A survey of the mathematics landscape within bioscience undergraduate and postgraduate UK higher education

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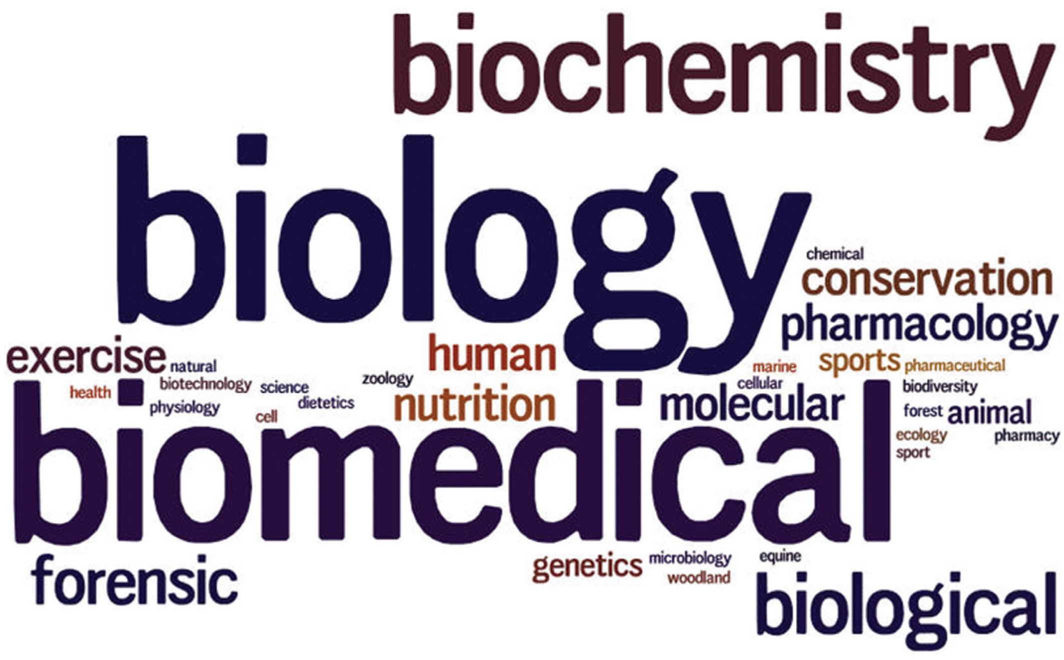
June 2011



Supported by the UK Centre for Bioscience,
Higher Education Academy

Acknowledgements

This report was commissioned by the UK Centre for Bioscience, Higher Education Academy in January 2011. The author would like to thank in particular Dr David Adams and Dr Jackie Wilson for their helpful feedback on the report and the survey designs and for assistance with distributing and publicising the surveys. The author would also like to thank the survey respondents and those who took part in thoughtful and insightful discussions by telephone and email.

First published in 2011 by the UK Centre for Bioscience, Higher Education Academy, Leeds LS2 9JT.

ISBN 978-0-9569288-1-8

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1. Executive Summary

This report focuses on two key issues: (1) ensuring that all bioscience graduates are equipped with basic mathematical skills and understanding; and (2) encouraging and increasing the number of bioscience graduates who develop their mathematical skills beyond A level standard so that they have the confidence and understanding to participate in increasingly quantitative and interdisciplinary research.

1.1 Basic Mathematical Skills

Students enter bioscience undergraduate degrees with a very wide variety of mathematics[1] qualifications from A at A2 Maths to less than C at GCSE. This wide variation causes difficulty in designing appropriate courses. Whilst online approaches are being used in innovative ways they are best combined with practical classes and small group tutorials which are resource intensive. Diagnostic testing is being used in some institutions to target resources effectively and/or to increase student motivation. Some universities have reported successes with the introduction of online approaches whilst others have not. **It is important to provide opportunities for University teaching staff to meet to share ideas, successes and difficulties in dealing with such a wide variety of mathematical backgrounds amongst their students**.

In many cases, problems with basic numeracy are evident and this reflects the fact that many students have grades less than A at GCSE Maths. These students are unlikely to be able to carry out many of the basic mathematical approaches, for example unable to manipulate scientific notation with negative powers so commonly used in biology, measurements of the length of a nerve cell or the concentration of a hormone in the blood. They are also unable to rearrange simple equations or to reliably use concepts such as ratio and proportion to calculate dilutions of solutions.

Most of the maths taught within bioscience undergraduate degrees is equivalent to the content of GCSE and AS level maths including concepts and techniques such as algebra, ratio and proportion, logarithms and exponential growth and decay. Whilst the mathematical concepts are similar the key difference is that at university level the maths is taught within a biological context. This is important because: (1) it provides a greater degree of motivation for students; and (2) students see how the concepts are applied and should then be able to use them in practice. **In the light of reports from the Nuffield Foundation and the Royal Society it is important to consider broadening post-16 education to ensure that students are encouraged and have the opportunity to study mathematics that is rigorous and delivered in a scientific context**.

Students' attitudes and expectations are major limitations in undergraduate bioscience maths education. Poor self-efficacy means that many students do not begin to attempt quantitative problems and this applies equally to those with A level maths as it does to those with C at GCSE. A lack of mathematics content in A level Biology means that students do not expect to encounter maths at undergraduate level. **There needs to be a more significant mathematical component in A level biology and chemistry along with opportunities for collaboration between academic bioscientists who use quantitative approaches and secondary maths and science teachers**.

1.2 The development of mathematical confidence and understanding required to participate in quantitative interdisciplinary research

A minority of undergraduate degree courses provide options for bioscientists to extend their mathematical knowledge beyond the equivalent of AS level maths and therefore bioscience graduates are largely unprepared for further study involving quantitative approaches, for example systems biology or computational biology, at postgraduate level. There are some taught Masters courses in quantitative biology and related topics but it is likely that they will have limited impact in terms of the number of scientists trained in quantitative approaches. There are some innovative approaches to incorporating more advanced mathematics within bioscience degrees and it would be helpful to encourage discussion and collaboration in this area. The BIO2010 project in the USA has led to the development of new teaching methods and resources incorporating mathematics into bioscience education. This project has supported shared development of resources with opportunities for collaboration between universities. **A more detailed investigation of the BIO2010 project and the impact it has had and continues to have is likely to yield a rich array of curriculum design ideas and resources. Opportunities for discussion of this alongside promotion and analysis of innovative approaches already taking place in the UK will perhaps inspire academic staff and provide a cost-effective mechanism to raise the level of mathematics within both undergraduate and postgraduate bioscience education**.

[1] The term "mathematics" is used throughout this report to include both mathematics and statistics.

2. Background

The driving force behind this report is the increasing realisation that biology is becoming a more quantitative science, relying very much more upon mathematics, computing and physical sciences [1], [2]. This development is acknowledged in the current BBSRC Strategic Plan[2]:

> *"BBSRC will … encourage interdisciplinary research and training …. As bioscience becomes increasingly quantitative there is also an urgent need to raise the mathematical and computational skills of biologists at all levels."*

It is important, therefore, to assess the impact that this will have upon bioscience education and to consider how bioscience education, both undergraduate and postgraduate, should adapt.

In the USA a similar realisation led to the BIO2010 project [2], [3] which has worked to modify the undergraduate biology curriculum to better incorporate mathematics, computing and physical sciences. This project began in 2000 and brought together faculty from a large number of universities to identify new topics and new methods of teaching and to create repositories of teaching and learning materials ([4] and references therein). The emphasis was on incorporating the maths into biology and bringing some of the new quantitative approaches into the undergraduate curriculum.

