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Cooke, J, Araya, Y, Bacon, KL et al. (27 more authors) (2021) Teaching and learning in ecology: a horizon scan of emerging challenges and solutions. Oikos, 130 (1). oik.07847. pp. 15-28. ISSN 0030-1299

https://doi.org/10.1111/oik.07847

OIKOS

Teaching and learning in ecology: a horizon scan of emerging challenges and solutions

Journal:	*Oikos*
Manuscript ID	Draft
Wiley - Manuscript type:	Research
Keywords:	horizon scan, teaching and learning, ecology, global challenges

Abstract:	We currently face significant, anthropogenic, global environmental challenges, and the role of ecologists in mitigating these challenges is arguably more important than ever. Consequently there is an urgent need to recruit and train future generations of ecologists, both those whose main area is ecology, but also those involved in the geological, biological, and environmental sciences. Here we present the results of a horizon scanning exercise that identified current and future challenges facing the teaching of ecology, through surveys of teachers, students, and employers of ecologists. Key challenges identified were grouped in terms of the perspectives of three groups: students, for example the increasing disconnect between people and nature; teachers, for example the challenges associated with teaching the quantitative skills that are inherent to the study of ecology; and society, for example poor societal perceptions of the field of ecology. In addition to the challenges identified, we propose a number of solutions developed at a workshop by a team of ecology teaching experts, with supporting evidence of their potential to address many of the problems raised. These proposed solutions include developing living labs, teaching students to be ecological entrepreneurs and influencers, embedding skills-based learning and coding in the curriculum, an increased role for learned societies in teaching and learning, and using new technology to enhance fieldwork studies including virtual reality, artificial intelligence and real-time spoken language translation.

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Abstract

We currently face significant, anthropogenic, global environmental challenges, and the role of ecologists in mitigating these challenges is arguably more important than ever. Consequently there is an urgent need to recruit and train future generations of ecologists, both those whose main area is ecology, but also those involved in the geological, biological, and environmental sciences.

Here we present the results of a horizon scanning exercise that identified current and future challenges facing the teaching of ecology, through surveys of teachers, students, and employers of ecologists. Key challenges identified were grouped in terms of the perspectives of three groups: students, for example the increasing disconnect between people and nature; teachers, for example the challenges associated with teaching the quantitative skills that are inherent to the study of ecology; and society, for example poor societal perceptions of the field of ecology.

In addition to the challenges identified, we propose a number of solutions developed at a workshop by a team of ecology teaching experts, with supporting evidence of their potential to address many of the problems raised. These proposed solutions include developing living labs, teaching students to be ecological entrepreneurs and influencers, embedding skills-based learning and coding in the curriculum, an increased role for learned societies in teaching and learning, and using new technology to enhance fieldwork studies including virtual reality, artificial intelligence and real-time spoken language translation.

Our findings are focused towards UK higher education, but they should be informative for students and teachers of a wide range of educational levels, policy makers, and professional ecologists worldwide.

Keywords: horizon scan, teaching and learning, ecology, global challenges

Data statement: We intend to deposit our data in Dryad.

Introduction

It is increasingly recognised that we are advancing into 'The Anthropocene' epoch (Crutzen and Stoermer 2000) and facing human-induced environmental challenges on a global scale. Temperatures are rising, species' ranges are changing, the oceans are acidifying, biodiversity is decreasing, and we are losing natural habitat, all at alarming and unprecedented rates (Oliver et al. 2015). The rate of change is causing concerns that life on Earth will not have sufficient time to adapt and that provision of a safe operating space for humanity is a challenge (Rockström et al. 2009). Ecology is the study of organisms and their relationships with other living things as well as their environment and thus ecological expertise is becoming increasingly important to understand the impacts of global change and species loss. Arguably therefore, the recruitment and training of future ecologists is critical, and people with ecological knowledge and a non-traditional suite of skills may also be needed if ecologists are to have an impact beyond academia (European Union 2014, Longhurst et al. 2014).

Despite this, to our knowledge, there has been no attempt to explore the future challenges that face the teaching of ecology as a discipline, and no recent review of the skills requirements for future generations of ecologists. Forecasting challenges is valuable for the prevention and mitigation of potential threats, but also allows the identification of potential solutions, and indeed opportunities (reviewed in Sutherland and Woodroof 2009). Such an exercise is particularly opportune as we move into the fourth industrial revolution, a time of rapid technological advancement (Maynard et al. 2015). Shifts in teaching and skills provision are expected, based on patterns of past revolutions, such as increased access to higher education through the rise of online distance education, and the development of MOOCs (Massive Open Online Courses) during the third industrial revolution (Penprase 2018). The impact of this 4th revolution is particularly relevant to ecology teaching with shifts to more sustainable industries predicted as a result of understanding product life-cycles and their ecological impact on the environment (Carvalho et al. 2018).

Here we present the findings of a horizon scan of learning and teaching in ecology, held in Milton Keynes, UK in 2019. Horizon scanning seeks to investigate what the future might look like in order to attempt to predict changes and challenges that could be mitigated by decision makers and practitioners (e.g. Sutherland et al. 2010, Roy et al. 2014, Antwis et al. 2017, Peyton et al. 2019). We sought to identify the most important challenges that are likely to be faced in teaching and learning in ecology, but also to identify potential solutions and opportunities for students, teachers and employers of ecologists.

