APPLICATION*)	2	Paul: So for example we work a little bit with, I don't know what your background is but what are called species area curves it's a way yeah, species area curves so I use those that's a very simple model but it's a model that allows them to sort of see what a simple model is and how to apply it especially to deforestation. … So it's quantitative it involves quantitative reasoning and models. I kind of use that as an emphasis to try to teach them a little - some about species interactions but even more so to get them to start seeing the idea of how to use models. Not asking them to make quantitative predictions with the models but these are in a sense they're using them conceptually and qualitatively. But they're still mathematical models. Carolee: Here's the Hardy Weinberg model. Here's how it applies, and here's how we use it. And then students learn how to plug and chug those numbers and being able to understand, "Well P is this, so then Q is this," but not really extrapolating out from there. And just like being able to look at a figure and understand what that figure – understand how to read the axis and understand relationships between data. That's a skill that it's not innate that students know how to do that. And so bringing in all these – all those pieces. Betsy: And so Hardy-Weinberg – we spend a lot of time on that. And a lot of that is just stuff that – understanding word problems. How do you take a written-out series of sentences and apply that to what we learned about a formula and know what things are what variables? So I think those word problems actually – that's really important. And a lot of them really struggle with that, and they want you to give them a method for solving those problems where they can go through step by step by step. And I'm like, "Well, I can kind of give you that for some of these things. But really it'd be better if you just could come to a point where you can do that. Like you'll make the formula for how to solve it" Paul: They couldn't think in that way they struggled with that, they struggled with mathematical models. And so I was determined to start them right away. (362) … get them to start seeing the idea of how to use models

Novel Category -- Affective Factors

Demonstrating Patience	5	David: I get the sense that the students expect everything to be a quick answer. You don't have to think about it because you can just Google it. I do the same thing. And to what extent that has effective their ability to do this quantitative reasoning sort of thing I can't say with any certainty. I think it could have an influence and probably not for the better. George: I think a lot of high school students come unprepared for intro bio in the sense that – talking to my high school teacher friends, there's a transition right now in high school _____ going from that _____ memorization to that more active learning, but it hasn't gone far enough yet. So this in between stage, I feel like students aren't strong in either.

Table 6 continued

	Ken - But I think the distraction of cellphones and other electronic devices and such. And it’s actually been a negative in terms of you know, an actual ability to concentrate and focus or be patient. Or, to spend time writing.
Demonstrating Confidence	Paul: What I would hope that they would come with is confidence in their ability to reason quantitatively and a lot of practice at it so that when they're encountering these new things that they enter them without trepidation. That they're open to it that they're confident that they can figure it out and they have a little bit of practice. I don't expect them to have taken a statistics course. Some have but I don't think that necessarily. I think that that's - and facility with basic math too. I would hope that come with that too. And honestly they don't always come there with those things at all. A lot of them are have a great lack of confidence about being able to do math. Whitney: students coming in and saying like I’m no good at this the first day and not participating because they think they’re not good enough to be there breaks my heart.
Demonstrating Curiosity	Whitney: “I think [curiosity] is one of the most important skills for scientists. If [they are] not interested I think they’re going to really struggle as a student in the classrooms because there’s nothing that sparks some interest.



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b d

Figure 1. Descriptor data relating to 15 faculty who teach in the introductory biology course sequence who participated in ethnographic interviews relating to the teaching of quantitative reasoning (QR). Faculty were drawn from universities and colleges in the 6 New England States. (a) Characterization of participant subject area focus: ecology/evolutionary biology or cellular/molecular biology; (b) Characterization of participant faculty rank; (c) Characterization of the years participants have spent teaching, in intervals representing early career/pre-tenure (0-4 yr), post-tenure (5-9 yr), mid-career (10-14 yr), and senior faculty (20+ yr). No participants were in the 14-19 yr category; (d) Characterization of the Carnegie Classifications of the participants' institutions.