Of equal importance in the UK, though, are the increasing clarion calls warning of the very wide range in mathematical literacy of bioscience undergraduates. Whilst there are some who have taken A level maths (and occasionally A level Further Maths) these students are in the minority and there are very many who lack even the basics. The report from the Nuffield Foundation [5] highlights the fact that the participation of students in post-16 maths in the UK is the lowest out of 24 OECD countries. Furthermore, the Royal Society report [6] notes that only 40% of students who take A level Biology also take A level Mathematics. Both of these reports recommended that post-16 education in the UK should be broadened to include a wider range of subjects and the Nuffield Report went further to recommend that mathematics should be compulsory (along with English Language).

Therefore we have two key issues at stake and it is helpful to keep them distinct. The first is ensuring that bioscience graduates are equipped with a reasonable, appropriate understanding of mathematics and statistics and the second is to ensure that those bioscience students who have the mathematical inclination can extend their application of mathematics to problems within bioscience and to ensure that they can participate in increasingly interdisciplinary research. This distinction between basic skills and advanced techniques was noted by The Association of the British Pharmaceutical Industry report in 2008 [7]. This report, through interviews with industry scientists and recruiters, identified problems with both the basic mathematical skills of graduates entering industry as well as the availability of graduates with a combination of mathematical insight AND biological knowledge and understanding required for interdisciplinary approaches in areas such as pharmacokinetic/pharmacodynamic modelling.

The aims of the current study are to investigate the whole of the mathematical landscape within bioscience education in the UK, from entry to undergraduate education through to postgraduate training, and in particular to consider the following:

1) The entry qualifications, attitudes and expectations of new undergraduates and the effect they have on students' abilities to cope with the mathematics provided within bioscience degrees.
2) The nature of the mathematics taught in biology degree programmes throughout the UK, both undergraduate and postgraduate. Furthermore we will examine how it is taught: whether it is integrated with the biological content or presented as a stand-alone module.
3) The increasing impact of systems biology, computational biology and bioinformatics. This has led to the development of new Masters level courses and the capacity of these courses to provide sufficient mathematical training for biologists will be investigated.

[2] http://www.bbsrc.ac.uk/publications/planning/strategy/theme-knowledge.aspx

3. Undergraduate bioscience degree courses: a survey of their mathematics content

3.1 About the survey and its respondents

The survey (see Appendix 1) was distributed by the UK Centre for Bioscience in February 2011 to 120 contacts from 96 Higher Education Institutions. There were 46 responses in total from 40 different UK Higher Education Institutions[3]. The degree courses covered the whole range of bioscience fields. Figure 1 on the front cover shows a "Wordle" diagram where the size of the text indicates how common the word was in the degree title.

3.2 Entry qualifications, attitudes and expectations of new undergraduates

3.2.1 Entry Qualifications

By far the majority (92%) of undergraduate degree programmes required GCSE rather than AS or A2 level Mathematics. Of those programmes that required GCSE Maths as the minimum requirement, students entered the courses with a wide variety of grades at GCSE. Figure 2 shows that almost 40% of institutions accepted GCSE grades from A* to C, a further 40% accepted predominantly B and C grades whilst a significant minority, 16%, accepted less than grade C at GCSE Maths. Other equivalent qualifications can be used instead of GCSE's for entry to some institutions but will not be considered further here.

There are two key points to be made from these data:

1) problems arise due to such a wide variation in grades

2) there are some areas of maths that these students have not covered and this leaves them at a disadvantage at university.

The variation in grades at entry causes problems:

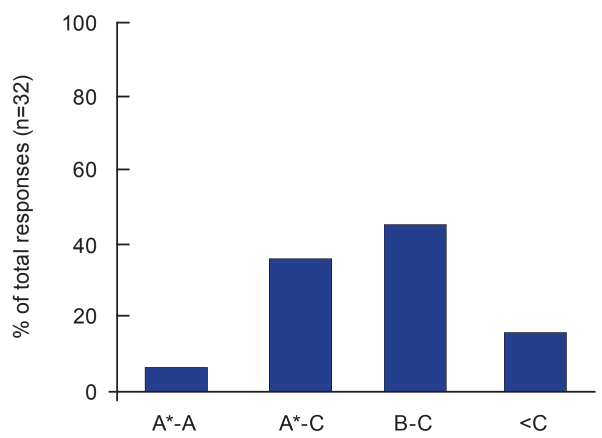
> *"… our students arrive with a range of Maths skills from A-level Maths down to GCSE C grade. The students who have studied A level Maths definitely have the foundation skills to build upon, whereas those with GCSE qualifications vary. The variety of skill levels makes teaching much harder."*

Some universities have developed methods using online resources to try to address this gap but not all feel that they have been successful (see below).

It is important to understand what these grades mean, to translate them into the knowledge that a student might be expected to have when entering University. The report "Understanding the UK Mathematics Curriculum Pre-Higher Education" [8] has a rather sobering list of the knowledge and skills that students with a C grade or lower may not have acquired:

- negative and fractional powers,
- scientific notation,
- solution of linear simultaneous equations,
- reverse percentage calculations
- plotting graphs of exponential functions
- working with quantities which vary in direct or inverse proportion
- trigonometry,
- cumulative frequency diagrams and histograms,
- probability calculations.

Figure 2. Responses to the question: "In programmes for which GCSE Maths is the minimum requirement, what grade at GCSE mathematics would these students have?"



[3] The institutions were representative of the HE sector and included 10 Russell Group, 11 other pre-1992 and 15 post-1992 universities.

At the meeting "Mathematical Challenges for Biologists" organised by the UK Centre for Bioscience, Higher Education Academy and the Biotechnology and Biological Sciences Research Council, and held at the University of Reading Nov 2010, many of the participants, mainly those teaching maths on first year university bioscience courses, recognised this description and many of these topics came up regularly when respondents to this survey were asked about particular difficulties (see below).

It's also worth noting, as Lee et al. [8] point out, that students with a B or C at GCSE Maths are likely to have an incomplete understanding of many of these topics. What this means in effect is that someone with a B at GCSE maths may have limited ability to manipulate numbers commonly used in biology such as measurements made in microscopy in micrometres or concentrations in nanograms per litre. They are also unlikely to be able to recognise an equation for a straight line and most probably unable to rearrange it. If they begin study of statistics at University level, they are unlikely to have a grasp of the basics of probability.

A grade of C or lower at GCSE means there are likely to be real problems with basic numeracy. One third of respondents noted lack of basic numeracy as a particular difficulty:

> *"The lowest end of the spectrum can even need help with working out how to calculate a percentage or have difficulty in reading decimal places having done a calculation and re-arranging simple formulae is also a problem for some students."*

There was also the suggestion that mathematics learning at school can be very procedural, learning for the exam rather than for a deep understanding:

> *"Cannot rearrange equations - stuck on the triangle method which teaches them nothing."*

This was linked by five respondents to an inability to estimate or approximate an answer:

> *"Lack of self-monitoring (students are not able to check their work for mistakes, often due to lack of approximation skills, understanding of dimension and inability to calculate without a calculator)"*

In addition to lack of basic numeracy, one third of respondents specifically mentioned calculating concentrations and dilutions as a problem area. It is not clear at this stage whether the root cause of this may be a problem with the fundamental understanding of ratio and proportion or whether students are unable to apply their understanding of ratio and proportion to this particular situation.