Materials and Methods

We combined information from both the broader ecological community, in addition to those who teach ecology. We used a combination of surveys and workshop discussions to identify future issues and solutions for teaching and learning in ecology (process summarised Figure 1). First, we conducted a two-part Delphi survey; an efficient, inclusive, systematic approach that allows a group of individuals to collectively consider complex problems with reduced social pressure bias (Mukherjee et al. 2015). We sought to contact teachers of ecology at a range of levels, from both formal and informal learning, students of ecology, and employers of ecologists. Each survey was open for four weeks and advertised on Twitter and through targeted emails, asking participants to circulate the link more broadly still. The surveys received ethical approval from The Open University Ethics Committee (HREC/3170/Cooke).

In Survey 1 we asked "What do you think are the most important challenges we are likely to face in teaching and learning in ecology, including those associated with the employment of ecology graduates, in the future?" allowing respondents to raise up to 20 issues each. Ninety-seven people completed the survey, responding with nearly 700 issues (demographic data in Table S1 and S2). Three people collated the responses, removing duplicates, and shortening long answers. The remaining 298 responses were grouped into 17 categories, outlined in more detail in the next section. The challenges were associated with (listed here alphabetically):

- Basic language, numerical and computer skills in students
- Careers of teachers/lecturers
- Data handling and analysis, including statistics
- Disconnect between people and nature
- Emerging biological challenges (e.g. climate change)
- Equality and diversity
- Fieldwork and practical science
- Funding
- Graduate career opportunities
- Pedagogy and teaching
- Political impacts (with Brexit an additional category, here merged)
- Provision of graduate capabilities
- School (primary and secondary) curricula
- Societal perceptions of ecology

- Technology and its use in ecology
- University-level issues

We sought to leave subtle differences and perspectives in the responses, and to approximately reflect the volume of responses relating to issues (i.e. if there were ~2% of responses relating to funding for fieldwork, there should be ~2% of issues in the final list relating to funding).

In Survey 2, participants first ranked the categories, and then issues within each category. An option to indicate “I do not think it is important to rank any issues below this line” allowed issue exclusion by respondents. Each category was ranked by 45 to 62 people as not all respondents ranked issues in every category. The purpose of the ranking was to more rigorously determine which issues respondents viewed as most important, but cross-linkages between categories and issues meant few or no issues existed in isolation and hence the result would not form a list which should be tackled in order. Two people then compiled the survey data, providing a set of ranked issues for each main category as well as the overall category rankings (see Figures S1-19).

The ranked data formed the basis for a workshop on May 23rd, 2019, which brought ecology teachers together to consider the issues and solutions that could be used to mitigate and address them. Attendees comprised postgraduate students with some experience of teaching ecology and a vested interest in the future of the subject, through to academics with extensive teaching experience. Thirteen UK universities were represented, across all categories typically used to describe UK universities, including Russell Group, pre-92, and post-92; these classifications represent research-focussed institutions, other traditional UK universities, and former technical colleges, respectively. All attendees are named as co-authors on this paper. Although all workshop attendees were based at UK universities, this profile was not unexpected given engagement required physical attendance at the workshop, and the event was communicated through British Ecological Society channels. However, respondents to the surveys were based in diverse countries, with most continents represented except for Africa (surveys 1 and 2) and Asia (survey 2; Table S1). Indeed, a range of nationalities, backgrounds, experience, and research expertise were represented, and perspectives of non-academics such as schoolteachers and NGO workers were gathered via the surveys (see table S2).

It was decided as a group that three categories “Funding”, “Politics” and “Brexit”, would not be discussed explicitly in the workshop, as these were addressed in other categories, affected all education, and/or focussed on very immediate issues, and we wished to focus on future ecology-specific challenges. All other categories were discussed, in order to maintain, as much as possible, the breadth of the topics suggested by survey respondents. For each category, self-selecting groups (minimum 4 people) considered the ranked issues, examining if there were many perspectives on few issues, or many issues, and then considered solutions that could address or mitigate the issues, with a focus on the most highly ranked. Each group discussion was facilitated by a member of the British Ecological Society Teaching and Learning Special Interest Group committee, who also kept notes of the discussions. Groups were directed to identify main issues, grouping similar topics or similarly ranked topics where possible, and innovative solutions using new knowledge, technologies, opportunities and tools, for the main issues. Each discussion lasted for 60 minutes and then participants re-organised into different self-selecting groups for the next topic.

The project leads attended parts of each session and collated notes during the workshop. They noted that issues were routinely considered from three main perspectives: student, teacher and society, and therefore we have presented the challenges in these groups, mapped with the original categories under which they were discussed. Perhaps surprisingly, many of the challenges raised and discussed were current, rather than the more futuristic challenges we had expected. Across the day, solutions that could address multiple challenges emerged, and were brought up in multiple discussion groups. These were identified by the workshop organisers and are reported in the form of an evidence-based forward-thinking essay. Perhaps unsurprisingly there were significant overlaps across both challenges and solutions; these are mapped in Figure 2.

Horizon scans harness the knowledge and thinking of experts to make predictions for the future and therefore innately involve uncertainty. Unlike predictions from mathematical modelling, the qualitative and subjective nature of horizon scans makes providing measures of this uncertainty (including practicality in this case) difficult. Hence, we interrogated the literature and sought to present any existing support for each of the solutions suggested – either with teaching or learning examples or, where that was not available, in work associated with other fields/applications. We considered that this approach would identify where our predictions were ideas resurfacing, those at the forefront of current thinking and application, and those incorporating concepts and technology only in the early stages of development. Through this we sought to provide information to allow ecology teachers to assess the practicality of the proposed for solutions for their given situations.

