Lack of quantitative training among early-career ecologists: a survey of the problem and potential solutions

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Abstract

Proficiency in mathematics and statistics is essential to modern ecological science, yet few studies have assessed the level of quantitative training received by ecologists. To do so, we conducted an online survey. The 937 respondents were mostly early-career scientists that studied biology as undergraduates. We found a clear self-perceived lack of quantitative training: 75% are not satisfied with their understanding of mathematical models; 75% feel the level of mathematics was “too low” in their ecology classes; 90% wanted more mathematics classes for ecologists; and 95% more statistics classes. Respondents thought that 30% of classes in ecology-related degrees should be focused on quantitative disciplines; likely more than what is taught in most universities. The main suggestion to improve quantitative training was to relate theoretical and statistical modeling to applied ecological problems. Improving quantitative training will require more mathematics classes for ecology-related degrees, and also more ecology classes containing mathematical and statistical examples.

Keywords: education, mathematics, statistics, teaching, ecology student

Introduction

Basic tasks in ecology sometimes involve fairly advanced statistics, especially outside of experimental science. Typical examples include capture-recapture models to census populations (Williams, Nichols and Conroy 2002), or elaborate multivariate statistics to reduce complex datasets of environmental records to a few manageable variables (Legendre and Legendre 2012). Most papers in mainstream ecological journals use today statistical and computational techniques beyond analysis of variance and simple linear regression. We surveyed the July 2012 issues of Ecology, Journal of Animal Ecology and Oikos, and found these more sophisticated statistical techniques are used in respectively 75%, 95% and 70% of articles. They include generalized, mixed, or nonlinear regression models; capture-recapture models; Bayesian statistics and Markov-Chain Monte Carlo [MCMC]; graph-theoretic algorithms for interaction webs; movement models derived from Brownian motion.

Theoretical ecology has been using a fair deal of mathematics since the 1920s and 1930s with the early attempts of Lotka, Volterra, or Fisher (e.g. Lotka 1925, Volterra 1931, Fisher 1930). For a while, theoretical ecology remained, however, rather separated from the rest of ecological science (Kingsland 1995), including statistical ecology. Therefore, the need for mathematics felt by theoreticians was much greater than that of the average ecologist. In contrast, nowadays theoretical ecology is more and more connected to ecological data (Hilborn and Mangel 1997, Codling and Dumbrell 2012), and this fusion of theoretical and statistical models increases the relevance of understanding theory in some detail to many ecologists.

Examples of a tighter link between theory and data abound in population dynamics (*e.g.* population projection models, Caswell 2001), behavioural sciences (*e.g.* hidden Markov models, Patterson et al. 2008), and community ecology (*e.g.* neutral models of Hubbell 2001; graph theory for food webs, Jordán 2009). These fields used already quantitative methods a few decades ago, but the rise of improved and often freely-available software has given increasing numbers of researchers access to complex mathematical and computational tools. The trend is clear from the recent proliferation of textbooks designed to teach students modern ecological modeling and statistics (*e.g.* Gotelli and Ellison 2004, Clark 2007, Otto and Day 2007, Bolker 2008, Matthiopoulos 2011), and the creation of new methodological journals (e.g. Methods in Ecology and Evolution). The open-source statistical programming language R (R Core Team 2012) has been embraced by much of the ecological community. Pielou (1969) thought ecology was becoming a mathematical subject. While it is unclear whether ecology is truly more mathematical, ecology has evidently become more statistical and computational (see references above), to the point that having little or no mathematical literacy can prohibit access to a large part of the literature. There are, of course, still some experimental fields where very good research can be performed with a modicum of statistical background, we certainly will not deny it; our impression from the percentage of published papers with complex statistical methods (see beginning of Introduction) is however that quantitatively intensive ecological research is taking over, at least in the academic milieu. Despite this, equations remain a barrier to effective communication between empiricists and theoreticians today (Fawcett and Higginson 2012), even if these problems are, perhaps, not as strong as when highlighted by ecological pioneers such as Elton (Kingsland 1995).