> *"… a difficulty with simple arithmetical activities such as applying a dilution factor or calculating molarity."*

> *"Individual students experience difficulty with concepts of ratio leading to difficulties in liquid handing such as diluting solutions."*

Another area of particular difficulty is algebra with one third of respondents specifically mentioning this as an issue:

> *"little or no knowledge of how to manipulate simple linear equations"*

There is a great deal of variation across higher education institutions in the reported proportion of students with the different mathematics qualifications. Figure 3a shows the average proportions of students with each entry qualification whilst Figure 3b shows the proportions for 24 institutions for which sufficient data were available.

There is also a great degree of variation in the proportion of students with an "Access to HE" qualification. It is difficult to find out detailed information about these qualifications as they vary widely across the country however most are unlikely to cover more than GCSE-equivalent maths.

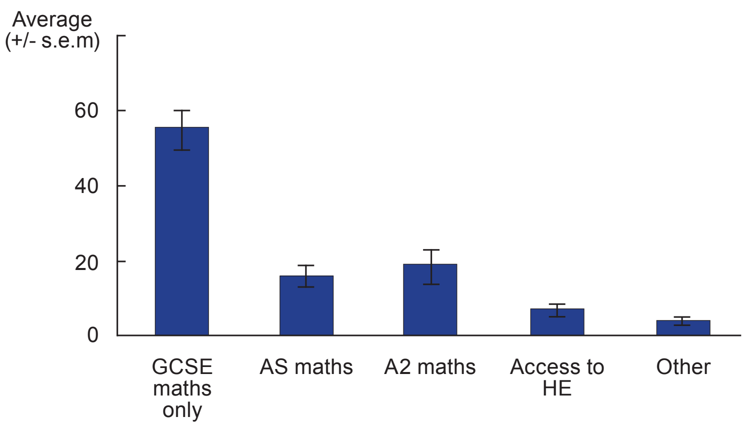
3.2.2 Expectations of Academic Staff

Overwhelmingly, the majority of respondents (34 out of 42) answered "no" to the question: "Do you think new undergraduates are on the whole sufficiently well prepared in maths when they arrive to study bioscience?" There does appear, though, to be somewhat of a mismatch between the expectations of academics and the maths covered in the qualifications students begin their degree course with. Seven respondents noted that there was a particular difficulty with logarithms:

> *"They are NOT good (that is, they have not done) anything with logarithms and cannot use them to work out pH, or the inverse calculations. The notation they use is also suspect, that is, they copy down the button that they press on the calculator."*

Academic staff are expecting students to understand logarithms but most have not done AS maths and it is not covered at GCSE. One might argue that logarithms must be covered within A level Chemistry through understanding pH or in A level Biology through understanding exponential growth. However the effectiveness of teaching of this sort of maths within A level Biology and Chemistry is largely unclear. Anecdotal reports from students are that calculating pH, for example, is just taught through which button to press on a calculator rather than as a fundamental mathematical concept [9].

Figure 3. (a) The proportion of students with the given maths qualification (as reported by survey respondents) averaged across 24 institutions (+/- standard error of the mean s.e.m.).



(b) The proportion of students with each maths qualification for each of 24 Higher Education Institutions.

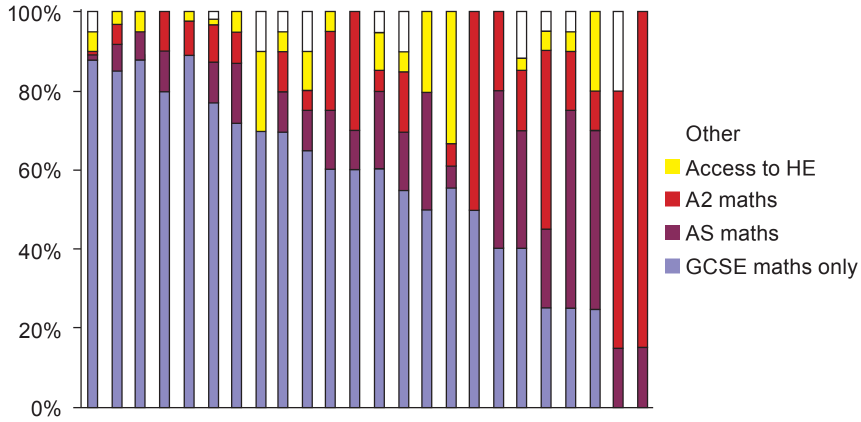
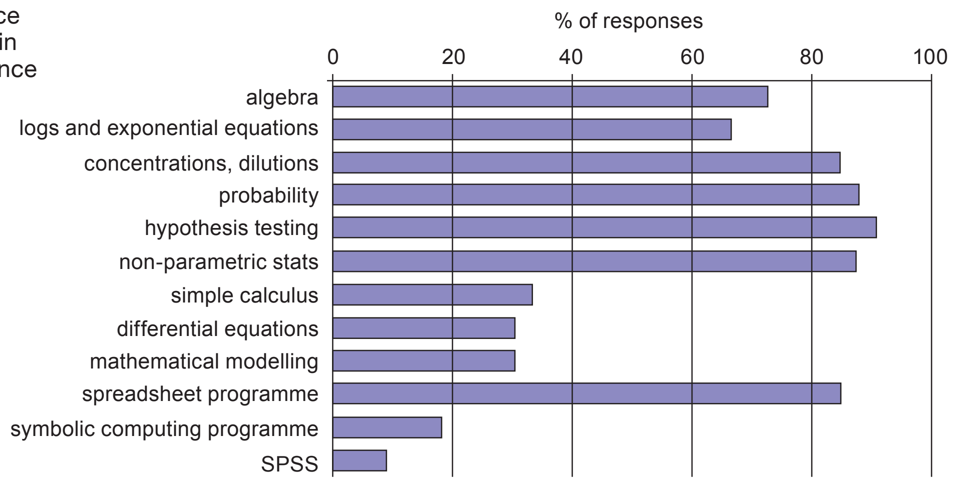


Figure 4. The prevalence of topics included within undergraduate bioscience courses.



Therefore it appears that expecting students to be familiar with logarithms via their knowledge of biology A level is unrealistic.

One respondent noted that:

> *"I believe there needs to be more of an understanding by university tutors about the mathematical capabilities of undergraduates. There need to be more opportunities created for FE and HE staff to discuss the issues."*

There is a considerable body of literature demonstrating that there has been a decline in mathematical ability of students entering higher education across a whole range of subjects [10]. Within the bioscience fields this has been demonstrated for pharmacy [11], psychology [12] and bioscience students generally ([13] and references therein).

3.2.3 Students' attitudes (as reported by academic staff)

A "fear of maths" or "maths-phobia" was commonly reported (12 out of 37 respondents) and it was noted that mature students in particular are more likely to lack confidence.

> *"But by far the biggest problem is the *fear* of maths. There is a culture amongst students, which is perhaps encouraged at school, in which it acceptable (almost fashionable) to treat maths as some kind of mystical dark art, sent to terrorise biologists. I am sure a more positive attitude would allow them to overcome most of the issues we encounter with the kind of basic maths we ask them to use/understand.*

> *"The key difficulty is not so much their lack of knowledge as their lack of confidence - an unwillingness to dig in and use number to solve problems and better understand biological systems."*

Academic staff report that students often do not expect to need any maths within a biology degree and the requirement for mathematical skills comes as a surprise.

