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

Frédéric Barraquand ${ }^{1,11^{*}}$, Thomas H.G. Ezard ${ }^{2,11}$, Peter S. Jørgensen ${ }^{3,11}$, Naupaka Zimmerman ${ }^{4,11}$, Scott Chamberlain ${ }^{5}$, Roberto Salguero-Gómez ${ }^{6,7,11}$, Timothy J. Curran ${ }^{8,11}$ and

Timothée Poisot ${ }^{9,10,11}$

1 - Department of Arctic and Marine Biology, University of Tromsø, Tromsø, Norway
2 - Centre for Biological Sciences, University of Southampton, Southampton, United Kingdom
3 - Center for Macroecology, Evolution and Climate, University of Copenhagen, Copenhagen,
Denmark
4 - Department of Biology, Stanford University, Stanford, USA.
5 - Biology Department, Simon Fraser University, Burnaby, BC, Canada
6 - Max Planck Institute for Demographic Research, Evolutionary Biodemography Laboratory, Rostock, Germany

7 - School of Biological Sciences, Centre for Biodiversity and Conservation Science, University of Queensland, Brisbane, Australia

8 - Department of Ecology, Lincoln University, Canterbury, New Zealand
9 - Département de biologie, chimie et géographie, Université du Québec a Rimouski, Rimouski (QC) Canada

10 - Québec Centre for Biodiversity Sciences, McGill University
11 - International Network for Next-Generation Ecologists, http://innge.net

Corresponding author *: frederic.barraquand@uit.no

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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 who studied biology as undergraduates. We found a clear self-perceived lack of quantitative training: $75 \%$ were not satisfied with their understanding of mathematical models; $75 \%$ felt that 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, which is likely higher than for most existing programs. The main suggestion to improve quantitative training was to relate theoretical and statistical modeling to applied ecological problems. Improving quantitative training will require dedicated, quantitative classes for ecology-related degrees that contain good mathematical and statistical practice.


## Introduction

Basic tasks in ecological research and management often 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 today use statistical and computational techniques beyond analysis of variance and simple linear regression. These include, among others: generalized, mixed, or nonlinear regression models; discrete probabilistic models fitted by maximum likelihood; Bayesian statistics and Markov-Chain Monte Carlo [MCMC]; graph-theoretic algorithms for interaction webs; and movement models derived from Brownian motion. We surveyed the July 2012 issues of Ecology, Journal of Animal Ecology, and Oikos, and found these more sophisticated statistical techniques are used in $75 \%, 95 \%$ and $70 \%$ of articles, respectively.

Theoretical ecology has been using fairly advanced mathematics since the 1920s and 1930s (e.g. Lotka 1925, Fisher 1930, Volterra 1931), but as a subdiscipline it has remained rather separated from the rest of ecological science (Kingsland 1995), for some time. Therefore, the need of theoreticians for mathematics was much greater than that of the average ecologist. In contrast, modern theoretical ecology is more and more connected to ecological data (Hilborn and Mangel 1997, Bolker 2005, Codling and Dumbrell 2012), and this fusion of theoretical and statistical models increases the need for many ecologists to have a detailed understanding of the theoretical and statistical sides of their discipline.

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, Hubbell 2001; graph theory for food webs, Dunne 2006). These fields have a long tradition of the use of quantitative methods, but the rise of improved and often freely available software has made complex mathematical and computational tools accessible to all. 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, Source Code in Biology and Medicine). Similarly, the open-source statistical programming language $R(R$ Core Team 2013) has been embraced by much of the ecological community. Fifty years ago, Pielou (1969) thought ecology was becoming a mathematical subject. While it is unclear whether ecology is truly more mathematical, the requirement for statistical and computational skills has certainly increased, and so did the rate at which new methods are developed and published (see references above). In the current landscape of ecological research, a lack of mathematical literacy can prohibit access to a large part of the literature, and run the risk of producing analyses that are considered sub-standard by reviewers and editors. Outstanding research can, needless to say, be performed without this elevated statistical background, but there is undeniably an impression that quantitatively intensive ecological research is becoming more dominant. This poses a problem for ecology as a whole: 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 more quantitative research in ecology, one might expect current ecology students to receive training rich in mathematics, statistics and programming. With the increase in the availability of advanced methods, this training ought to focus on (i) understanding how they work and (ii) when to use them. 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). As such, undergraduate courses in ecology can resemble story telling without strong mathematical or statistical foundation, which is far removed from current ecological science. 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. However, data on the level of quantitative training that early career ecologists themselves consider appropriate are rare. Are more undergraduate mathematics classes the answer? How many
ecologists are distressed by their lack of formal mathematical and statistical training? Earlycareer scientists are 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. Here we attempt to assess the size of the "quantitative gap" in young scientists through an online survey (see Supplementary Information [SI], Appendix 1) 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. diffusion on the American ECOLOG-L mailing list (16 ${ }^{\text {th }}$ of February, 2012). 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].

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 Cls, e.g. Agresti-Coull, are available but those used here are sufficient given the large sample size, Agresti 2007).

## Control questions: survey composition

## 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, Cl [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: Survey composition. Partitioning of the respondents with respect to (a)
(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 quantitative approaches to ecology. 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; note that this question also assess statistical models, and not only dynamical ones). 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).

Figure 2: Distribution of variables quantifying attitudes towards mathematics. (a) Distribution of "Feeling" variable (from 1:"really dislike" mathematics to 5 :"really like") and (b) Distribution of "Modeler" variable (1:"do not model" to 5:"specialist modeler"). 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.