Given the trend for a more quantitative ecology, one might expect modern ecology students to receive a training rich in mathematics, statistics and programming. However, many ecology students at the undergraduate or graduate level do not have the required background to formulate statistical or theoretical models, or even to understand their properties (Ellison and Dennis 2009). Based on their experience, Ellison and Dennis (2009) advocate the teaching of ecological statistics only after a two-semester calculus course at undergraduate level, possibly supplemented by linear algebra and probability theory for graduate students. Data on what ecologists think is appropriate quantitative training are however scarce. Are more undergraduate mathematics classes the answer? How many ecologists are distressed by their lack of formal mathematical and statistical training? Early-career scientists are especially well-equipped to comment on these issues: they are lead authors on many papers, and therefore deal first-hand with many of the technical issues that arise. Furthermore, many aspects of their formal education and training are fresh in their memories. Thus, we tried to assess the size of the “quantitative gap” in young scientists and designed an internet survey (see Supplementary Information [SI], Appendix 1) that was diffused through various list-serves (see below for details). We wanted to know what early-career researchers (mainly PhD candidates and postdocs) think about the mathematical and statistical training they have received, and what (if anything) they think should be done to improve it.

Survey design, data, and methods

We designed this survey as a short online questionnaire (see SI, Appendix 1). The survey was launched on the 13th of February, 2012, through the INNGE network (http://www.innge.net/, initially through Facebook). The last answers were recorded 10/04/2012, with a peak in participation after diffusion on the American ECOLOG-L mailing list (16/02/2012, 13458 members). After ECOLOG-L, the survey was forwarded to a number of networks including the Indian YETI mailing list and members of the French Ecological Society as well as being diffused globally through social media (Twitter) and a number of science-related blogs (including that of the ecological journal *Oikos*). The total number of responses was 937, of whom 250 also left free text comments that we categorized (see section Comments of respondents). The data have been deposited in an online open archive [*link to suitable online archive here*].

Key proportions presented in the paper, and differences between those proportions, are accompanied with their 95% asymptotically normal confidence intervals, using a binomial model (more complex CIs are available but these are enough given the large sample size, Agresti 2007).

Control questions: survey composition

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Demographics: education, geography and gender.

Most respondents (84%) were trained as biologists (Fig. 1). Nearly half of the respondents are PhD students (42%), with 20% postdocs and 20% lecturers or professors (Figure 1). Based on free text comments, the category “other” (18%) includes numerous MSc students. The survey contains a relatively balanced provenance according to gender (44% females, CI [40.8;47.2]%). Most respondents are from either Europe or North America (43%: Europe, 41%: North America). There was no general correlation between geography and gender (the results for PhD students suggest only small differences among them in Europe and North America, for example, Fig. S1 in SI).

