# Numerical competence and quantitative skills for BSc-students in biology

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**ABSTRACT: Biology as a natural science is becoming increasingly quantitative in approach, description and methodology. Numerical procedures and mathematical models are now commonplace features in the process of studying life and nature. This development of the field has been partly neglected in the education of new practitioners. An increasing number of undergraduate biology students are perceived as lacking the necessary quantitative skills for making learned use of numerical methods. The problem is epistemological and has roots in tradition, teaching, preconceptions and motivation. Here we investigate the patterns and trajectory of intended learning outcomes in undergraduate biology teaching at the University of Bergen, Norway, with regards to basic numerical competence. We use surveys of course descriptions and interviews with students and teachers to map and illustrate the structure of explicit and implicit learning outcomes, teaching and expectations. We find that numerical proficiency is under-communicated and partly neglected in the biology courses. We also find a distorted alignment in the curriculum trajectory, where abstract theoretical concepts are taught before practical data handling and collection. We think that the lack of motivation for learning numerical methods observed among some students can be traced back to the distorted alignment and neglected emphasis on importance. In order to remedy the widening gap between practice and education we suggest a set of concrete learning outcomes with a more structured alignment and integration of the present curriculum. This approach has the added value of allowing the development of a personal 'numerical pedigree', which documents the acquisition of important job-relevant skills, for each student.**

## 1 INTRODUCTION

Over the past decades, there have been repeated calls to better align undergraduate biology education with the demands of society and with the development of modern biology as a scientific field (NRC 2003, AAAS 2011). A recurrent theme in these calls is that while biology as a science has transformed to an increasingly numerically- and quantitatively-based practice, the training students receive, is still largely in the descriptive and narrative roots of biology motivated by observing and discussing natural phenomena. Numerical and quantitative competence is highlighted in the influential '*Vision and Change'* (AAAS 2011) report on biology education as a vital core competence within the discipline, as well as for STEM (Science, Technology, and Mathematics) in general. The lack of sufficient numerical and quantitative competences and skills have repeatedly been identified as a challenge for biology graduates entering the academic as well as the non-academic workforce (Gross 1994, Hastings and Palmer 2003, Blickley et al. 2013).

There are many initiatives that take up the Vision and Change (AAAS 2011) challenge to improve the numerical competence of biology graduates. Many programs require students to take mathematics and statistical courses as part of their degrees assuming that students then have the necessary skills before embarking on biology. However, empirical evidence show that simply having the background knowledge in an adjacent discipline is not sufficient; students need to learn to use the mathematical and quantitative skills *in context* (Fesner et al. 2013). Developing calculus courses specifically for biology is the obvious next-level solution (e.g., Stele & Kilic-Bahi 2008, Robeva et al. 2010), but such stand-alone modules have also been showed to not have the desired impact on student learning (Speth et al. 2010, Hester et al. 2014).

It is not enough for students to be well-versed in mathematics and statistics as a discipline; they also need to be able to *translate* these skills into their subject context – which means that students should be trained in the use of quantitative methods *within biology*. Quantitative skills, often referred to as 'numeracy' (Galligan 2013), entail not only having the necessary competence, but also the awareness of how and when it can be applied. Rather than the traditional 'theory first, practice later' teaching of numerical skills, the 'numeracy' perspective advocates building the necessary knowledge in an integrated way throughout the curriculum. Galligan (2013) suggests that at the first level of competence, students should be able to apply and interpret numerical analyses and figures within a context. At the second level, they should be able to select and use appropriate tools within a context, and at the third stage, they should be able to evaluate and select complex tools across contexts.

Here, we investigate how numerical and quantitative skills are integrated in the BSc program in biology at the Department of Biology (BIO), University of Bergen. BIO is a large and broad-ranging department, offering a range BSc and MSc programs in basic and applied biology. Education is based in research in evolutionary biology, ecology, marine biology, and applied biology geared towards solving global challenges. The research typically has strong quantitative components.

We assessed how different aspects of numerical and quantitative skills and competences were described, taught, and evaluated in courses in the biology education at BIO. Specifically, we ask if there is a correspondence between the numerical competences and skills we offer and what we see as necessary for understanding biology, for continuing a career in the subject, and for fulfilling society's need. From this we discuss how to better align what we expect, how we teach, and how we evaluate biology students' learning of numerical and quantitative competences.

## 2 MATERIAL AND METHODS

*Course intended learning outcomes (ILOs):* In order to make an inventory of how numerical skills are represented and described in the various biology courses at BIO we collected the course descriptions of all active BSc and MSc courses (n=70). For each course, we analyzed the texts under the headings "Objectives and Content", "Learning Outcomes", and "Recommended and/or Required Previous Knowledge". We counted all instances where quantitative skills or activities were mentioned, and mapped the 'transferrable skills' learning outcomes. Lastly, we examined how the course content of the compulsory introductory math and statistical courses for biology students at UIB correspond to the numerical skills needed in biology.