Challenges

Student challenges

Mapped to: Basic language, numerical and computer skills in students; equality and diversity; graduate career opportunities; disconnect between people and nature; school (primary and secondary) curricula; emerging biological challenges (e.g. climate change); university-level challenges

In recent years there has been broad recognition that there is an increasing disconnect between people, particularly children and young people, and nature (reviewed in Soga and Gaston 2016). Increasingly we live in suburban areas and cities (https://www.un.org/development/desa/publications/2018-revision-of-world-urbanization-prospects.html). This, in conjunction with parental fear for child safety (Carver et al. 2010), the rising popularity of sedentary pastimes, and overscheduling of children's lives (Hofferth 2009), means that children and young people are spending less time outdoors (Clements 2004). There is now very limited practical and fieldwork learning in the UK school curricula and, coupled with the disconnect with nature, the lack of experience of ecology may mean that students either do not understand what ecology means, or do not appreciate its value, to the extent of self-excluding from the discipline at a young age.

Even when students do know and understand what ecology is, a perceived lack of jobs in the field may discourage students from studying ecology. This is potentially exacerbated by the increasing focus on graduate income as a measure for ranking the value of degrees, as there is a tendency for ecology jobs to be more poorly paid than those in other bioscience professions. The importance of quantitative skills to the field may also represent a barrier to young people engaging with ecology. Advanced statistics are routinely required to analyse the complex datasets encountered in ecological research (Barraquand et al. 2018), yet it is well documented, in the UK at least, that many bioscience students fear mathematics, and students exhibit a broad range of maths-related abilities, particularly in the first year of their studies (Koenig 2011, 2012). Teaching quantitative skills is therefore a challenge, and concerningly, it can be tempting to remove them from the curriculum in favour of more popular subjects, as these tend to receive more favourable student evaluations (Uttl and Smibert 2017). However, early career ecologists report that more quantitative training in both theoretical and statistical modeling specifically applied to ecological problems, would have been very beneficial for their career (Barraquand et al. 2018), suggesting that efforts in teaching quantitative skills for ecology should be increased rather than decreased. An additional factor reducing engagement with ecology is the lack of diversity in the field, which, like most sciences, is not representative of broader cultural and societal diversity (e.g. Holman et al. 2018, Wanelik et al. 2020). A diverse workforce is perhaps particularly important in ecology, which deals with global issues; practitioners need to have diverse cultural and societal norms to be able to constructively engage with those living on the frontline of where the issues are being played out.

Finally, students that decide to study ecology are likely to be increasingly aware of their own impact on the environment, and of purported impacts and biases associated with neo-colonialism on research practices (reviewed in Baker et al. 2019). While in the past, higher education institutions have sought to introduce international field trips to attract students to courses (Smith, 2004), in the future there may be a backlash against the current trend for flagship overseas field courses and fieldwork due to the environmental and ethical impacts (e.g. Wynes et al. 2019). This in turn could make it harder to recruit students.

Teacher challenges

Mapped to: Fieldwork and practical science; data handling and analysis, including statistics; basic language, numerical and computer skills in students; equality and diversity; careers of teachers/lecturers; pedagogy and teaching; technology and its use in ecology; provision of graduate capabilities; emerging biological challenges (e.g. climate change); university-level challenges

There are significant institutional barriers with potential to impact ~~on~~ ecology teaching, if they are not already doing so. Although ecology does not necessarily have to be field-based, field work can be an important component. There are conflicting views as to whether there has been a reduction in the amount of field teaching in UK universities in past decades (e.g. Smith 2004, Ashton et al. 2015), or whether it has remained stable (e.g. Mauchline et al. 2013, reviewed in Goulder and Scott 2016). However, given funding challenges and increasing corporatisation (Robertson 2010), there is a risk that university administration and management will consider field-based teaching too expensive in both money and staff time.

Despite field-based teaching often being less costly than laboratory practicals (Fleischner et al. 2017), and invaluable in terms of student skills development (Andrews et al. 2003), student satisfaction (Griset 2010, Hix 2015), bridging the staff-student divide in higher education (Hart et al. 2011) and institutional marketing (Mauchline et al. 2013), ecology educators increasingly struggle to justify field courses to budget holders.

The way in which universities tend to operate can also inhibit the successful and sustainable delivery of ecology learning and teaching. The science of ecology benefits from working across diverse disciplines including mathematics and all sciences, but also the arts and humanities (Likens 1992). The multidisciplinary nature of ecology is highly beneficial to student development and employability (Newing 2010), yet university education is often compartmentalised and modularised, making it progressively difficult to teach across departments and disciplines with a view to multidisciplinarity (Carson 2019). Rigid timetabling across the calendar year can also be problematic; in the UK at least, most teaching occurs between October and April, when biodiversity is least visible and most difficult to identify.

Putting aside the challenges of teaching new ecologists, the current generation of ecology practitioners themselves face problems. Ecology positions tend to be short-term and low-paid contracts (Hance 2017). Many positions require prior experience, and work experience is often unpaid, or in some cases demands payment, which is likely to be impacting on sector retention of personnel, in addition to contributing to low diversity in the discipline (Fournier and Bond 2015, Wanelik et al. 2020). In the age of the UK Research Excellence Framework, and the focus on ‘impact’ as a measure of scientific quality, there is the potential for significant barriers to progression for university-based ecologists, especially as ecological research is typically long-term in comparison to other STEM disciplines; for example, at least a decade of consistent monitoring is needed to capture statistically significant trends in vertebrate populations (White 2018) and a resulting impact case would take even longer to develop.