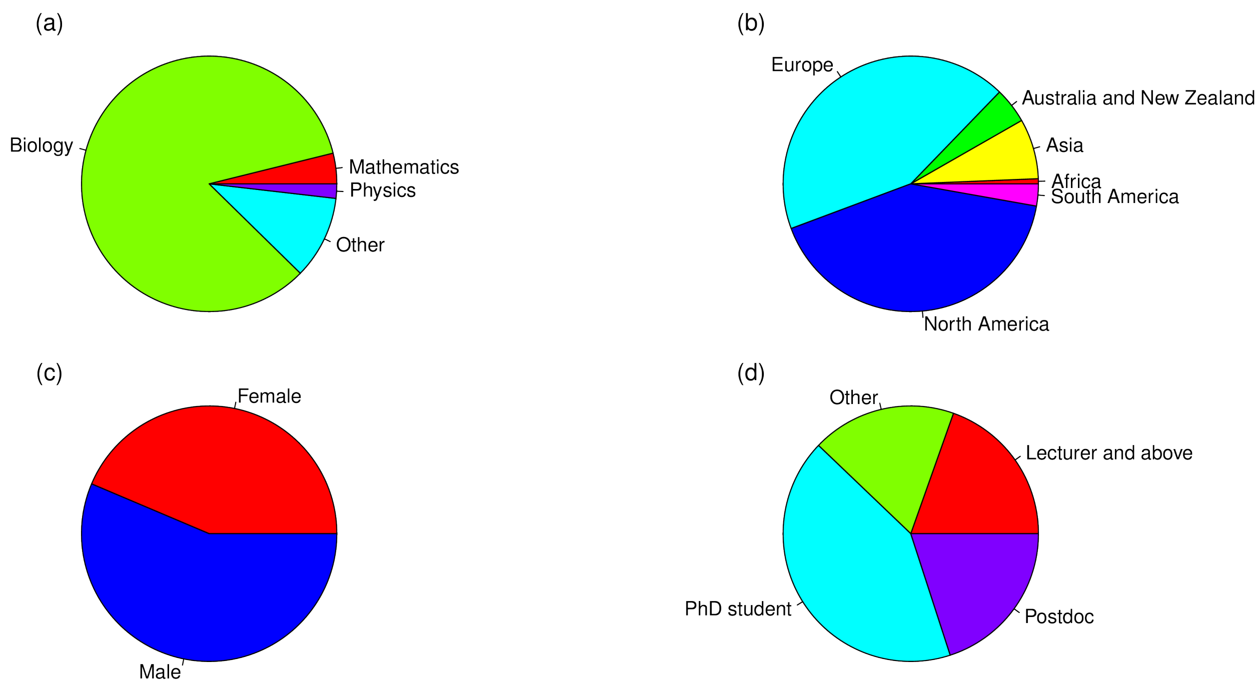

Figure 1: Partitioning of the respondents with respect to (a) background (i.e. discipline of undergraduate studies), (b) geographic origin, (c) gender, and (d) employment status/level.

Involvement in modeling and "mathematics-friendliness".

A survey such as this could be biased if the respondents predominantly liked or disliked modeling or mathematics. As it was not possible to control the composition of participants with a voluntary survey, we attempted instead to assess the extent of this bias by asking respondents questions about their own feelings about mathematical and statistical training. To do so, we asked the respondents "Rate your feeling towards using equations" and "Rate your involvement in the process of ecological modeling in your field" (Appendix 1 Questionnaire). The two scores are moderately correlated (Fig. S2, Spearman's rho = 0.53). We found that most self-identified modelers (Modeler scores 4 and 5) have positive feelings associated with mathematics; conversely, quite a few (42%) of the mathematics-friendly respondents (Feeling score 4 and 5) do not identify as modellers (they have a Modeller score <4, Fig. 2 and Fig. S2).

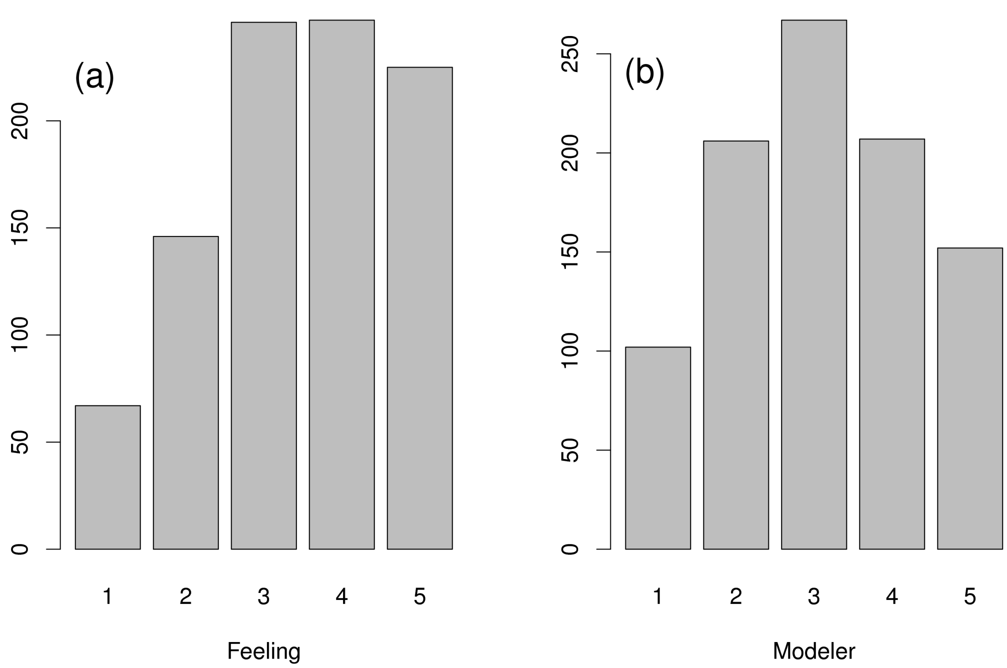

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Figure 2: (a) Distribution of “Feeling” variable and (b) Distribution of “Modeler” variable (see Fig. S2 for correlation between these two variables)