> *"However, there are a significant proportion of students attracted to Biology that are quite poor in their maths skills, having not done post-GCSE maths. The maths content of a Biology degree comes as quite a shock to these students. I believe there should be more maths in both GCSE and A level Biology to help secondary students understand that it is part of modern biology."*

> *"I find that many undergraduates arrive with a skewed interpretation of mathematics... Consequently, many students arrive with the perception that mathematics and statistics are both abstract and a little 'arcane'. When they see the application for themselves, many do shift their opinion and attitude towards mathematics."*

Negative attitudes have been reported amongst secondary school students generally [14] and a number of factors have been identified as contributing to the development of these attitudes and these are: perceived difficulty, lack of confidence, perceived dislike and boredom and lack of relevance [14]. It is clear from this study that these attitudes persist into undergraduate bioscience education.

3.2.4 To what extent do the entry qualifications of new undergraduates limit what bioscience degree programmes can provide?

Is it possible for students to extend their mathematical knowledge and understanding if they wish to do so? Only a quarter of undergraduate degree courses (6 out of 25; 24%) provide options for bioscientists to extend their mathematical knowledge beyond the equivalent of AS level maths during their undergraduate degree and therefore bioscience graduates are largely unprepared for further study involving quantitative approaches, for example systems biology or computational biology, at postgraduate level.

> *"... offer some final year options … which have a lot of maths and students taking this course will be well-prepared for masters level systems biology. But most students avoid the courses with more than a glimpse of maths - and that's a cohort of students where around 80% have A grade maths A level."*

> *"our experience is that although students have grade A maths, many still have problems applying their mathematical skills to solving problems in bioscience."*

Should more advanced mathematics be taught at undergraduate level? The majority of survey respondents (16 out of 27; 59%) involved in teaching maths for bioscientists at undergraduate level thought that advanced concepts and techniques such as mathematical modelling should be taught at postgraduate level if required and not become a standard part of an undergraduate course. Only 22% (6 out of 27) thought that advanced concepts and modelling should be taught at undergraduate level with 5 respondents "on the fence".

Some comments which may shed light on the barriers to teaching more advanced mathematics within undergraduate courses are:

> *"Most undergrad courses don't cover "hard" topics for fear of lower marks, fewer 2.1s, student complaints etc."*

> *"We need to start much earlier making clear the value of a quantitative approach. However, this has the potential to scare off many students and it must be done engagingly and imaginatively."*

> *"It is easy for lecturers to shy away from numbers because they are often seen by students as boring and difficult… "*

3.3 What mathematics is taught and how?

Statistics is the most commonly taught mathematical topic along with algebra, calculating concentrations and dilutions, and exponential equations and logarithms (Figure 4). Only approximately one third of degree programmes included topics such as calculus, differential equations and mathematical modelling.

The majority of degree programmes (59%) include both a standalone mathematics course and mathematics embedded within other subjects whilst 16% have only a standalone mathematics course and 25% only teach mathematics embedded within other subjects. The majority (72%) of degree programmes include mathematics teaching over two or more years of the degree whilst 19% include mathematics teaching only in the first year.

Figure 5 shows that lectures and tutorials are the most common (91% and 84% respectively) methods for teaching maths. Online methods were often used, most commonly as formative assessment (53%).

Diagnostic testing was used in 13 out of 42 institutions with seven of these cases being introduced very recently. The purpose was to (a) help students identify areas of weakness and/or (b) target remedial support more effectively. However student engagement with the remedial support is variable from one institution to another, some report oversubscribed classes whilst others report poor student participation. Large classes and lack of staff and resources have been reported as problems.

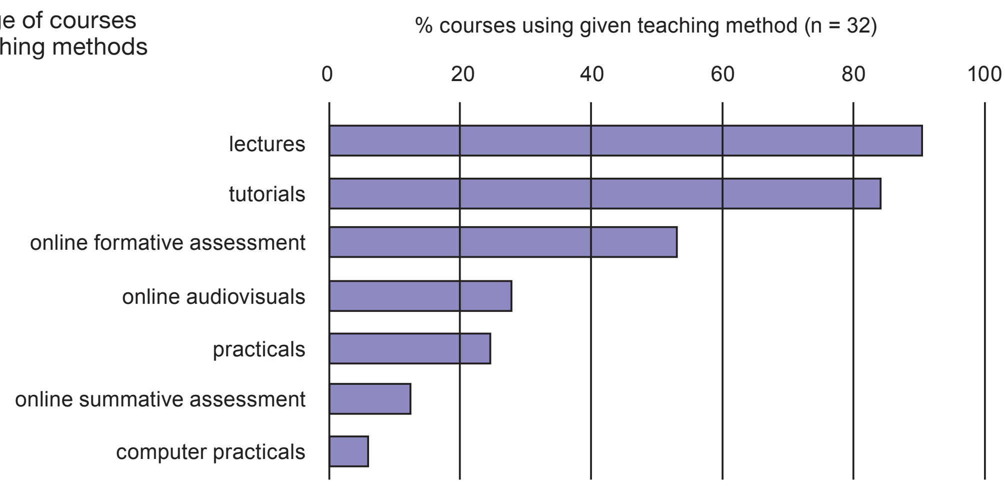
Overall there was a very wide range of views on the value of e-learning but the consensus appeared to be that it could be valuable when combined with appropriate tutorial support. Seven respondents noted that online techniques had been introduced recently but in most cases these were combined with face-to-face workshops or other support. Interestingly there were some examples where use of e-learning had been very successful and others where it had not.

Another recently introduced innovation that was mentioned several times was embedding mathematics teaching within practical classes or key skills sessions. Six respondents reported that they had recently changed their courses to embed the calculations within practical classes and four reported that they now included mathematics within other modules such as "Key Skills", "Skills for Biologists", "Communication and Analysis".

When asked "what works best?" the overwhelming response was the importance of emphasising the biological applications.

> *"It is important to move away from abstract mathematics to make it applied to the biosciences."*

Figure 5. Percentage of courses using different teaching methods



In particular the application within practical classes was given great importance.

> *"The most effective method appears to be the incorporation of data analysis into laboratory exercises. It can be difficult to engage bioscience students in lecture sessions on subjects such as maths & statistics but when they can apply the techniques to real data they begin to engage."*

> *"We approach maths teaching from the perspective of solving biology problems - answering research questions, which happen to need quantitative tools. Asking and answering questions - riddles - fun, rather than "here's some numbers to crunch according to some arcane rules".*

Small-group workshops and tutorials were mentioned by ten respondents as being particularly useful but barriers to this approach included the modular nature of degree programmes and expense/ lack of resources.

> *"My ideal would be to integrate it in with other modules … Unfortunately, the real world of shared modules with other degree programmes makes this almost impossible."*

> *"This isn't always practical with such high student numbers"*

The benefit of small groups was partly the flexibility in being able to respond to individual students but also the psychological and motivational factors.