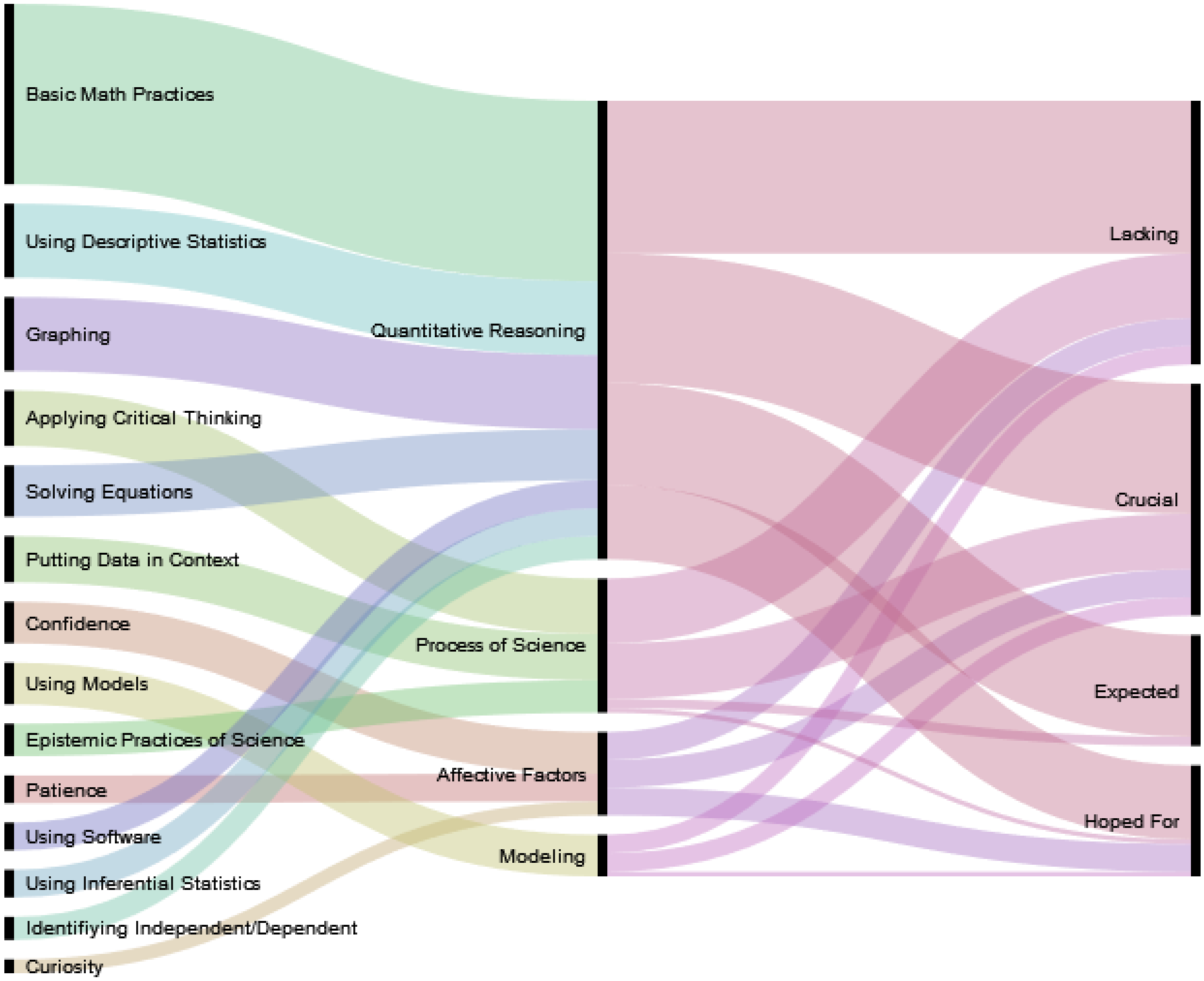

Figure 2. Alluvial diagram representing the grouping into BioSkills Guide (Clemmons et al., 2022) core competencies of thirteen QR skills that participants indicated were necessary for success in introductory biology courses. The height of the vertical bars represents the number of participants that coded the **individual competency** (left-hand bars), the **BioSkills Core Competency** (middle bars),and **participant designation** (right-hand bars). Note that Affective Factors is not included in Clemmons et al. (2022). The width of the stream represents the size of the components contained in both blocks and connected by the stream.