Use of mathematics/statistics and current training

What are the respondents using mathematics for?

The first question of the survey reveals that 96% of respondents use mathematics for statistics, 39% use mathematics for theoretical modeling and 24% for decision making overall (see supplementary graphs at https://sites.google.com/site/mathematicsandecologysurvey/summary). A small fraction (11%) use mathematics for decision making but not theoretical modeling (correlations between these variables are shown in Fig. 3). Theoretical work is mostly carried out in combination with other math-intensive practices; very few pure theoreticians responded (2%) and 47% of respondents use mathematics only for statistics (Fig. 3). It is therefore possible that the proportion of theoreticians in our sample is slightly above that of the average population of ecologists, but not overly so.

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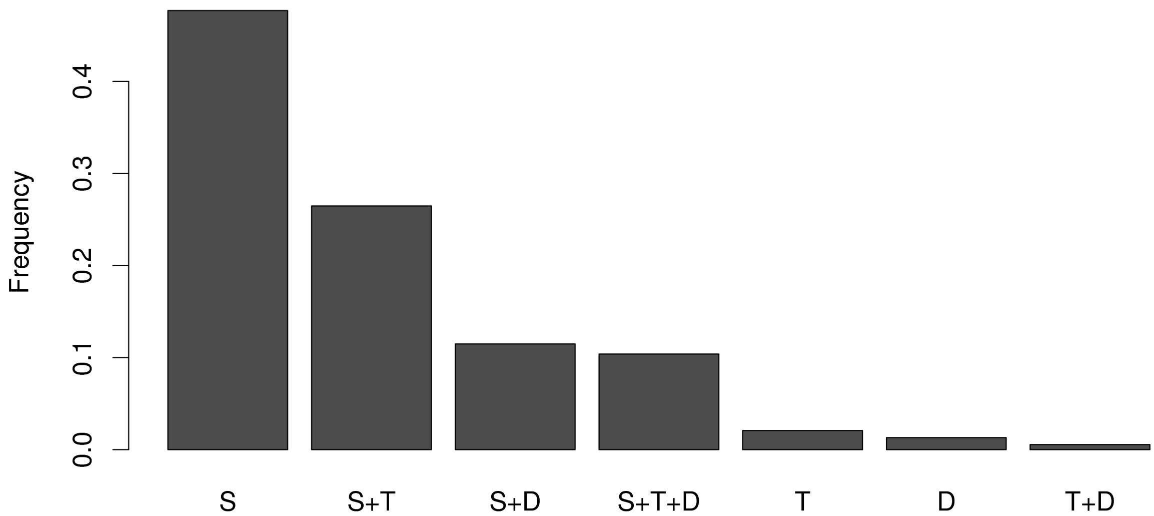

Figure 3: Repartition of the uses of mathematics and association between categories. Most respondents use primarily mathematics for statistics (S), and some other for statistics+theory (S+T, 26%), and the remainder 11% statistics+decision making (S+D) and 10% statistics+theory+decision making (S+T+D). Pure theoreticians (T) are therefore negligible in the sample.

Understanding models within one's field.