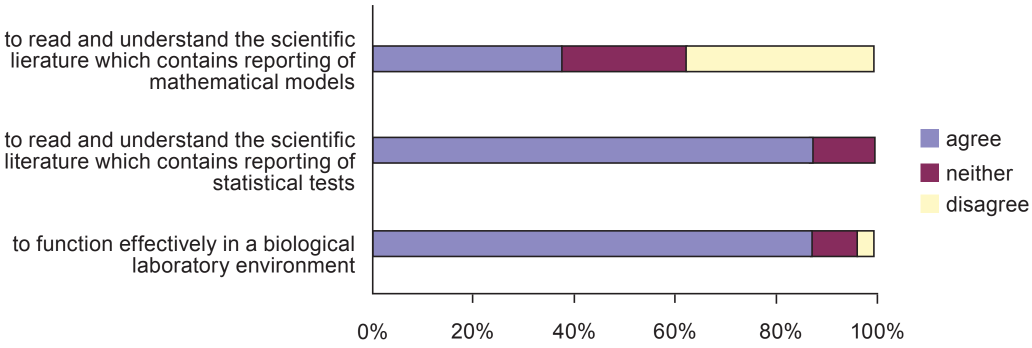
> *"Workshops are about the most effective means of teaching. Students need the opportunity to practice and have a tutor on hand to correct them when they go wrong. It is important that they are encouraged to 'have a go' and not to feel bad about making mistakes as they learn."*

3.4 Academics' views of mathematical skills of bioscience graduates and their preparedness for research careers

How well do those teaching mathematics think graduates are prepared with the basic mathematical and statistical knowledge? Figure 6a shows that the overwhelming majority (87%) think that students are well prepared to function in a biology laboratory environment (e.g. calculating concentrations and dilutions, using equations). Similarly 88% are of the opinion that graduates are able to understand statistical tests reported in the scientific literature. In contrast, less than 40% agreed with the statement: *The degree programmes we provide equip students with the mathematical understanding required to read and understand the scientific literature which contains reporting of mathematical models.*

Very few respondents (6% of 32, Figure 6b) thought that their graduates were well prepared to go on to a Masters in Systems Biology or Computational Biology whilst 56% thought that graduates were partially prepared. Some respondents felt that teaching the mathematics of modelling was not a necessary part of an undergraduate bioscience degree and that it should be taught at postgraduate level if necessary. Others explained that the nature of their degree programme was such that mathematical modelling skills were not a priority: *"There is always scope for further development of analytical skills, but this must be balanced with other programme content."*

Figure 6. How well prepared is a bioscience graduate in quantitative understanding and knowledge?
(a) Percentage of respondents who agree, neither agree nor disagree, or disagree with the following statements (n=32).



(b) Percentage of respondents who consider that students from their courses are prepared to go on to study at Masters level in Systems Biology and/or Computational Biology (n=32).

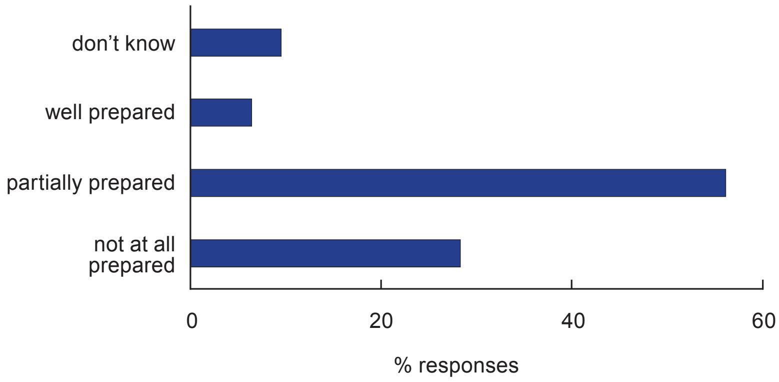
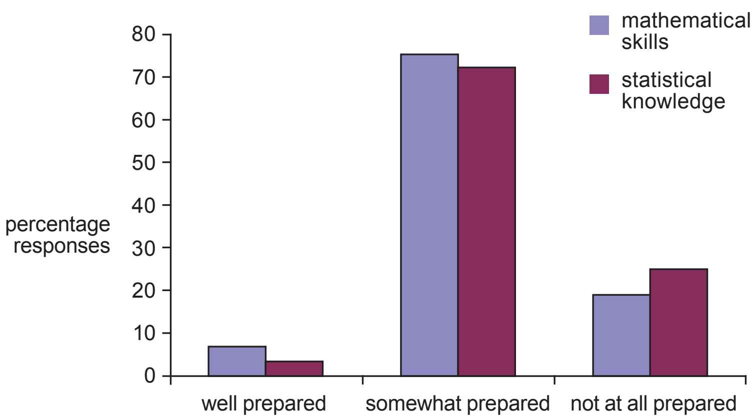


Figure 7. Academics' opinions of the preparedness of bioscience graduates with respect to basic mathematical skills (e.g. calculating dilutions, doing linear regression for a calibration line) and statistical knowledge (choose the appropriate statistical tests and to design experiments effectively) (n=32).



4. Is there a mathematical skills shortage amongst bioscience graduates? A survey of academic researchers

4.1 The survey and its respondents

The aim of this survey was to ask academic researchers their views on the mathematical skills of bioscience graduates working in research laboratories. The survey questions are shown in Appendix 2. There were 36 respondents to this survey from 25 different institutions[4] in a range of subjects including biomedical, environmental and agricultural sciences.

4.2 Are new postgraduate students prepared for quantitative approaches?

There was unanimous agreement with the statement: "as bioscience becomes increasingly quantitative there is also an urgent need to raise the mathematical and computational skills of biologists at all levels." Furthermore 97% (n = 29) of respondents agreed or strongly agreed with the statement: *Lack of mathematical knowledge, skill or confidence is preventing bioscientists from becoming involved in interdisciplinary teams using quantitative, integrated or computational approaches.*

Very few respondents (<10%) thought that bioscience graduates were "well prepared" whilst over two thirds of respondents thought they were "somewhat prepared" with basic mathematical and statistical knowledge (Figure 7).

4.3 Provision for mathematical and statistical training during postgraduate degrees

With regard to provision of training during postgraduate study (MRes and PhD), 79% of respondents reported some form of training (either lectures or online) in basic mathematics and statistics. Approximately half of those responding provided a combination of lectures and informal on-the-job training in basic maths and statistics. One-fifth provided only on-the-job training in basic mathematics and statistics. Online independent training either with or without on-the-job training is rarely used (8%) (Figure 8a). In contrast only 50% of respondents reported any formal training provision in the form of lectures or online instruction for more advanced mathematical and statistical techniques with most of this training occurring via lectures (Figure 8b).

4.4 The role of taught Masters courses for increasing quantitative skills amongst graduate bioscience researchers

Taught Masters courses in mathematical or quantitative biology tend to fall into two main types, those which require a significant mathematical background through prior undergraduate degree level study of maths and those that do not. Seven institutions that provide taught Masters courses[5] designed for bioscientists which develop mathematical, statistical and computational skills responded to the survey. For most of these courses approximately half of the students are bioscientists with the remainder of students coming from mathematics, physical sciences or computing backgrounds. For two of these courses 90-100% of students are bioscientists. The mathematics qualifications required for entry to these courses are GCSE mathematics, with one course requiring A level maths, in addition to an undergraduate degree.