APPENDICES

APPENDIX A1.

Recruitment email for faculty participants.

Thank you for your consideration in participating in my research study. I am a biology professor at Maine Maritime Academy, and also currently a graduate student in the Research in STEM Education Center at the University of Maine, pursuing a Master in Science Teaching. I am interested in learning to what extent faculty of introductory majors biology courses incorporate teaching of quantitative reasoning skills. My hope is that an understanding of current curriculum practices may inform teaching and textbook resources. Please read this form and ask any questions you might have before you agree to take part in this research.

What You Will Be Asked To Do

You will be asked a series of questions, such as “Do you teach quantitative reasoning skills in your introductory biology course?” or “What are some of the obstacles you encounter when teaching quantitative reasoning skills in your introductory biology course?” Interviews will take place at your convenience, **will last approximately 45 minutes**, via videoconferencing. Your verbal responses will be audio recorded only.

Risks

The only anticipated risks to you are the time and possible inconvenience involved in participating in the study.

Benefits

There are no direct benefits to you, except perhaps having the opportunity to reflect on your classroom teaching and possibly being indirectly encouraged to incorporate quantitative reasoning skills into your courses.

This study may add to the knowledge of barriers to, and opportunities for, increasing the amount of quantitative reasoning taught in general biology courses. This knowledge may lead to improvements in introductory biology textbooks and other resources to facilitate student development of quantitative reasoning skills.

Confidentiality

Your name will not be on any of the data. A pseudonym or code number will be used to protect your identity; I will de-identify the audio recordings by having the interviews transcribed by a service, and by using that pseudonym or code number. An electronic key linking your name to the data will be stored on a password-protected computer, only accessible to me as the principal investigator. When the results of this research are published or discussed in conferences, no information will be included that would reveal your identity. Upon completion of the study in approximately May 2020, any audio recording that links you to your responses will be destroyed. De-identified transcript data will be stored indefinitely.

Voluntary
Your participation is entirely voluntary. Should you choose to participate, you may withdraw at any time without consequences of any kind. You may skip any questions you do not wish to answer.

Questions about the Study
If you have questions or concerns during the time of your participation in this study, or after its completion you would like to receive a copy of the final summary of results of this study, please contact:

Dr. Ann Cleveland
ann.cleveland@mma.edu
207.326.2395

Dr. Asli Sezen-Barrie, Faculty Advisor
asli.sezenbarrie@maine.edu
207.581.2413

Questions about Your Rights as a Research Participant
If you have any questions about your rights as a research participant, please contact the Office of Research Compliance, University of Maine, 207/581-1498 or 207/581-2657 (or e-mail umric@maine.edu)."

APPENDIX A2.

Fifteen faculty who teach in the introductory biology course sequence participated in ethnographic interviews relating to the teaching of quantitative reasoning (QR). Faculty were drawn from universities and colleges in the six New England States.

Text in brackets are notes to help guide the interviewer in the event that a participant needs a prompt. Text in italics are prompts from the interviewer to the participant, exclusive of the question being asked.

Now I want to talk a bit about quantitative reasoning with you; for this part of the interview I want to focus on QR in the context of biology.

1. What does the term "quantitative reasoning" mean to YOU? [participant might use different terms, e.g., quantitative skills, so we need to clarify if they are using the terms synonymously, or whether they view them as different things. Also, ask for examples here if the participant does not provide them.]