Exercises such as the Research Excellence Framework are highly metric-driven, yet for ecology and its sub-disciplines metrics can be poor predictors of scientific quality (Tyler 2018). There is a risk that metric-induced barriers to progression will be further compounded by the UK Teaching Excellence Framework (Whalley 2019) given the additional burden on teachers, and the potential conflict between teaching and research (Perkins 2019).

Societal challenges

Mapped to: Emerging biological challenges (e.g. climate change); societal perceptions of ecology; disconnect between people and nature

A key challenge for teaching and learning is how the field of ecology and ecologists are perceived by society. The public likely underestimates the complexity of ecology, a perception exacerbated by documentaries simplifying nature and focussing on the behavioural ecology of charismatic species (Dingwall and Aldridge 2006). Ecologists are often viewed as being 'nice' preservers of harmony (Ladle and Gillson 2009) rather than, for example, climate scientists who are potentially perceived more as activists. The public may be unaware that ecologists are tackling major societal challenges as diverse as disease epidemiology, conservation and population dynamics. Where wider issues related to ecology are discussed in public arenas, there is a focus on negative stories rather than the success stories, a reflection of media appetite for bad rather than good news. In addition, ecologists tend to be unwilling to use strong or polarising language, more commonly used by environmental activists to successfully garner attention (Derville 2005). In part this is because the many sources of variation in complex ecosystems, mean ecological research tends to explain part rather than all sources in any given study.

A related challenge is the long-term nature of ecological research. The public perceive many of the problems that ecologists are trying to address, for example the impacts of climate change, as distant in both time and space (Lorenzoni and Hulme 2009), which can cause a barrier to engagement and understanding. Similarly, ecologists are comfortable with the uncertainty of science in contrast to the public, and it has been argued that uncertainty can be and has been used by the media to drive a wedge between the scientific and public communities (Zehr 2000). Instances where government policy has publicly ignored ecological studies, such as in the case of the UK badger cull (e.g. https://www.bbc.co.uk/news/science-environment-39418554), damages societal perceptions of the credibility of ecology.

These challenges, coupled with the perception that ecology careers are limited and poorly paid, and the increasing disconnect between people and nature, both discussed above, suggest that ecology has an image problem. The resultant impact on engagement with the wider society, is in turn likely to be reducing the interest of young people in ecological careers, and encouragement from parents and advisors to pursue them.

Solutions

The following solutions are not listed in any particular order.

Living labs on campus

The living lab approach means taking students out of the classroom and into the local environment, be it natural or artificial habitats close by or on campus. Such environments may already exist, or may be developed specifically for the intention of being a living lab. Examples include the use of campus wetlands to introduce ecological surveying at Mahidol University, Thailand (Sukhontapatipak and Srikosamatara 2012), the development of a student campus stewardship organisation at Cornell University, USA (Krasny and Delia 2015), and the restoration of a local woodland by students from the Musahi Institute of Technology, Japan (Kobori and Primack 2003).

Living labs initially gained traction in the discipline of urban sustainable development (Hossain et al. 2019), but there are increasing calls to utilise such an approach in ecology teaching (e.g. AASHE 2013). This is timely, as many if not all school and university campuses are seeking to make the educational environment more sustainable in line with national calls (e.g. McCoshan and Martin 2012). Living labs offer a multitude of benefits. At pre-school and school level, encouraging children to engage with the natural world in their local area is beneficial to their physical and mental wellbeing (reviewed in Louv 2006), and can also result in a more positive attitude towards conserving it (e.g. Bizerril 2004, Soga et al. 2016). At higher education levels, living labs can be used to engage local wildlife trusts and charities to share their expertise, and to train students in working in an interdisciplinary manner with external stakeholders (e.g. Evans et al. 2015). Active, inquiry-based learning and the gaining of real-world experience help students develop enhanced research and employability skills (Healey 2005, Healey and Jenkins 2009), and such projects can be used to introduce credit-bearing work experience to the curriculum, which has been shown to be beneficial to student development and learning (e.g. Toledano-O'Farrill 2017). Data collected can also contribute towards citizen science projects which can aid in training students to consider robust research methods and data accuracy. Field work in a familiar local environment can increase accessibility and inclusivity, and also helps students build confidence, for resilience in the face of uncertainty of unfamiliar sites, by initiating fieldwork in a familiar setting (Leon-Beck and Dodick 2012). In addition, local sites facilitate fieldwork with a limited or negligible budget (Bacon and Peacock 2016) and still allow the social benefits among peers and staff-student collegiality that develops during fieldwork (Peacock et al. 2018). It is notoriously difficult to collect 'real' data on short, intensive, residential field courses. In contrast, long-term collection of field data from local environs provides the opportunity to generate meaningful scientific data, particularly with involvement across departments and even across institutions. Finally, living labs may help mitigate increasing student concerns about the impacts of travelling for fieldwork on the environment.

At the institutional level, living labs save both money and staff time, and there is also an appreciable reduction in the level of health and safety risks. At society level, the living labs approach can result in positive and sustainable change in the local environment, and can be used to engage the general public in ecological and sustainability initiatives (e.g. Farrell et al. 2015, Steppe et al. 2016).

Teacher memberships in professional societies

Benade (2016) argues that while learned and/or professional societies aim to advance their cause through research and dissemination primarily, a closer relationship between academics and practitioners can have mutual benefit. The capacity of ecology professional societies to collate and facilitate communication of new findings and best practice amongst researchers could be extended to better provide accurate, relevant, up-to-date information to teachers. Reciprocal benefits could see learned societies increasing teacher knowledge and confidence in ecological teaching, which should in turn increase the ecology knowledge and skills of students entering further education and/or the workforce. Currently ecology societies vary in their membership offers and provision of resources for teachers, who in turn are often unaware the societies and resources exist.