We asked respondents to assess whether they were satisfied with their understanding of models in their own field; the goal was to assess quantitative understanding in directly relevant areas for them rather than general theory. Based on the response to this question, 75% (CI [73.2;77.8]%) of respondents do not feel satisfied with their understanding of models (and likely with the mathematical training they received). To interpret this number, it is worthwhile to note that humans, including academics, are prone to over-rate their own abilities (van Veelen and Nowak 2011, and references therein), so, if anything, the 25% of satisfied respondents is an overestimate of true satisfaction with mathematical understanding. Given our large sample size (>900 answers), these results most likely reflect a true lack of understanding of models within the ecological community. Even among self-diagnosed modeling “specialists” (score 5), only 60% consider themselves satisfied with the mathematical training they received and this figure drops to under 50% for all other “Modeling” groups (Fig. 4). To make sense of this result, consider that 27 of the 36 respondents with a mathematics-based undergraduate degree are, in contrast, satisfied with their understanding of models - though not all of them identify currently as modelers. We found no influence of gender, and only a weak effect of geography (Fig. S3) on these results. This suggests that such unsatisfaction is global and understanding of mathematical models is strongly dependent on having mathematics classes at undergraduate level.

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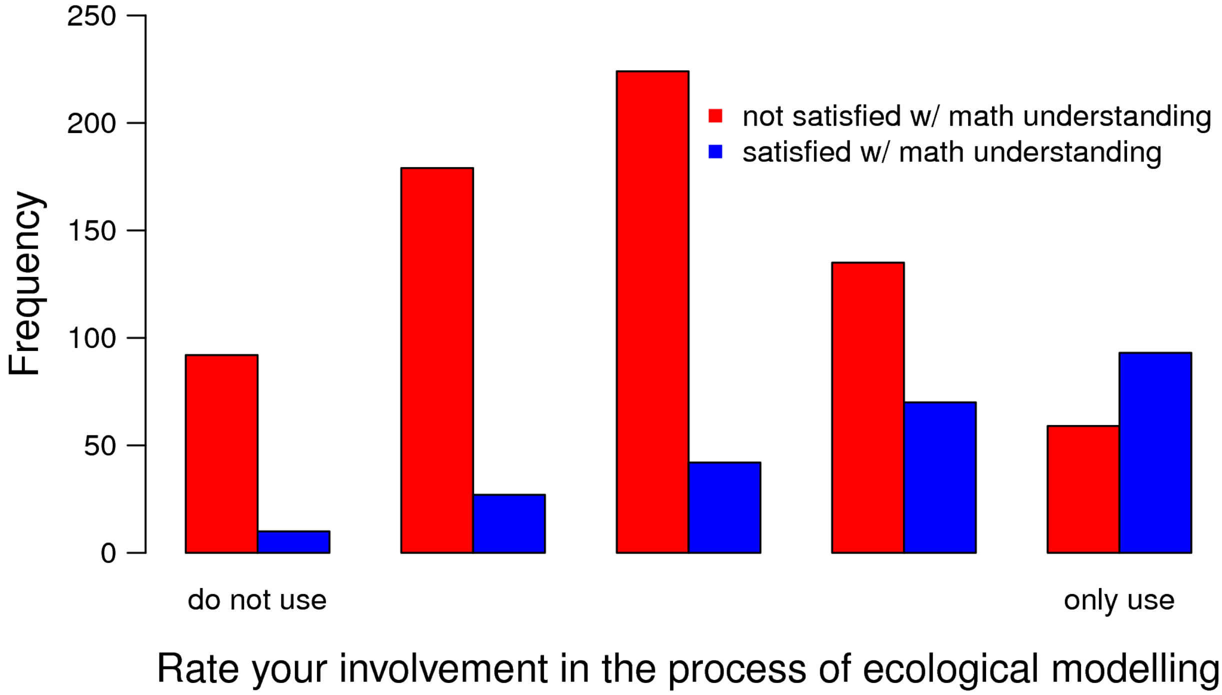

Figure 4: Importance of involvement in modeling ("Modeler" score) on the understanding of mathematical models ("Satisfied?" variable).

Is there enough mathematics in general ecology courses?