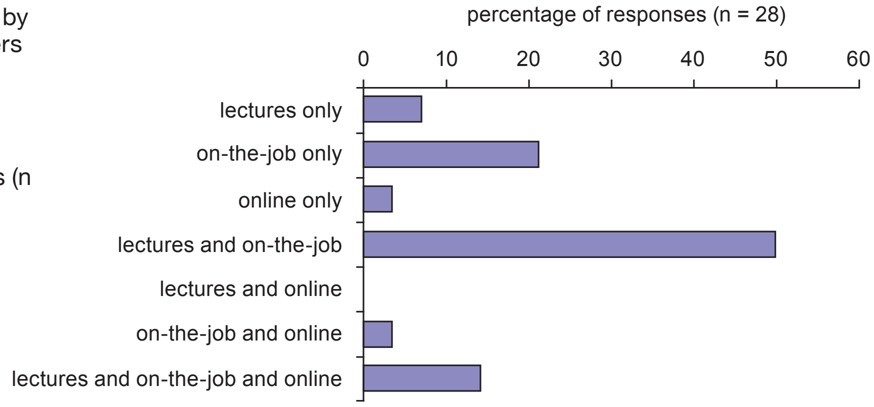
Some of these taught Masters courses have been very recently introduced and more work will be needed to ascertain the numbers of students they take, the impact they have on the supply of mathematically confident bioscience researchers and the employment destinations of their graduates.

[4] The institutions included 6 Russell Group, 11 other pre-1992, 5 post-92 universities and 3 research institutes.

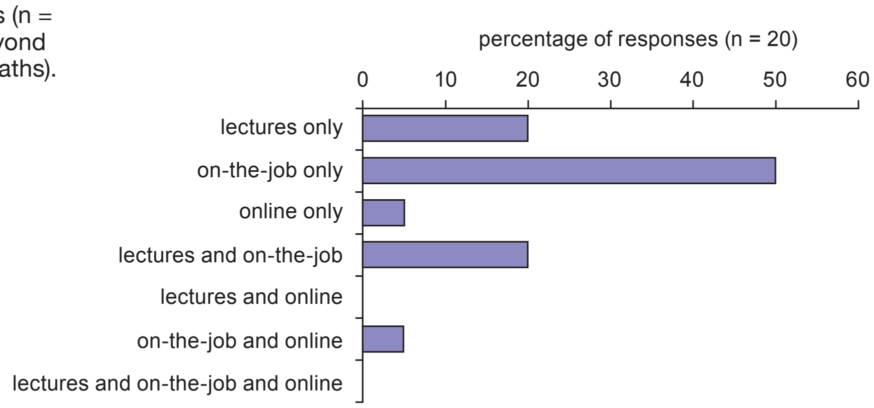
[5] Those who took part in this survey were: MSc Mechanistic Biology, Sheffield; MSc Bioinformatics / Medical Informatics, Exeter; MRes Bioinformatics, MRes Molecular Functions in Disease, Glasgow; MSc in Computational Biology Heriot-Watt; MSc Bioinformatics with Systems Biology, Birkbeck; MSc Biomodelling and Informatics, Middlesex; MSc/MRes Environmental & Conservation, MSc/MRes Biol Aquaculture, Swansea.

Figure 8. Training provision for bioscience postgraduate researchers (as described by those academic researchers who indicated that they provided training).

(a) Training in basic mathematics and statistics (n = 28).



(b) Training in advanced mathematics and statistics (n = 20) (includes concepts beyond those covered in A level maths).



5. Discussion

Students enter undergraduate bioscience degrees with a very wide range of mathematical backgrounds and it is clear that many of the negative attitudes that have been shown to exist amongst students at secondary school [14] persist into undergraduate and postgraduate bioscience study. The decline in the mathematical competencies of new undergraduates has been well documented amongst the physical sciences and engineering for the past twelve years [16] and more recently in the life sciences [11], [12].

Universities are modifying their first year programmes and there have been some successes but many are still struggling to find solutions within the constraints of increasing class sizes and the wide variation in the mathematical backgrounds of students. Greater opportunities for discussion and collaboration, such as those provided by the UK Centre for Bioscience[6] and Sigma Network[7] are important for University teaching staff to develop new ideas and share experiences. In addition support for the development of online resources such as BioMathTutor[8] and the NuMBerS[9] (Numerical Methods for Bioscience Students, Anglia Ruskin University) project as well as identification and review of open educational resources through the OeRBITAL project[10] are important to enable academics from different universities to share and reuse resources.

Universities cannot address this problem entirely on their own however: one could argue that some of the mathematical concepts, such as logarithms, negative and fractional powers, basic calculus, are best taught at secondary school where class sizes are smaller. A number of reports have recently noted that the structure of UK secondary education is limiting subject choices. In the Nuffield Foundation report "Is the UK an Outlier?" [5] England, Wales and Northern Ireland recorded lower levels of participation in post-16 mathematics education than any other country surveyed. Furthermore England, Wales, Northern Ireland and Scotland are 4 of only 6 countries out of the 24 surveyed which do not require compulsory participation in mathematics after the age of 16. In the report "Choosing the right STEM degree course" [15] over 40% of admissions tutors (n=105) made some unprompted reference to promoting or improving mathematics ability when asked to name one specific change they would like. The Royal Society report [6] recommends that the choice of subjects is broadened at A level. Increasing uptake of AS mathematics would make a significant improvement.

Teaching mathematics within the biology context, thus increasing the relevance, improves motivation. Design of a "mathematics for sciences" course at A level standard could include many of the important basic mathematical concepts that are covered in A level maths but apply them in the context of science. This would require the development of new teaching materials and greater collaboration between biological scientists and mathematics teachers. There are already some good teaching resources aimed at schools such as the BioNRICH[11] project. Extending these so that they appear within bioscience websites rather than mathematics websites would signal their fundamental importance to bioscience. There are many good online resource collections in the biosciences (for example the Scibermonkey website[12]) which could be usefully enhanced with more quantitative topics.

Most undergraduate bioscience programmes in the UK are largely teaching the basic, minimum level of maths and statistics and only a small minority of universities provide an opportunity for bioscience students to pursue more quantitative approaches in their undergraduate study. Furthermore at post-graduate level, whilst there are often lecture courses in statistics, most mathematical training is "on-the-job" and the extent of this is likely to depend upon the presence of mathematically-minded colleagues. The effect of these mathematically-minded mentors on those trained in biology can be substantial and can significantly influence their research direction [17] but clearly this will vary from one institution to another. The BBSRC Review of Mathematical Biology in BBSRC-sponsored institutes in 2006 recognised that:

> *"Some institutes benefited from the critical mass created by closer working with mathematical biologists at neighbouring universities including the running of joint Masters courses. This also had the effect of acting as a pipeline for recruitment for students and postdocs."*

Thus training provision in advanced mathematics for postgraduates is patchy and the end result of this is that it can be very difficult for bioscientists to improve their mathematical capabilities.

[6] http://www.bioscience.heacademy.ac.uk/
[7] http://sigma-network.ac.uk/
[8] http://www.bioscience.heacademy.ac.uk/network/numeracy.aspx
[9] http://web.anglia.ac.uk/numbers/
[10] http://heabiowiki.leeds.ac.uk/oerbital/index.php/Main_Page
[11] http://nrich.maths.org/6139
[12] http://www.scibermonkey.org/default.htm

Whilst there is clear concern and a consensus regarding difficulties surrounding basic maths, what has been less clear from this study is whether there is a real consensus as to whether more advanced mathematical approaches should be taught at undergraduate level. Does it matter that undergraduate bioscientists are largely not introduced to mathematical modelling, computing and advanced statistical techniques? This question is actually quite a complex one that deserves more study; we have only just scratched the surface. The majority of respondents thought that more advanced approaches should not be taught at undergraduate level however it would be useful to extend this work to find out more about why they gave that response. There are a number of possibilities:

1) It may be that they do not feel comfortable teaching at that level. Alternatively it is possible that more advanced maths was not considered for inclusion during design of the curriculum. There were a few comments in the open-ended responses in the survey looking at postgraduate bioscientists suggesting that there is a mathematical skills shortage amongst bioscience principal investigators. This would be a logical conclusion as this problem is not actually that new. Writing in Science in 2004, Bialek and Botstein [1] were more forthright:

> *"Virtually all biologists today must use some sophisticated programs… yet distressingly few academic biologists feel comfortable teaching the underlying principles to their students… Most biologists require consultations with biostatisticians in order to do anything but the simplest statistics"*

2) It is possible that they feel that it is more important to ensure that all students are confident with the basics and that that is where they should be putting their efforts and resources.