*Teacher questionnaire:* The teachers were asked to comment or elaborate on the text in the course description, focusing on the role of numerical and quantitative aspects of their course. The results were sorted and tabulated with regards to numerical and quantitative subject content, activities, and skill training mentioned in the ILOs. When possible, we also categorized the numerical or quantitative ILOs into one or more of the categories 1) basic statistics, 2) advanced statistics, 3) conceptual models, 4) numerical models/simulations, 5) general quantitative / numerical competence.

*Course evaluations and educational reports*: Information was gathered from the Study Quality Database, an archive of course evaluations and education reports at UIB. Here we checked how often numeracy/quantitative skills or aspects were mentioned, both by students and teachers.

*Student meeting: To* gauge how students perceive the extent to which numeric skills were included in the biology education we met and talked to a group of students. The students present at this meeting (n=12) were asked how much and what type of numeric skills they had encountered in their education, whether it had been taught in an aligned and useful manner, and whether they consider numeric skills to be important for a biologist.

*Requirements for statistical and numerical competence at the Master's level:* Finally, to examine whether the BSc biology education at UIB provides the students with sufficient numerical skills to prepare them for MSc-level, we interviewed the teacher responsible for the mandatory introductory course in statistics and experimental design for Master's students at BIO.

## 3 RESULTS AND DISCUSSION

### 3.1 Numerical or quantitative skills in intended learning outcomes

The intended learning outcomes reflect the broad thematic range of the biology educations at the department, from basic level courses covering the foundations of the discipline to advanced courses in various specific direct ions and specializations (Figure 1). The ILOs contain a wide range of biological terms, with a few concepts recurring across the curriculum. There is less variation in the methodological and epistemological language of the ILOs, which are dominated by words linked to disciplinary understanding ('knowledge'/'know', 'understand'/'understanding', 'insight') and knowledge reproduction ('describe', 'explain', 'present'/'presentation'). Explicit numerical terms are sparse ('data' is a moderately common word) and 'statistical' and 'model' being the only clear numerical terms found (Figure 1). ILOs that describe transferable skills and competences are generally less frequent than subject knowledge. For the five mandatory biology courses at the introductory level, on average 75% of learning outcomes are related to specific biological topics or concepts. Our textual analysis of the ILOs confirmed the overall impression of a relatively moderate representation of quantitative or numerical skills in the biology programs. The proportion of courses with numerical or quantitative ILOs averages 20% and is relatively evenly distributed across the introductory, intermediate and master level (Figure 2).


*Figure 1: Wordle plot illustrating the most frequently used terms in the intended learning outcome description of all the biology courses at UIB (n=70). The size of the word is proportional to the frequency of use.*

The teacher survey revealed significantly more numerical and quantitative activities at the higher level BSc courses (BIO2xx). In 45% of 31 courses students are supposed to perform computations or calculations related to laboratory or field work. In half of these (7 courses) numerical competence is needed in mandatory assignments or reports, but only one course included quantitative competences and numerical skills in student assessments.

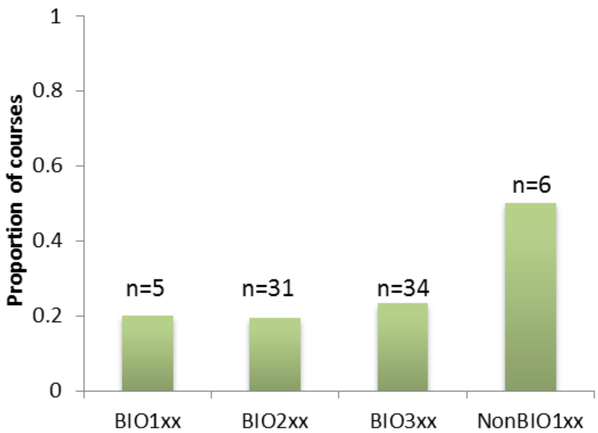


*Figure 2: Relative proportion of courses at the introductory (BIO1xx), intermediate (BIO2xx) and master's level (BIO3xx) that specify numerical or quantitative learning outcomes in the course description. The proportion of numerical learning outcomes for the mandatory non-biological courses in the BSc program is included for comparison.*

Mathematical or quantitative ILOs are more prominent in the mandatory non-BIO1xx courses in our Bachelor's program, where students get basic mathematical and statistical training, including programming in R. These non-BIO courses are concentrated early in the study program, during the first three semesters of the BSc program. It is striking that few biology courses explicitly make use of the student's expected numerical competences, in particular during the 4-6 semester of the BSc degree.