We asked: "In the general ecology courses you have followed, how would you describe the level of mathematics (in retrospect)?", with three possible answers: "Too low", "Just right", and "Too high". We included "in retrospect" because it seems a common experience for ecology students to initially appreciate verbal descriptions of ecological theories and analytical tools, rather than a mathematical description of those same theories using equations. Quite often, students discover later that these concepts and tools involve some fairly advanced mathematics (Ellison & Dennis 2009). For a number of ecologists, this late discovery seems quite troublesome (see section “Comments of respondents”). Of those surveyed, 75% thought, in retrospect, that the amount of mathematics presented in their ecological coursework was “too low” (22% said “just right” and 2% “too high”). These results do not depend on geographic origin, but are weakly related to whether the participants use mathematics for statistics only or for other purposes as well (7% percent difference, 95%CI: [1%; 13%], Fig. S4).

What should be done?

More mathematics and statistics classes.

We asked whether there should be more mathematics and statistics in the ecological curriculum. We asked for opinions (“Do you think...”) instead of absolute answers (“Should…”) to allow for more personal inclinations in the responses. The overwhelming majority of respondents want more mathematics courses (91%, CI [89.1;92.9]%) and more statistics courses (95%, CI [93.6;96.4]%). More than half of respondents want more mathematics and statistics at both undergraduate and graduate levels (61% for mathematics and 76% for statistics). Additionally, a fraction of 14% wants more mathematics only at undergraduate level, and another 16% desires more mathematics only at graduate level. For statistics, 7% want more statistics only at undergraduate level, and 11% only at graduate level. In essence, respondents want more mathematical and more statistical training. The opinions do not depend much on what people use mathematics for: we found only a 5% difference between respondents using mathematics for statistics-only or other purposes as well (Fig. S4).

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A fraction of 30% of courses in mathematics, statistics, or programming.

To assess what fraction of the university curriculum respondents thought was appropriate to devote to mathematics, statistics, or programming, we asked: "What percentage mathematics, statistics, and programming should approximately cover of the university curriculum of an ecologist, in your opinion?". Given the inherent interdisciplinary nature of ecology, the responses should produce a wide probability distribution whose median indicates the best approximation of a "consensus". In our results, the median was 30% and the mean 28.3% (two modes at 20% and 30%, Fig. 5). ANOVAs on this fraction, with explanatory factors such "Feeling" or "Modeller", yielded mostly statistically significant results due to the large sample size, but the magnitude of these effects were very small, nearly all below 4% (for a justification of using ANOVAs given the discrete number of options, see Norman 2010). Thus, most respondents, regardless of "Modeller", "Feeling", "Status" or "Geographic origin", agree that one-fourth to one-third of classes in ecology programs should be devoted to quantitative training (Fig. 5).

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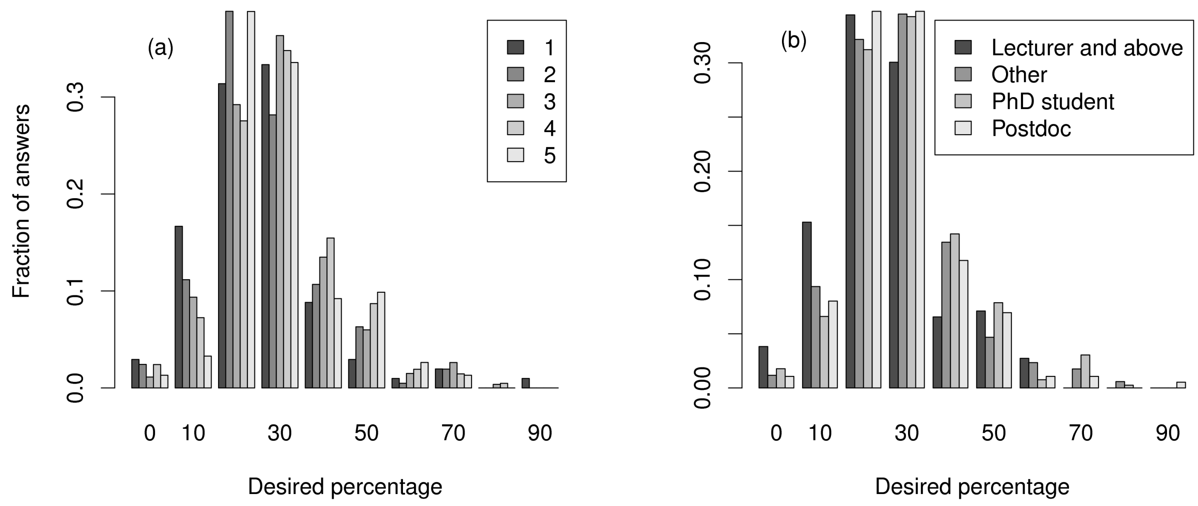

Figure 5: Distribution of the desired percentage of mathematics, statistics and programming (in the ecological curriculum). (a): with respect to involvement in modeling ("Modeler" score); (b): with respect to status / employment level.