[at this point, if the participant easily starts to answer the question, only ask questions/provide prompts if we do not understand what they are saying. However, if the participant is vague or hesitant we will add *"People and documents have slightly different definitions of QR. It can mean different things but in your mind, in the context of biology, how might you describe/define QR? I am not looking for a book definition."*]

2. What QR skills are crucial for general biology students to be successful in your class at introductory level?

3. [The purpose of Question 3 is to provide a baseline description of QR to assess how participants respond to a specific prompt regarding QR.] I am going to share a slide with a working definition of QR. [Reinforce that there is no "right answer" and that the participant's definition has been as on track as anyone else's.] How does this definition fit with your concept of QR? If you were to modify it, what would you add or delete?

> *Quantitative reasoning is a "habit of mind" of working with numerical data. Individuals with strong QR skills in the context of biology can reason and solve quantitative problems using words, tables, graphs, and simple mathematical equations to create sophisticated arguments supported by evidence.*

4. If you have thought about QR skills in the context of biology, how did this "get on your radar"? [if the participant does not mention it specifically, ask if they are familiar with the V&C document]

APPENDIX A3

Table A1. Theme 1 – Sophisticated QR skills. Additional examples of excerpts for each child code for participant conceptualization of quantitative reasoning (QR). Fifteen participants were interviewed -- 4 cellular/molecular biologists and 11 ecologists/evolutionary biologists. Examples in bold for each code are the ones presented in the text of the paper.

Child Code Name	Brief Explanation of Code with Example Excerpts
Conceptual Sensemaking Through Data	Working with data to better understand a concept, to extract conceptual meaning from a figure, or create a figure that graphically demonstrates a concept **"I think a little bit more broadly about quantitative reasoning as the ability of the students to be able to take some of the concepts and the concrete information that they've learned in class, and be able to apply it to some sort of problem to answer questions, analyze data." (Lynda, c/m)** "… a certain level of unconsciousness… that comes when you see data…your mind automatically starts to process what the data means [sic]. …I see habit of mind." (Bruce, e/e) "So, basically, it means that they [students] can look at a set of numbers and extrapolate what it means." (Barbara, c/m) (In response to the question "What does the term quantitative reasoning mean to you?) "…working with numerical data in diverse ways… and being able to sort of broaden their [students] perspective through quantitative reasoning as part of the creative process." (Maryanne, e/e) "not making *quantitative* predictions with the models but … using them conceptually and *qualitatively …*to understand species interactions." (Paul, e/e) "[Quantitative reasoning is] just being able to understand new data and what it means I guess colloquially… what it means in the real world, kinda extrapolating it to the bigger picture." (George, e/e)