### 3.2 Teacher perspectives on numerical and quantitative expectations and learning outcomes

When asking the teachers whether the ILO description gave a correct representation of the numerical content of and background required for the courses, the common attitude was that students were expected to have the necessary numerical background; hence there was no need to state this explicitly:

*"Egentlig forventer vi at studentene kan grunnleggende databehandling (Excel, statistikk m.m.). Dette har ikke blitt spesifisert tidligere, og noe av grunnen kan være at dette er generelle basisferdigheter jeg mener studenter skal ha på hovedfagsnivå"* (Teacher, master level course BIO)

Many teachers mentioned that several numerical aspects, topics and competences were not sufficiently covered in the program. They raised the general concern that students lack the relevant background and have variable numerical skills: *"The students differ very much in their skills and motivation. This makes it challenging to run a course that is satisfactory for the majority".* (Study Quality Database, teacher evaluation)

This statement emphasizes the impression that the background education and skills of new students is getting progressively more uneven. While some students have the necessary numerical background to perform elementary statistical analyses, others are virtually starting from scratch. Our analyses reveal that, although teachers seldom state numerical learning goals and are frustrated by the student's poor performance, they often do not see building these quantitative skills as part of their responsibility.

### 3.3 Student perspectives on numeracy in biology

Students embarking on a university education in biology have little awareness of the quantitative aspects of the scientific process, and they perceive biology to be the least quantitative field within the natural sciences. The motivation for learning statistics and mathematics is therefore often low, as students do not see the relevance of quantitative methods for biology. There are several numerical courses early in the BSc program, but according to the students it is not clear at this point why they need these skills, and they struggle to see the links between these courses and the later curriculum: *"Det er ikke noe særlig rød tråd gjennom studiet når det kommer til numerisk kompetanse"(Response from student group bioCEEDS student meeting 17.02.16).*

Mathematics, statistics and biology are initially seen as separate independent fields of knowledge, with little mutual relevance. The introductory courses cover descriptive statistics, distributions, correlations and regressions, which are all highly relevant for biology, and they also introduce the statistical program *R* which is later used in a mandatory Master's course. Although students gain basic competence, through the compulsory statistics and mathematics courses early on, it seems that they do not see the connection until much later in their education. A major challenge for the students is to understand the basic nature of a scientific investigation from observations of nature via collection of quantitative data to statistical analyses and inference. It appears that teachers under-communicate these relations and expect students to spontaneously acquire the awareness and confidence necessary for developing their scientific numeracy skills (*sensu* Galligan 2013). The interview with the teacher at the mandatory Master's level course in statistics supports our view that a major challenge for the BCs students are the missing cognitive links between data collection, statistical analysis and biological inferences.

In essence, students have acquired many of the building blocks, but they lack the knowledge to construct the building. Both according to students and teachers, the compulsory mathematical and statistical courses in the BSc program do not seem to have the desired impact on the students' learning. The numeracy literature suggests that infusing these courses with more context and practice of applications could be done without losing the mathematical or statistical rigor or learning outcomes (reviewed in Aikens & Dolan 2014), and would at the same time provide the job market with graduates with better and more relevant numeracy skills (Matthews et al 2010, Robeva 2010, Galligan 2013, Thompson et al. 2013). Staff training and collegial collaboration both between and within biology and mathematics may facilitate the development of such modules (Wilder et al 2014), with increased cross-referencing and collaboration across courses as an added value.

There is a clear need for a better structure and plan in the organization of training in quantitative methods and numerical competence and skills in the bachelor's program. In particular, there is a need to focus on 1) stimulating a gradual buildup of numeracy and quantitative skills through the BSc program, 2) improve students' understanding of the nature of the scientific process from question via experimental design to data sampling, analysis and interpretation, and 3) align the theoretical method courses with introductory and intermediate level biology courses. Numerical learning outcomes need to be clearly identified, described and communicated in biology courses, and the biological relevance and applications should be clearly demonstrated in the compulsory statistical and mathematical courses. At the program level, we suggest that students should be able to i) make inferences about biological phenomena using mathematical and statistical tools and ii) use relevant computer programs to compute, test, present, report and store biological data and analyses. For better alignment, these learning goals need to be broken down to a set of specific ILOs with a gradual progression through the BSc program (see Box 1).

**Box 1:** For numerical skills and quantitative competences, we suggest that the BSc candidate should be able to:

1. Describe biological patterns and processes using mathematical language
2. Perform calculations and quantitative measures in field and lab
3. Apply the basic principles of sampling and experimental design
4. Organize data and perform simple computations using spreadsheets
5. Do basic programming operations and statistical analysis in R
6. Interpret datasets and communicate those interpretations using graphs and other tools
7. Select, perform, interpret, and make inferences from statistical analysis of biological data
8. Interpret conceptual models and relate them to biological processes and patterns
9. Understand, and be able to use and manipulate numerical models and simulations

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