Tilling (2018) showed that, in English secondary schools, “quantity and quality of ecology fieldwork has been declining in recent decades at a time when the scope, complexity, and interdisciplinarity of ecological science has been growing”. Increased cross-sector sharing and collaboration would make the production of teaching materials more efficient, and introduce an interdisciplinary approach to help address issues of rapidly changing environments. Provision of protocols for ecological experiments appropriate for specific regions (countries) or environments (urban vs rural) are possible, and the rise of distance education using the internet (tutor-supported paid online courses, webinars, Badged Open Courses etc.) could allow efficient delivery for time-poor teachers (Kyriacou 2001). However, to ensure effective use of professional societal resources, memberships likely need to be actively advertised to teachers. Mentorship programs could allow strong and direct connections between ecology researchers and teachers (for example Howitt et al. 2009 and the related Akres et al. 2016), and increase confidence in field trips.

Integration of coding

In the modern age, there are many fundamental applications of coding to most fields of biology. In ecology, coding is used, amongst other techniques, to analyse molecular data, model population interactions, and construct phylogenetic pathways, in addition to performing more 'traditional' data analyses (Baker 2017). It is increasingly common for job advertisements to specifically require coding as a skill in candidates (Auker and Barthelmess 2019), and ecology PhD students and post-grads often find subsequent employment using their coding skills in fields in governmental and charitable organisations and departments.

Yet despite coding being fundamental to ecological research, and to students' personal development more broadly (Tu and Johnson 1990), it is still rarely taught in the UK at any level of education (Koenig 2012). It has been suggested that the best way to introduce coding is to start at an early age, preferably at primary school (Flórez et al. 2017). At university level, strategies that have been shown to be effective in teaching coding to beginners include the use of peer-peer assessment (e.g. ArchMiller et al. 2017), the use of blended learning (Cigdem 2015), and the development of automated e-learning and assessment systems to facilitate student learning with reduced educator input (Alu-Mutka 2005). To foster collaborative approaches, single platform coding across degrees is recommended, with the programme 'R' (Ihaka and Gentleman 1996; R Core Team 2018) in particular gaining traction within ecology (Petchey et al. 2009, Auker and Barthelmess 2019).

There are challenges to learning and teaching coding. Like maths, students, and in particular biology students, tend to have a fear of coding (Koenig 2011). Students may quickly become frustrated and lose motivation if they experience repetitive failure, and the fact that there is no 'correct' answer can be difficult for students to come to terms with. Hence to properly integrate coding into curriculum, staff development and/or interdisciplinary teaching will likely be needed to break down barriers to education and facilitate. These approaches above, with early integration and the use of a single platform, could enable the teaching of coding and reduce both student and staff concerns about engaging with maths and coding.

Ecological entrepreneurships

Ecological entrepreneurship involves identifying and translating environmental concerns into actionable solutions which can involve policies, technologies, products and business engagement (Koch-Weser, 2015). Marsden and Smith (2005) provide examples of networks which encourage development in local communities through increased quality (rather than quantity) through sustainable food production and branding which identifies local produce. There is an opportunity to provide ecology students with training - both the ecological knowledge and skills, but also approaches from business - to allow the development and participation in ecological entrepreneurial initiatives. Interdisciplinary ecology projects/assessments and challenge-based learning, and also the integration of other subjects could be included in the current curriculum to equip students with the necessary skills to allow them to incorporate environmental responsibility into businesses (Valeryanovna 2012).

Ecology teachers could make use of existing entrepreneurship education programs, at assignment and/or module levels, to equip students to be ecological business participants and drivers of solutions to environmental problems. Categories of ecological entrepreneurs include inventors/pioneers of green technical, policy, and business solutions as well as communicators, forecasters, watchdogs and transformers (Koch-Weser 2015). In this way there is potential more easily employed and integrated into corporate positions and for society to perceive ecology and ecologists as entrepreneurial contributors to solutions.

Developing skills-based learning and skills-based degrees

It is now well documented that passive learning in the lecture theatre is not as effective as student-centred active learning (Tanner 2009), and when students can simply web search for information on their mobile phones, there are calls for a more enquiry-based approach to education (Chong 2010). In addition, in this, the age of the fourth industrial revolution, technology is evolving at an ever-increasing pace, skills are increasingly viewed as more valuable than knowledge, and the nature of work is changing. As a result, universities are progressively incorporating skills and employability development into their curricula, utilising more active and flexible learning approaches, and working collaboratively with employers to provide work experience opportunities for students (UUK 2018). Such initiatives are particularly important in ecology teaching. Ecology is inherently interdisciplinary, and, given the rapid manner in which the planet is changing, ecology students need to learn to be adaptable, utilise ever-changing technology, and work in an interdisciplinary manner with diverse stakeholders.

While enquiry-based learning is an effective mode of student learning (Healey 2005), educators are increasingly introducing work-integrated learning into the curriculum, which has been shown to be extremely beneficial to students in terms of employability (Reddan and

Rauchle 2012). Work-integrated learning can encompass a variety of forms including sandwich degrees, placements, internships, and field work, and exposing students to the world of work through such activities can lead to the development of key transferable skills and better preparedness for entry into the workforce (Jackson 2015). Furthermore, encouraging students to reflect on their skills profile and career-readiness as part of a work-integrated learning experience compounds the positive impact of student learning, and assists them in articulating their assets to employers in later life (Manathunga and Lant 2006, Hansen et al. 2018). Enabling students to undertake work-integrated learning as part of, or associated with, the curriculum also enables them to gain valuable work experience without having to undertake unpaid voluntary positions, which are rare, tend to be highly competitive, and can exclude certain groups of students (Fournier and Bond 2015). Related, degree apprenticeships are a relatively new idea in the UK and offer students the opportunity to gain a degree whilst also undertaking on-the-job training (Prospects 2019). However, there are concerns that apprenticeships can be used to fund low-skilled jobs (https://www.bbc.co.uk/news/education-50973579), and thus such courses require careful design. In addition, to date, such apprenticeships tend to be related to biomedical subjects, and have not been adopted by fields such as ecology.