Comments of respondents

After carefully evaluating the comments left by 250 out of the 937 respondents, we categorized them into four categories (see the website https://sites.google.com/site/mathematicsandecologysurvey/summary for a selection of emblematic representative comments). Categories 1 and 2 below were pre-determined, as they correspond to alternative teaching strategies (1: Teach mathematics within ecology/tune teaching to biologists, 2: Increase mathematics requirements/add mathematics classes as recommended by Ellison and Dennis 2009). We added categories 3 and 4 to account for other

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frequently observed comments. Note these categories are not mutually-exclusive (below), and some comments (26%) could not be tied to any particular category and were therefore excluded from the following classification.

1. Teach mathematics for ecologists/biologists (36% of comments). Many respondents feel abstract mathematical/statistical classes, or teachers from pure or applied mathematics, do not bridge the gap between mathematics and application. Some respondents pointed out much of the theory/statistics taught is not particularly applicable to the empirical datasets gathered by ecologists.
2. Inform “mathematics avoiders” of the quantitative nature of ecology (34% of comments). Many ecology students come to ecology programs hoping to avoid mathematics. Many respondents feel we need to advertise early on to high-school and undergraduate students the quantitative nature of ecology-related disciplines. Variant: make classes of mathematics/statistics compulsory.
3. Teach students how to program (14% of comments). Use R (R Core Team 2012) or other computing software, not point-and-click statistical packages.
4. Personal story in favour of mathematical training (11% of the comments). ’I wish I had learned more mathematics, I encounter difficulties now’ or ’I’ve been lucky to learn some mathematics, and that puts me at a huge advantage now.’

The last anonymous comment in the sample speaks for the general sentiment: “*Given the nature of the field, and despite the outsourcing of modeling to specialists, it is good to at least understand what is going on within the model or behind the model, if not directly programming it yourself. This deeper understanding allows for better theory. It has taken me months of just focusing on statistics/mathematics and models to just get up to speed with fundamentals that I wish had been given during undergrad.*”

Discussion

Overall, our results indicate that (1) quantitative training in ecology (mathematics/statistics/programming) is often insufficient; (2) PhD students and postdocs feel a lack of quantitative training; and (3) improving quantitative training should include both extra classes and better integration of quantitative methods within existing classes. Efforts are therefore required within both classes of mathematics/statistics for ecologists and ecology classes per se. Most of our ecological respondents seem to agree with Ellison & Dennis (2009) and Hobbs & Ogle (2011) that calculus is important (and 57% feel they miss notions of calculus). Calculus, however, it not taught at all universities; our results therefore concur with those of Ellison & Dennis (2009) that a pre-statistics calculus course should be introduced for ecologists when it is absent. Insofar as additional mathematics and statistics classes go, our interpretation of the survey results is in line with the proposed coursework of Ellison and Dennis (2009). We note in passing that such calculus at undergraduate level might allow students not pursuing in ecology to switch to other educational branches more easily (e.g. economics). However, our results also suggest that for quantitative training to be successful we should (1) advertise the quantitative nature of ecology earlier and (2) better connect mathematics and statistics to particular ecological problems and datasets (suggested also in Hobbs & Ogle 2011).

How to convey the quantitative nature of ecology to high-school students and undergraduates before they specialize (the time of specialization varying a lot between countries) is a puzzling question, given that many aspiring ecologists entered the discipline not only because they loved nature, but also because they were less inspired by more quantitative physical sciences (as the comments of our respondents and our personal experiences make clear). We can offer several suggestions, such as having formulas representing models used in ecology on webpages and brochures presenting ecological research, or former students emphasizing their struggle with mathematics and statistics to newcomers. The subject is difficult, given one also wants to recruit students; a potential argument might be that mathematics, statistics and programming boost employment prospects both inside and outside of academia (i.e. these generate transferrable skills).