Figure 3: Relative frequency of the uses of mathematics and association between categories. Most respondents use mathematics primarily for statistics ( S ), and some other for statistics+theory (S+T, 26\%), and the remaining 11\% for statistics+decision making (S+D) and $10 \%$ for 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 participants), 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 75\% of respondents with a mathematics-based undergraduate degree (27 of 36) 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 dissatisfaction is international and understanding of mathematical models is strongly dependent on having mathematics classes at the undergraduate level.


Rate your involvement in the process of ecological modelling

## 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]\%). Surprisingly, these percentages (90\% for more mathematics and $95 \%$ more statistics) do not vary much across categories, and hold for the categories 1 and 2 of the "Feeling" variable ( $>200$ respondents), who therefore reported disliking the use of equations to construct mathematical models (Feeling = 1: "really dislike", Feeling=5: "really like"). More than half of respondents want more mathematics and statistics at both undergraduate and graduate levels ( $61 \%$ for mathematics and $76 \%$ for statistics). Additionally, 14\% want more mathematics only at the undergraduate level, and another $16 \%$ desire more mathematics only at the graduate level. For statistics, $7 \%$ want more statistics only at the undergraduate level, and $11 \%$ only at the graduate level. In essence, respondents want more mathematical and 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).

## Thirty percent of the ecological curriculum should be 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 e.g. 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).


Figure 5: Frequency distribution of the desired percentage of mathematics, statistics and programming (in the ecological curriculum). (a): with respect to involvement in modeling ("Modeler" score, 1: no modeling to 5:specialist); (b): with respect to status / employment level.

## Comments of respondents

After carefully evaluating the comments left by 250 out of the 937 respondents, we classified 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/highlight ecological relevance of mathematical principles, 2: Increase mathematics requirements/add mathematics classes, as recommended by Ellison and Dennis 2009). We added categories 3 and 4 to account for other 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 2013) or other computing software that requires users to understand all steps of the analysis, instead of point-and-click statistical packages.
4. Personal experience 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 quantitative training in ecology is often insufficient and that arresting this insufficiency requires both extra classes and better integration of quantitative methods within existing modules. 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). We had expected probability to be the sub-discipline that respondents felt was currently most lacking (see SI, Appendix 1 "Questionnaire") because ecologists mainly use mathematics for statistics and because probabilistic models are used in both theory and decision-making. Contrary to our expectation, calculus, linear algebra, and even graph theory were also described as areas in need of further training (Fig. S5). One possible explanation for this unexpected result is that ecologists encounter difficulties directly tied to their knowledge in calculus and linear algebra while trying to understand statistics and probability (e.g. partial derivatives and matrices are used in many advanced statistical courses). What is clear, however, is that a few classes sprinkled across disparate modules do not provide the holistic overview of quantitative training as requested by the respondents. Our interpretation of the survey results is in line with the proposed coursework of Ellison and Dennis (2009) - a two semester course of calculus (broadly defined, perhaps including some linear algebra) as well as introductory statistics for undergraduates; at graduate level, an additional two semester sequence of probability and advanced statistics. For quantitative training to be successful we should also (1) advertise the quantitative nature of ecology earlier and (2) better connect mathematics and statistics to particular ecological problems and datasets (as suggested in Hobbs \& Ogle 2011). We elaborate on these points below.

Conveying the quantitative nature of ecology to high-school students and undergraduates before they specialize is non-trivial. The comments of our respondents indicate that many
aspiring ecologists entered the discipline not only because they loved nature, but also because they were less inspired by other, more quantitative, physical sciences. Combining math-intensive activities with fieldwork has been suggested (Gimenez et al. 2012) as one way of better integrating the quantitative and empirical approaches to ecology and introducing the necessity of both to new students. Moreover, mathematics, statistics and programming are transferrable skills that boost employment prospects inside and outside of academia - this should be highlighted. Our results indicate that ecologists want mathematics and statistics to be taught by quantitative ecologists so that the curriculum is applied and relevant. This suggests that departments who provide quantitative training via service teaching from mathematicians may not provide the optimal training for their students. 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". This appears to us as a sound proposition, because it allows students not to be overwhelmed at first by simultaneous struggles with computing and statistical/model thinking. As soon as some familiarity with computer programming is established, however, ecology/biology-driven courses help to show students the usefulness of programming (e.g., Valle and Berdanier 2012) and how the approach can be used to test ecological hypotheses.

Note that we do not imply that basic knowledge in ecology, evolutionary biology, or any related discipline such as geography, physiology or molecular genetics should be replaced in undergraduate curricula by mathematics and statistics. Indeed we do not believe that adding more effective quantitative training precludes the teaching of other fields. Many biological courses require rote or "by-heart" learning, especially at the undergraduate level. Currently, these courses often contain a significant amount of detailed taxonomy or morphology. Much of this knowledge is actually less fundamental and less transferrable to the world of
employment than general principles of calculus and statistics. A more sustainable career strategy is to learn to ask appropriate questions of an expert, than to be oneself an expert in everything. Asking the appropriate question requires the foundations of knowledge. It is additionally possible to learn biology while learning maths (e.g. biology-inspired calculus, Schreiber 2009). Later, students used to a little applied mathematics from classes of population genetics or demography can also, and often do, become naturally more quantitative.

The elements listed above form a compelling practical argument to include more mathematics and statistics in ecology-related degree programs (see also Anderson et al. 2001, for a more applied perspective). The changing landscape of how data is collected and analyzed in ecology means that ecology departments will need to invest more in the teaching of quantitative methods. According to our survey, the community would welcome this investment.

## Conclusion

Ecology is moving into an increasingly quantitative era (Hastings et al. 2005), which demands a general review of mathematical, statistical and programming training (Brewers and Smith 2011). 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 calculus and algebra for undergraduates, when these are absent) and more quantitative ecology classes, combining mathematical, statistical, and programming concepts with ecological knowledge.

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