As for the living labs concept discussed above, the introduction of more skills-based and work-integrated learning affords the opportunity for academics and students to work more closely with local ecological organisations. Bringing employer-led learning onto campus, and the introduction of challenge-type activities, would be beneficial for students with respect to skill development and network expansion (Tejedor and Segalas 2018), and input from such organisations would ensure that we are teaching the skills sought by employers.

One of the challenges identified was that the diversity of topics and skills required (both new and traditional) is difficult to fit into an ecology curriculum. One solution to this would be to offer skills based degrees embedded in a specific field of ecological knowledge (e.g. ecological engineering, ecological microbiology). Such degrees could have the benefit of equipping students with good ecological understanding (or another field), but also well-developed and specific, but transferable skills. Co-teaching of modules in such a degree would allow subject specialists to contribute key concepts and knowledge to students, while their skills would be developed by specialist practitioners. In this way graduates would have in-depth ecological knowledge, but highly developed specific skills, with degrees in science communication (ecology), microbiology (ecology), field studies (ecology), engineering (ecology) or data analysis/science (ecology) as examples.

Ecological influencers

Researchers are frequently encouraged to do more to communicate with the public, while at the same time, the rise of social media offers a platform for communication that is immediate, accessible, direct and visual, and easily curated. Social media has allowed an explosion of influencers, defined as people who endorse products or ideas associated with a particular identity (Khamis et al. 2017). An increasing societal awareness of environmental and climate change concerns means the public need explanations of complex science issues and accessible information on positive, practical ways to take action and mitigate feelings of climate change anxiety and depression (Moser and Boykoff 2013). Such explanations are perhaps particularly important in this age of distrust of 'experts'. Real behavioural change for action on climate change and ecological preservation is most likely with community involvement (Moser and Pike 2015). Hence there is scope for large impact from ecological influencers recommending products such education resources, behaviours, and experiences associated with ecological awareness, benefits or learning, well supported by research. This will rely on ecologists self-branding, that is, individuals "having a unique selling point, or a public identity that is singularly charismatic and responsive to the needs and interests of target audiences” (Khamis et al. 2017).

STEM academics as influencers have had a demonstrated impact on other science fields; for example Prof. Brian Cox is credited with increasing interest in particle physics, influencing public debate on science, and recruiting students to physics/science and societal education through unique broadcasts (Manchester REF 2014). Information from authentic and expert endorsers can lead to “internalization and deeper processing of the endorsers message” (Kapitain and Silvera 2016). Ecological influencers have the potential to increase the visibility and societal valuing of ecologists and facilitate the valuing and understanding of both applied and fundamental ecology (Courchamp et al. 2015). Influencing is, however, not without it costs, as it takes substantial time and energy to have an impact. An alternative is for ecologists to engage with existing influencers more effectively, rather than ‘reinventing the wheel’.

Virtual reality and field trips

Virtual reality is the replacement of the real world with a simulated version, while augmented reality is a simulation enhanced with additional perceptual information. Both technologies have the potential to revolutionise ecology teaching, and indeed have already gained traction, particularly in the geographical sciences (e.g. Bursztyn et al. 2017, Friess et al. 2016). Virtual reality is a tool to complement traditional ecology teaching, both in the classroom and in the field, rather than a replacement, but with potential to increase accessibility and remove some of the barriers associated with field teaching. Virtual resources that can supplement more traditional ecology teaching range from simple virtual guides and resources (reviewed in France et al. 2015), through to fully immersive virtual reality experiences (e.g. Tarng et al. 2015). For example, Markowitz et al. (2018) used a virtual reality underwater experience to teach school and university students about the effects of climate change on seawater acidity.

Using virtual or augmented technologies in teaching has several benefits. In the Markowitz (2018) study, virtual reality resulted in the students developing more positive attitudes about the environment. Student use of digital video technology in the field can develop employability skills (Fuller and France 2016), while virtual or augmented technologies can enable remote fieldwork for students with mobility impairments (e.g. Stokes et al. 2012), or overcome financial barriers to a field course (Cliffe 2017) and allow students an experience of inaccessible locations such the ocean floor (Whitelock 1999). Virtual introductions to field sites pre-field trip can enhance student confidence and allay fears of the unknown. However, while evidence shows benefits of virtual or augmented reality technologies as additional teaching resource to traditional field courses, students suggest that they should not replace them (Spicer and Stratford 2001). It is worth noting that some studies show immersive virtual reality can be detrimental to learning (e.g. Makransky et al. 2017), while others demonstrate no additional benefits to learning compared to non-immersive virtual reality technology (e.g. Moreno and Mayer 2002).