Appendix A3. Table A1 continued

Using Models	Understanding/creating a model (conceptual, graphical, numerical) to represent data or evidence as a facet of QR **“[QR is] the ability to use, and apply, and understand mathematical models to understand natural situations and the world around us” (Betsy, c/m)** **“so being able to understand the Hardy Weinberg Equilibrium [a mathematical model] and applying it to a problem and understand the outcome is sort of that baseline level [of understanding modelling], but then there’s the higher level of being able to think numerically and understand that what’s happening in the world around us can be represented in an equation, or in a formula, or change can be modeled out.” (Carolee, e/e)** “So [QR] also being able to … look at an equation, and … be able to kind of interpret it not just as numbers, but as kinda like what – how different variables can affect each other. Thinking about like, well, if you increased, you know, this variable that's on one side of the equation, how would it affect, you know, your output variable. So it was kind of using – so it's, again, reasoning with numbers, right, thinking about how changes in one variable affects changes in others in kind of this numerical way.” (Melinda, e/e) “Let's look at the curve. How does the curve change? Versus just having them plug numbers into the equation and not understanding the predictive part of the model.” (Betsy, c,m) “I want them to not see the data [itself]; I want them to imagine the shape of the data and what it says.” (Maryanne, e/e) “I give them the figure, and then I'll ask them to draw a new figure if say the hypothesis was not supported, or I'll give them a hypothesis and a blank set of axes and … they have to draw me what the trend looks like.” (George, e/e) (In response to interviewer asking participant to clarify what he meant about using models as QR.) “[QR is] using population growth models to understand, okay, if we start at a different starting population, how is that gonna change what the curve looks like? So I don't have them [students] necessarily solve – give them the starting population and whatever and have them solve the equation. I'm more interested in having them draw – like how would the curve change if we changed this?” (Betsy, c/m) “like not just think about it as like, *r* [intrinsic population growth rate], right, and population growth. What does *r* mean, right? What is the per capita population growth rate? What does that actually mean is going on, and if your *r* is this, does that like mean your population's increasing? Does it mean it's decreasing, like what can you – and so then you can look at your number that you get when you do.” (Melinda, e/e)
Thinking in Numbers	“Doing math” in one’s head, e.g., 10% of a sample of 73 trees”, would be close to 7, and not 3 trees **“what I'll have them do is sometimes look at an equation, and they have to be able to kind of interpret it not just as numbers, but as kinda like what – how different variables can affect each other, so I don't do this a lot 'cause there's not a lot of places to put this in. But thinking about like, well, if you increased, you know, this variable that's on one side of the equation, how would it affect, you know, your output variable. So it was kind of using – so it's, again, reasoning with numbers, right, thinking about how changes in one variable affects changes in others in kind of this numerical way.” (Melinda, e/e)** “[you] connect it to the biology, based on, you know, kind of the biological context that's given, which also has to be like translated into numbers or can be thought of numerically. And so but making those connections, so it's not just plug and chug. It's not just like, oh, I can do this and get this number, but it's like knowing, understanding like what those numbers mean that are going into it biologically” (Melinda, e/e) “quantitative reasoning is that whole habit of mind piece…where you can think what is ten percent? Does that number make sense?” (Betsy, c/m)

Appendix A3. Table A1 continued

	“[in the context of *r*, the intrinsic population growth rate] you can look at your number if *r* is two, and you are adding two individuals like every year? No, you’re adding two individuals per individual in the population so like getting to understand what that looks like [in your head].” (Melinda e/e)
Applying Comparative/Inferential Statistics	Applying statistical tools to support hypothesis testing, including the use of tools such as t-tests, analysis of variance (ANOVA), and correlation/regression. **“[I see QR as] how to interpret data and do hypothesis testing with statistical tests... and that’s [descriptive statistics] not as important as understanding sampling or – and variability [in data] And understand that in science, we can falsify hypotheses, but we can’t really prove hypotheses .... And how you can look at two means that are different, but that difference may not mean anything in biology.” (Jim, e/e)** “what we wanna do is put numbers to it so that we can measure it, so that we're not just seeing what we think we see but quantifying how much. How strong is the relationship? Are there correlations in these things we're comparing? So, yeah, that's how I would define it. Quantitative reasoning is thinking about what you're seeing but putting numbers to it so that you can apply statistical analysis to it and you can be sure that what you're seeing is real. Within a certain amount of allowance for error due to chance and chance alone” (Don, e/e) “Another thing is, them understanding statistical significance, right? If something is statistically significant versus not, what does that mean?” (Barbara, c/m) “I think statistics is something that you’re gonna see in the primary literature, understanding what it means, and understanding what it doesn’t mean too is something that’s important” (Cindy, c/m) “[understanding] that the bar graph is [not] the ANOVA, rather than a representation of the data. So rather than seeing a graph as something that can enhance your readers’ understanding, they [the students] think of it as the output of the analysis.” (Maryanne, e/e) “For QR, I think I would add the word “statistics” in here somewhere. Application of statistical techniques. Hypothesis testing comes in here to me.” (Don, e/e) “It means that the - if you are looking at the phenomenon testing for something then you do it in a way that is verifiable with - in most cases statistical testing to make sure you have enough observations, replicates to verify that there is a reasonable chance that it’s for real rather…. How do I set things up to test for and how many replicates do I need? And I also error on that more is better than how few do I need?” (Ken, e/e) “You looking at the graph and saying, ‘It looks close’ – that's not objective, which is – obviously objectivity is one of our goals in science. So I'm like, ‘Here's how we do that objectively’ ” (Betsy, c/m) [in the context of teaching QR, this example was given] “Later on in the semester we do a second similar type of workshop where we require comparative statistics to be incorporated so by their last writing assignment they're not only describing a group of data they're also having to tease apart some subtle difference and make a distinction of whether those differences are statistically real or not.” (David, e/e) “So for me, a lot of it is learning how to manipulate data, learning now to calculate averages, variances, standard errors, and … some statistical tests – T-tests, chi-squares – this year, we’ve gone up to analysis of variance – a very simple one. I think it’s [QR] using numbers in biology in a variety of different ways, either – I tend to – I’m biased, I – because of my ecology background, I tend to want students to learn how to interpret data and do hypothesis testing with statistical tests.” (Jim, e/e)