3) The effort of developing new curricula and new teaching methods may be creating too high a barrier. It is important to note that in the US, the BIO2010 project involved significant amounts of funding to organise summer workshops etc to galvanise collaborations between universities. These helped ensure new curricula were developed that brought the latest quantitative research approaches into the undergraduate classroom. A listserv and wiki were created along with many teaching resources for quantitative biology [18]. The report BIO2010 [2] recommends an outline curriculum which includes, in brief:

> *"The concepts of rate of change, modeling, equilibria and stability, structure of a system, interactions among components, data and measurement, visualizing, and algorithms are among those most important to the curriculum. Every student should acquire the ability to analyze issues arising in these contexts in some depth, using analytical methods (e.g., pencil and paper), appropriate computational tools, or both. The course of study would include aspects of probability, statistics, discrete models, linear algebra, calculus and differential equations, modeling, and programming."*

To return to the question: Does it matter that undergraduate bioscientists are largely not introduced to the sorts of mathematical modelling, computing and advanced statistical techniques that can be useful in quantitative approaches to biology research? It clearly matters to the respondents to the survey about the mathematical skills shortage amongst postgraduate bioscientists. They were unanimous in agreeing with the statement "Lack of mathematical knowledge, skill or confidence is preventing bioscientists from becoming involved in interdisciplinary teams using quantitative, integrated or computational approaches." It is of course likely that the respondents to this survey were self-selecting, with those who consider this to be a problem much more likely to respond to the survey. Also the sample size is small and clearly does not reflect the whole of the bioscience community. All that we can say from this study is that many bioscientists do feel that it matters but that it is possible that those who do not did not become involved in this survey.

Thus the unanimous agreement of academic researchers that "Lack of mathematical knowledge, skill or confidence is preventing bioscientists from becoming involved in interdisciplinary teams using quantitative, integrated or computational approaches" is at odds with the majority of opinions of those involved in undergraduate maths teaching in bioscience who thought that "advanced concepts and techniques such as mathematical modelling should be taught at postgraduate level if required and not become a standard part of an undergraduate course". This is an area that will need a greater degree of discussion and debate. Some very interesting examples of innovative teaching of more advanced concepts such as mathematical modelling [19] and using computer simulations [20] have been reported and this area would benefit from more opportunities for academics to collaborate and share ideas. This discussion would be usefully informed by an analysis of the progress made in the USA with the BIO2010 project.

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7. Appendices

Appendix 1 - The survey: Mathematics Content of UK HE Undergraduate Bioscience Degrees

1.

This survey aims to assess the mathematics and statistics content of undergraduate bioscience degree programmes in the UK. We would like to know what mathematics qualifications students begin their courses with and then to what extent their mathematical and statistical competence is extended through their degree course (if at all) and how this is achieved. Finally we would like to hear your views about the purpose of mathematics provision with bioscience degrees: in particular are students prepared for the basic mathematical tools they will need in a biology lab? or to read scientific papers? or to participate in systems biology and/or computational biology research? Please fill out the survey even if no mathematics is taught within your degree courses (in this case the survey will be very short).

We would like to follow up with a number of individuals to capture case studies and your participation would be warmly welcomed.

The results of the survey will be compiled into a report to be prepared for the UK Centre for Bioscience and made available on its website.

This survey is aimed at those organizing bioscience degree programmes (not including medicine, dentistry and veterinary medicine) and those involved in teaching the mathematical and statistical components of these degrees.

There are five sections in this survey and many of the questions are optional. The survey may be completed anonymously though we will need to know your institution to avoid duplications. It should take about 15 minutes to complete.

Thank you in advance for your assistance and participation. * Denotes mandatory questions.

2. Name, Institution and Contact Details

1. Name: (responses will not be attributed to individuals or their institutions without prior agreement)
2. *Department and Institution:
3. * Would you like to be contacted with a copy of the results of this survey and its report?
   ❍ yes ❍ no
4. May we contact you if we have any further questions (just briefly!)?
   ❍ yes ❍ no
5. If you have answered yes to either of the above please include your email address here

3. The Mathematical Skills of New Undergraduates

1. * Do you carry out diagnostic maths testing of new undergraduates in biosciences courses?
   ❍ yes ❍ no
2. * Do you think new undergraduates are on the whole sufficiently well prepared in maths when they arrive to study bioscience?
   ❍ yes ❍ no
3. Have you observed any particular difficulties in the mathematical skills of new undergraduates?
4. If you have made any recent major changes to your mathematics courses or introduced any initiatives please describe them here explaining also the driving force for them

4. Undergraduate Degree Programmes for which GCSE Maths is the minimum require...

We recognize that many institutions offer several distinct bioscience degree programmes and to avoid having to enter details separately for each onew we have decided to ask for information regarding programmes for which GCSE Maths is the minimum requirement on this page and then on the next page we will ask about degree programmes for which A level maths is a requirement.

1. *Please give the name(s) of the undergraduate bioscience degree programmes you provide for which GCSE Maths is the minimum requirement (for example Biomedical Sciences, Natural Sciences, Biological Sciences, Molecular Biology)

2. *Thinking about the degree programmes for which GCSE Maths is the minimum requirement, what grade at GCSE mathematics would these students have? (please check all that apply)
   - ❑ A*
   - ❑ A
   - ❑ B
   - ❑ C
   - ❑ <C

3. *Roughly what percentage of students taking this degree programme would have the following?
   - GCSE maths only (or equivalent) %
   - AS maths (or equivalent) %
   - A2 maths (or equivalent) %
   - Access to HE %
   - Other %
   - Don’t know %

4. Considering the maths/stats taught throughout the degree programme, how is it taught (choose one)?
   - ❍ as a separate standalone maths/stats course
   - ❍ embedded within bioscience subjects
   - ❍ both of the above
   - ❍ none of the above (no maths is taught)

5. Undergraduate Degree Programmes for which GCSE Maths is the minimum require...

1. Is the maths/stats taught: (choose all that apply)
   - ❑ first year
   - ❑ second year
   - ❑ third year
   - ❑ not at all

   Other (please specify)

2. What sort of maths is covered (include the maths taught in all years of the course)? Please check all that apply
   - ❑ basic algebra (eg rearranging equations, solving equations)
   - ❑ logarithms and exponential equations
   - ❑ calculating concentrations and dilutions of solutions
   - ❑ probability
   - ❑ hyphothesis testing
   - ❑ non-parametric statistical methods

❑ simple differentiation and integration
❑ differential equations
❑ mathematical modelling
❑ use of a computer spreadsheet
❑ use of a symbolic mathematical computing package (e.g. Matlab, Mathcad)

Other (please specify)

3. Considering the maths/stats taught throughout all years of the degree programme, what teaching methods are used (please check all that apply)?
   ❑ lectures
   ❑ tutorials
   ❑ online formative assessment
   ❑ online audiovisuals
   Other (please specify)

4. In your experience have you found a particular method of teaching maths for bioscientists to be especially effective? Please explain.