Artificial intelligence

Artificial intelligence (AI), defined as the capacity of computers or other machines to exhibit or simulate intelligent behaviour (Oxford English Dictionary), is a burgeoning field. It has many applications for ecology, including the identification of individual animals from video data (eg. Sherley et al. 2010), investigating complex animal behaviours (Kunz and Hemelrijk 2012) and to collate complex information from multiple sources, including feedback loops, to facilitate decision making in natural research management decision making (eg. Liu et al. 2018). Computer programs are already routinely used in both ecology teaching and research to help identify vegetation communities from field data (eg. MATCH and MAVIS facilitate using the National Vegetation Classification system), and online keys aid species identification using known or available features (eg. EUCLID for Eucalyptus identification), hence using AI in teaching is a logical next step. This scan identified that employers are concerned future graduates should have species identification skills (See supplementary Table/Figure). There is potential to use AI to assist species identification (MacLeod et al. 2010), while teaching the limitations of technology (such as the impressive but imperfect Seek by iNaturalist) will serve to maintain an appreciation for the role and value of traditional species identification skills. For example, in arthropod species identification, the frequent requirement to use minute external or internal morphological traits makes it unlikely that a photo-based AI app identification system could replace human experts.

In addition to using AI to aid in species identification, ecology teaching and learning could benefit from being an early adopting sector of AI to increase capacity to process large numbers of samples or big data sets and facilitate consistency during student research, increasing student satisfaction and also the potential for data publication. Long-term ecological data (such as that collected across multiple student cohorts) is more likely to contribute to ecological theory and policy (Hughes et al. 2017), and the publication of long-term data collected in field teaching has been a persistent and rarely achieved aim, though there are successful models (Bishop et al. 2014).

Ecology teachers, however, are concerned about managing their own knowledge of fast-evolving technology as well as finding space in the curriculum to embed new as well as traditional skills (See Supplementary information table/figure). To embed AI in ecology teaching, communication and cooperation between teachers and machine learning specialists would be essential. This collaboration could in turn contribute to overcoming the major challenges in collaborative aspects of using AI in ecology and environmental sciences more broadly, identified Liu et al. (2018). Given the rise of AI in both ecology and many other sectors (Russell and Norvig 2016), training students in using and developing AI systems will increase their employability. Including machine learning specialists in course and curriculum development could serve to form a link between consumers versus producers of technology, as well as facilitate the enhanced employability.

Real time spoken language translation

A more audacious solution, with less supporting evidence for success but worthy potential, is real time spoken language translation. Technology enabling students to engage with people speaking any language, could reduce language barriers affecting diversity and equality in teaching and learning. Attainment gaps in science are in part due to different language knowledge and skills in students (Lee 2005) and excluding studies in languages other than English introduces large bias (Morrison et al. 2012). Real time spoken language translation technology could benefit field teaching in ecology, where much information is exchanged orally rather than in writing. For field studies in international locations, this technology could also enhance learning by enabling students to hear from all knowledge holders, not just those speaking a common language. For example, the knowledge, perspectives and approaches of traditional and indigenous landowners are recognised as critical for developing effective conservation plans, and language differences between interested parties can be both a barrier and enrich knowledge exchange (Gadgil et al. 1993, Moritz et al. 2015). It could contribute to the decolonisation of ecology and related fields, through improved collaborative relationships, and recognition of these, and reducing assumptions that perpetuate colonial attitudes (Eichhorn et al. 2019)

This technology, however, is currently far from ready for the applications outlined above, not least for localised, indigenous languages. Text translation is increasingly sophisticated for more common languages, but automated translations from audio still often render problematic results for all languages, as algorithms struggle to include correct punctuation, frequently fail to recognise uncommon words (including scientific terminology) and cannot interpret speakers with accents on which the program has not been trained (Heer 2019). In addition, for functional real-time language translation, cadence, intonation and expression will need to be incorporated, adding another layer of complexity. However, automated translation is an active area of technological development, and increasingly common in computer programs and social media platforms. Programs are beginning to use artificial intelligence to predict the likelihood of the next spoken word to enable real time translations for widely spoken languages (https://www.technologyreview.com/f/612730/google-assistant-now-comes-with-a-real-time-translator-for-27-languages/). While real-time spoken language translation is currently aspirational for field teaching, it is noteworthy that various forms of translation technologies are already used to increase accessibility for students in STEM, such as speech-to-text and text-to-speech (Lee and Templeton 2008), sonograms (visual displays of sound waves e.g. Huffling et al. 2018) and sonification (audible versions of data e.g. Vines et al. 2019).

Discussion and Conclusions

The solutions identified during the workshop were a mixture of novel ideas and building on recent innovative approaches participants had encountered. It is noteworthy that supporting evidence for the potential success of the nine solutions was available, due to reports from early adopters of technology and pedagogy, or where ideas have been successfully developed and applied in other fields. For example, *ecological entrepreneurs* is a term already in circulation (for example Koch-Weser 2015), but equipping students with the skills for this role is as yet not part of the ecology curriculum. Similarly, real time translation technology for speech is in development, but its potential to enhance fieldwork learning has not been explored and articulated.

Four of the nine solutions arising from the workshop are linked to advances in technology, and while some of their specific limitations were considered above, there are additional broader issues. Managing privacy and security in e-learning (El-Khatib et al. 2003), as well as archiving and storing digital data properly for the future (Michener and Jones, 2012) are essential. In addition, dependence on technology for field trips where electricity and reception/signal are unreliable or unavailable may limit the use of some proposed solutions. Technology evolves rapidly, hence technological hardware and software can quickly become dated and resourcing new technology may be problematic for some. Encouraging students to bring their own devices is a way of ensuring cohorts have new and updated technology, but this approach can easily introduce inequality among student learning (Afreen 2014). Finally, as noted in the section on virtual reality above, technology should be seen as a tool to complement and enhance traditional skills and techniques, rather than replace them. In short, although technology offers innovative solutions to a wide range of challenges, there are numerous limits surrounding its use about which ecology teachers must not be complacent.