Appendix A3. Table A1 continued

Using Intuition	Drawing key scientific ideas by looking for trends or patterns in a data set, without having to do calculations
	“the intuition about data and numbers...So I think there’s kind of like this tug of war situation where ... intuition is going to be something that lends itself to quantitative reasoning, and strong quantitative reasoning skills” (Cindy, c/m)
	“I agree that [QR] is definitely a habit of mind. That whole habit of mind piece to me is – and you were talking about it: some intuition; what *is* ten percent? Does your number make sense? Does your intuition match your calculation?” (Betsy, c/m) [Note: this statement was co-coded for both “Thinking in Numbers” and “Using Intuition”. Determining ten percent of something is arriving at a number, but intuition is knowing whether that number makes sense.]
	“Intuition is going to be something that lends itself to quantitative reasoning, and strong quantitative reasoning skills.” (Cindy, c/m)
	“Use your common sense. Look at the data, and think about what we’re measuring. Does this smaller value or this larger value make sense considering what we’re measuring? In other words, there seems to be a divorce between them concentrating on the statistics and the numbers, and then thinking about what we’re dealing with – what biological concept we’re dealing with. I want students to have that intuition about – all right, we’re measuring length of fish. So does it make sense to have a fish that is 50,000 meters long?” (Jim, e/e)

Appendix A3. Table A2. Theme 2 – Basic QR skills. Additional examples of excerpts for each child code for participant conceptualization of quantitative reasoning (QR). Fifteen participants were interviewed -- 4 cellular/molecular biologists and 11 ecologists/evolutionary biologists. Examples in bold for each code are the ones presented in the text of the paper.