5. *To what extent do you agree or disagree with the following statements?

   The degree programmes we provide equip students with the mathematical understanding required:

	strongly agree	agree	neither agree nor disagree	disagree	strongly disagree
to function effectively in a biological laboratory environment	❍	❍	❍	❍	❍
to read and understand the scientific literature which contains reporting of statistical tests	❍	❍	❍	❍	❍
to read and understand the scientific literature which contains reporting of mathematical models	❍	❍	❍	❍	❍

6. *To what extent do you think the students from your courses are prepared to go on to study at Masters level in Systems Biology and/or Computational Biology?
   ❍ well prepared ❍ partially prepared ❍ not at all prepared ❍ don't know

6. Undergraduate Degree Programmes for which A level Maths is the Minimum Require...

1. *Do you provide undergraduate degree programmes or options within them which require A level maths?
   ❍ yes ❍ no

7. Undergraduate Degree Programmes for which A level Maths is the Minimum Require...

1. *Please give the name(s) of these undergraduate bioscience degree programmes (for example Biomedical Sciences, Natural Sciences, Biological Sciences, Molecular Biology).

2. What A level grades in mathematics would these students have (please check all that apply)?
   - ❑ A or A*
   - ❑ B
   - ❑ C
   - ❑ D
   - ❑ E or lower

   Comments:

3. Considering all years of this degree programme is the maths/stats taught:
   - ❍ as a separate standalone maths/stats course
   - ❍ embedded within bioscience subjects
   - ❍ both of the above
   - ❍ none of the above (no maths is taught)

8. Undergraduate Degree Programmes for which A level Maths is the Minimum Require...

1. When is the maths/stats taught? (choose all that apply)
   - ❑ first year
   - ❑ second year
   - ❑ third year
   - ❑ none of the above (no maths is taught)

2. What methods are used (please check all that apply)?
   - ❑ lectures
   - ❑ tutorials
   - ❑ online formative assessment
   - ❑ online audiovisuals

   Other (please specify)

3. Based on your experience what do you think is the most effective way of teaching maths/stats within undergraduate degree programmes?

4. What sort of maths/stats is covered? Please check all that apply and elaborate if possible
   - ❑ Statistics
   - ❑ applied maths including calculus

   Other (please specify)

5. **To what extent do you agree or disagree with the following statement?**

The degree programmes we provide equip students with the mathematical understanding required:

	strongly agree	agree	neither agree nor disagree	disagree	strongly disagree
to function effectively in a biological laboratory environment	❍	❍	❍	❍	❍
to read and understand the scientific literature which contains reporting of statistical tests	❍	❍	❍	❍	❍
to read and understand the scientific literature which contains reporting of mathematical models	❍	❍	❍	❍	❍

6. To what extent do you think the students from your courses are prepared to go on to study at Masters level in Systems Biology and/or Computational Biology?

❍ well prepared ❍ partially prepared ❍ not at all prepared ❍ don't know

9. Some final general questions

1. We value your thoughts and comments about how well bioscience students are prepared for the increasing amount of mathematical understanding and quantitative analysis required in bioscience research. If you have any further comments on this topic please explain here

2. We would like to do some short (10 minute) telephone interviews to follow up on some of these answers. Would you like to be involved with this?

❍ yes ❍ no

3. If you answered yes and didn't leave your email address earlier please do so here

4. Thank you for your time and effort with this survey. If you would like to leave any further comments please do so below. If you would like to discuss anything in relation to this survey please email jenny@sci-etc.co.uk

Appendix 2 - The survey: Is there a mathematical skills shortage amongst bioscience postgraduate researchers?

1.

This survey aims to gather opinions and thoughts of UK academic bioscience researchers on the question "Is there a mathematical skills shortage amongst bioscience postgraduate researchers"? This question divides into two main aspects:

(1) to what extent are bioscience graduates equipped with the basic toolkit of mathematical and statistical techniques needed for the least quantitative of the biological sciences?

(2) to what extent do bioscience graduates have sufficient maths to understand and participate in research in systems biology and computational biology working in interdisciplinary teams and communicating effectively with engineers, physicists and mathematicians?

Following on from these questions: If there is a lack of supply of mathematically-skilled bioscientists what training provision exists to correct this?

The results of the survey will be compiled into a report to be prepared for the UK Centre for Bioscience and made available on its website. There are four short sections and many of the questions are optional. There are spaces for free text responses so that you can qualify or explain your answers. The survey may be completed anonymously though it would be helpful to know your institution to assess the range of types of institution who have responded. It should take about 10 minutes to complete.

Thank you in advance for your assistance and participation.

2. Section 1: General

1. Name: (responses will be anonymous and you will not be quoted without your express permission)

2. * Department and Institution

3. Would you like to be contacted with a copy of the results of this survey and its report?

   ❍ yes ❍ no

4. May we contact you if we have any further questions (just briefly!)?

   ❍ yes ❍ no

5. If you have answered yes to any of the above questions please include your email address here

6. To what extent do you agree with the following statement: "as bioscience becomes increasingly quantitative there is also an urgent need to raise the mathematical and computational skills of biologists at all levels"

   ❍ strongly agree
   ❍ agree
   ❍ neither agree nor disagree
   ❍ disagree
   ❍ strongly disagree

3. Basic mathematical and statistical knowledge

1. Are new postgraduate students sufficiently well prepared with the mathematical skills required to work in a bioscience lab, for example calculating dilutions, doing linear regression for a calibration line etc?

   ❍ well prepared ❍ partially prepared ❍ not at all prepared

2. If you would like to elaborate on your answer please do so here.

3. Are new postgraduate students sufficiently well prepared with the statistical knowledge required to choose the appropriate statistical tests and to design experiments effectively?
   ❍ well prepared ❍ partially prepared ❍ not at all prepared
4. If you would like to elaborate on your answer please do so here.
5. Do you provide training for graduate students or post-docs in basic mathematical skills and/or statistics? Please check all that apply.

	basic maths eg dilutions, using simple equations, linear regression	statistics
lectures/seminars	❑	❑
on-the-job, informal training	❑	❑
online independent learning	❑	❑

4. More advanced quantitative and computational approaches

1. To what extent to you agree with the following statement: "Lack of mathematical knowledge, skill or confidence is preventing bioscientists from becoming involved in interdisciplinary teams using quantitative, integrated or computational approaches"
   ❍ strongly agree
   ❍ agree
   ❍ neither agree nor disagree
   ❍ disagree
   ❍ strongly disagree
2. Do you provide training in any of the following for bioscience graduates (please don't include taught Masters degree training as that is addressed in the next section)? Please check all that apply.

	mathematical modelling	advanced statistical techniques	computational techniques
lectures/seminars	❑	❑	❑
on-the-job, informal training	❑	❑	❑
online independent learning	❑	❑	❑

3. Please describe your area of research (e.g. immunology, ecology, environmental biology, neuroscience)

5. Masters level courses in systems biology / quantitative biology / computat...

1. *Are you involved in teaching or organising a postgraduate course in systems biology/quantitative biology/computational biology?
   ❍ yes ❍ no
2. If yes, please give the name of the degree course and the institution

3. If yes, what proportion of the students on your course have a bioscience degree?

4. If yes, what are the mathematical qualifications required for entry to this degree?

6. Thank you

1. Thank you for your time in completing this questionnaire. If you have any further comments please write them here.

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