The second point, ecologists want teaching of mathematics and statistics to be more integrated within their discipline, implies that more classes should be taught by quantitative ecologists, starting at undergraduate level. Our experience with such statements, however, is that they generate some controversy. Hence we elaborate here on what we mean, and more

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importantly, what we do not mean. We certainly do not mean that basic knowledge in ecology, evolutionary biology, behaviour or geography (and other useful disciplines for ecologists such as physiology or molecular genetics) should be replaced by mathematics and statistics. Several reviewers of previous versions of this paper remarked there might be an opportunity cost to more quantitative classes, i.e., if you add quantitative classes, something must go out to make room. We think this opportunity cost is minimal, for two reasons. First, it is possible to make ecology courses (and courses in related disciplines) more quantitative with minimal effort. When explaining concepts of, say, population genetics or demography, teachers could explain and emphasize the mathematical foundations of these fields, rather than just discussing general principles. Ellison and Dennis argue that statistics courses before calculus are useless, no matter how many you might attend, you will never fully get statistics without calculus; it could be similarly argued that mathematics-free demography or population genetics classes are not very useful, as they deliver mostly superficial, rather than foundational knowledge. But a little more time might be required on such classes. On that second point, we remark that much biological courses require rote or “by-heart” learning, especially at the undergraduate level. Though memorization has obviously to be trained, many biologists would likely agree that in biology the amount of morphological attributes or detailed taxonomical knowledge that enters the cursus is very high. Much of this knowledge is actually less fondamental than general principles of calculus and statistics, for instance, and this is all the more important that not all undergraduates will continue in ecology: they need often a general formation. Note that our remark does not apply to less straining ways of gaining taxonomical knowledge, e.g. field trips that are an important part of an ecologist's training.

The elements listed above form a compelling practical argument to include more mathematics in ecology-related degree programs (see also Anderson et al. 2001). It might require ecology departments to invest more in teaching resources for quantitative methods. According to our survey, this investment would however be welcomed by the community as an improvement to the education that universities and research institutes provide. Two topics deserve further inquiry: the integration of programming with quantitative training and specific areas of mathematics that need more emphasis. For the first, we asked whether programming classes should be taught separately or merged with mathematics and statistics. The results did not show a strong preference (63% merged, 37% separated, with no trend according to respondents' profiles). Merging classes would allow a clearer integration of programming with practical problems; separated programming classes would promote higher levels of programming ability. One respondent commented: “initially separate, then merged” - which sounds like a reasonable option. The second topic pertains to what specific mathematical knowledge respondents felt is currently most lacking. Choices included probability, calculus (broadly defined), linear algebra, graph theory, geometry, and “other” (see SI, Appendix 1 “Questionnaire”). Given that ecologists mainly use mathematics for statistics, and that probabilistic models are useful for both theory and decision making, we expected probability to be the most-requested subject. Yet, we found that calculus, linear algebra, and even graph theory reached response frequencies similar to probability theory. One possible explanation is that while trying to understand statistics and probability, ecologists encounter difficulties directly tied to their knowledge in calculus and linear algebra (e.g. partial derivatives and matrices are used in many statistical courses). Needless to say, specific mathematical needs and training requirements differ among sub-fields or personal experiences.

Conclusion

Ecology and other biological disciplines are moving into an increasingly quantitative era (Hastings et al. 2005), which demands a general review of mathematical, statistical and programming training. Collaborative research projects and data sets are both expanding in size and complexity, for which we need ecologists trained in state-of-the-art modeling (Hobbs & Ogle 2011). This survey points to the widespread recognition of the need for better quantitative training in ecology among early-career ecologists, and highlights two useful means to do so: additional mathematics and statistics classes (especially, for undergraduates, calculus and sometimes algebra, when these are absent) and also more quantitative ecology classes, combining mathematical, statistical, and programming concepts with ecological knowledge.

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