Child Code Name	**Brief Explanation of Code with Example Excerpts**
Creating/Describing Graphical Data	Identifying independent and dependent axes, units of measure, and numerical data, e.g., mean, standard deviation, regression line **“So, basically it [QR] means that they [students] can look at a set of numbers and extrapolate what it means. So, you can look at a graph and you can read the graph and understand what it means…. But if you can look at a graph and you can look at in a way that - you can clearly look at it to see if the axis makes sense, and what the person is saying about the graph actually is what the data represents. That being in a major quantitative reasoning.” (Barbara, c/m)** “I am just looking for them to be able to do what I would call seventh grade math. And I have no idea it’s actually seventh grade math. But that’s what I learned in seventh grade math [laughs]. So, powers, the foiling things, reading a graph. I don’t know when I really learned to be able to look at a graph and know what the X and Y axis were. That was probably high school or middle school, I’m not really sure. But those are some of the math skills, or quantitative skills that I would expect them to come in with, know what and X and Y axis is. Know how to graph something basic on Excel….It’s a simple graph that you can do in two seconds.” (Barbara, c/m) “[It is] how to make graphs and read basic graphs. I don't necessarily expect them [students] to understand like error bars or anything like that, but they can read a basic graph, and then interpret that graph. And I'm assuming that they're learning these things. I mean, I'm hoping they're learning these things in high school. I know that the next generation's science standards are starting to be implemented.” (Melinda, e/e) “It [QR] is the simple things like being able to see graphs and what [the mean] is for. What an error bar means when you’re looking at bar graphs and things like that. Or, when we use a scatterplot versus a bar graph. Or, when - what’s a dependent or independent variable?” (Lynda, c/m) “So we start out with basic descriptive statistics. The idea of measures of location, measures of variability, we calculate those things and how do you present those things in a meaningful pictorial way that's going to tell that story that you're going to try to tell” (David, e/e) “So before they even create a basic graph we just have them draw two axes and label them, that’s it. What patterns, what variables do you have, and that’s it. So they don’t even need to collect the numbers to be able to make this skeleton of a graph.” (Carolee, e/e) “So we would look at graphs. So actually that is quantitative reasoning. But we weren't solving equations or plugging in our own numbers. So we would have to look at and understand graphs, which is quantitative reasoning. I pretty much expect them to be able to look at a bar graph or a line graph or something and know what those mean.” (Betsy, c/m) “[QR is] being able to read basic data tables. And I mean even just the most – not even talking about graphs, but just if you look at a table and it has units, and it has numbers, and it has some categories and be able to orient themselves in that.” (Whitney, e/e)

Appendix A3. Table A2 continued

Organizing Data	Organizing information or messy data sets into a useful or meaningful form **“[QR is] the ability to understand what data means and how to organize data so that it makes sense...And then again, how are you going to organize that information into some useful form that has summarized things quickly so that people can understand what it is that you’re talking about.” (Lynda, c/m)** So, the ability to understand what data means and how to organize data so that it makes sense, interpret graphs. (Lynda, c/m) I think it can be where students collect their own data and organize it and then work it up. (David, e/e)
Using Descriptive Statistics	Identifying measures of central tendency and variation **“So we start out with descriptive statistics… So before they even learn what biology is, they learn that when we have to have a look at the world, we observe it, ... and we quantify what we're seeing...We're analyzing the data we got. And so they're doing descriptive statistics. What is the mean? What does that mean? The central tendency of the data. What is the standard deviation? It's a measure of variance. And it's how wide this histogram is at a certain place. So we're trying to get the idea that data are not perfect, that there's variance in the data, and that we have to make decisions based on how the mean and the standard deviation reflect each other.”(Don, e/e)** “[QR is] just descriptive statistics and graphing and that sort of thing.” (David, e/e)
Making Measurements	Attributing a unit measurement to an object or observation This code was applied to only two participants; the full excerpts are below. **“I think the [QR] skills around some of their [experimental] designs revolve around getting comfortable with both the tools and the types of measurements that are appropriate for particular experiments for what we do in the lab. So the tools being the hydrometers that they build, how did they scale things properly, what are they measuring and have they measured it properly with the appropriate equipment.” (Whitney, e/e)** “what we wanna do is put numbers to it so that we can measure it, so that we're not just seeing what we think we see but quantifying how much. How strong is the relationship? Are there correlations in these things we're comparing? So, yeah, that's how I would define it. Quantitative reasoning is thinking about what you're seeing but putting numbers to it so that you can apply statistical analysis to it and you can be sure that what you're seeing is real. Within a certain amount of allowance for error due to chance and chance alone.” (Don, e/e)

APPENDIX A4

Table A3. Number of participants in each teaching experience category for whom the codes for conceptualization of quantitative reasoning (QR) were applied, based on years of teaching experience at the undergraduate level. Fifteen participants were drawn from faculty at universities and colleges in the 6 New England States; these 15 faculty teach in the introductory biology course sequence and participated in ethnographic interviews relating to the teaching of quantitative reasoning (QR).

		Theme 1 – Sophisticated QR Skills					**Theme 2 – Basic QR Skills**			
Years of Teaching	Number Of Participants in Each Category	Conceptual Sensemaking Through Data	Using Models	Thinking in Numbers	Applying Comparative/Inferential Statistics	Using Intuition	Creating/Describing Graphical Data	Organizing Data	Using Descriptive Statistics	Making Measurements
0-4 years	**5**	4	4	2	2	2	3	2	1	1
5-9 years	**4**	3	2	1	0	0	2	1	0	0
10-14 years	**1**	1	1	1	1	0	1	0	0	0
20+ years	**5**	4	1	3	4	2	2	2	1	1

APPENDIX A5

Table A4. Number of participants in each Carnegie Classification category for whom the codes for conceptualization of quantitative reasoning (QR) were applied. Fifteen participants were drawn from faculty at universities and colleges in the 6 New England States; these 15 faculty teach in the introductory biology course sequence and participated in ethnographic interviews relating to the teaching of quantitative reasoning (QR).

		Theme 1 – Sophisticated QR Skills					**Theme 2 – Basic QR Skills**			
Carnegie Classification	Number Of Participants in Each Category	Conceptual Sensemaking Through Data	Using Models	Thinking in Numbers	Applying Comparative/Inferential Statistics	Using Intuition	Creating/Describing Graphical Data	Organizing Data	Using Descriptive Statistics	Making Measurements
R1	**4**	4	3	1	1	1	2	0	0	0
R2	**2**	2	1	1	0	0	0	0	0	1
Masters	**4**	3	2	2	2	1	3	3	1	1
Baccalaureate - Diverse	**2**	1	1	1	2	2	0	0	0	0
Baccalaureate – Arts & Sciences	**3**	2	2	2	2	0	2	2	1	0

*Carnegie Classifications: **R1** – Doctoral Universities, Very High Research Activity, **R2** – Doctoral Universities, High Research Activity, **M1** -- Master's Colleges and Universities, Larger Programs (200+ degrees), **M2** -- Master's Colleges and Universities, Medium Programs (100-199 degrees), **M3** -- Master's Colleges and Universities, Smaller Programs (50-99 degrees), **Baccalaureate Colleges – Arts and Sciences, Baccalaureate Colleges – Diverse Fields**

BIOGRAPHY OF THE AUTHOR

Ann Cleveland was born on 29 January 1960, in Beverly, MA, and was raised in Ipswich, MA, where she graduated from Ipswich High School in 1978. Ann earned a Bachelor of Arts degree in Zoology at the University of New Hampshire in 1982, and then was employed by the National Marine Fisheries Service until her first return to graduate school. She earned a Master of Science degree in Zoology at the University of Rhode Island in 1987; her thesis research compared reproductive behavior in two species of stickleback fishes in Rhode Island estuaries. After earning her Master of Science degree, Ann spent the next seven years in the workforce, first as an environmental consultant with a company in Providence, RI, then as a research diver and aquarist at The Living Seas, EPCOT Center, in Orlando, FL. From there, Ann returned to the National Marine Fisheries Service as served as a Fisheries Observer on trawlers and longliners fishing in the Bering Sea and the Gulf of Alaska. Those experiences rekindled a passion for research, so Ann returned to graduate school to pursue doctoral studies at Northern Arizona University in Flagstaff, AZ. She earned her Doctoral Degree in 1998, where her research investigated the feeding ecology and physiology of damselfishes in Panama.

Ann is currently employed as a Professor of Marine Biology in the Corning School of Ocean Studies at Maine Maritime Academy. Ann joined the faculty at MMA in August 2002 as the first hire for the new Marine Biology major. Ann's research area focuses on the tripartite symbiosis of anemonefishes, anemones, and symbiotic algae on reefs in the Philippines. However, Ann developed a strong interest in biology education, and formally enrolled in the Master's in Science Teaching program in September 2015. If you ask Ann, she will tell you "it is all about the fish", but now she adds that "it is for her students, too."

Ann is a candidate for the Master of Science degree in Teaching from the University of Maine in May 2023.