The challenges identified comprised a mixture of emerging challenges and persistent challenges for which we as yet have not identified solutions. Although we asked people to predict issues in teaching and learning for the future, we did not constrain this with a particular time scale. As a result, there is some focus on issues of the current and near future. For any future repeats of this horizon scan, additional insight would be gained by specifying the future period, but also by collecting perceptions of the solvability of challenges and priority of solutions. We also appreciate there is a focus on the UK education system reflecting the experiences of the participants. Investing additional effort to diversify respondents to the surveys is recommended as more representation of students and employers, from a broader geographical reach, would also likely provide further perspectives. Nevertheless, we anticipate many of the main issues raised are likely to be global, that our findings will be thought-provoking, and that this manuscript will incite further discussion.

Although horizon scanning has been applied to the environmental science discipline on regional scales (e.g. Shackleton et al. 2011), and to ecology course planning using recent, innovative teaching methods (Nordlund 2016), to our knowledge, this is the first time horizon scanning techniques have been formally applied to the learning and teaching of ecology. The issues raised in both the surveys and the workshop were raised by multiple respondents and attendees, from different backgrounds, institutions, and countries in the case of the surveys, adding confidence that challenges identified represent most people across the sector.

Ecologists worldwide are employing innovative strategies to encourage interest in ecology, maximise student skills development, and improve collaboration across and between educational institutions, and ecological, charitable, and governmental organisations. We have identified ten solutions that addressed issues raised by the broader ecology teaching and learning community, and are supported with evidence of their potential for adoption and further development. In reporting the outcomes of the workshop, the resultant bibliography should form a useful reference list for ecology teachers. We hope that our findings will ignite discussion, and that together we can ensure the health - in all senses of the word - of the future of ecology.

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Tables and Figures

Figure 1. Schematic diagram of the horizon scan process and main outcomes.

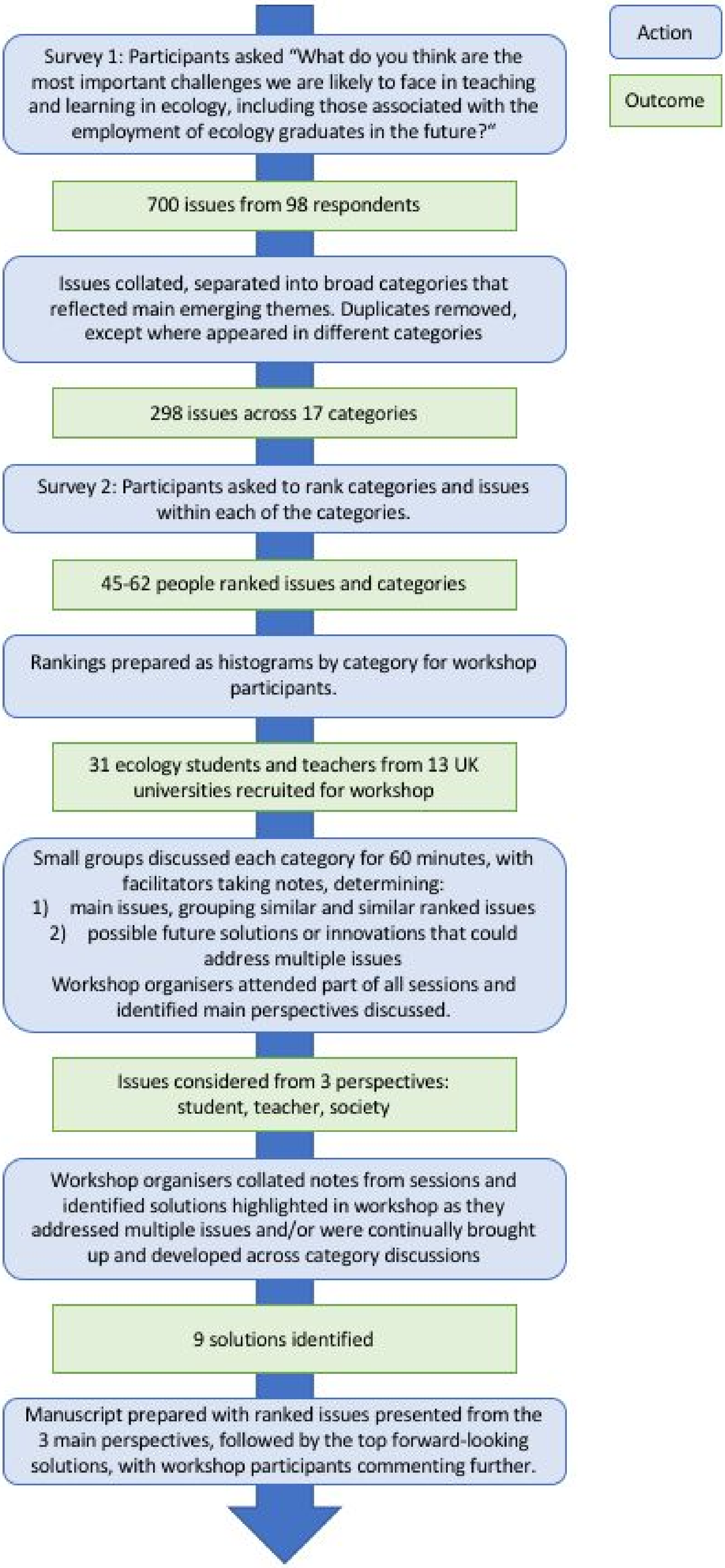
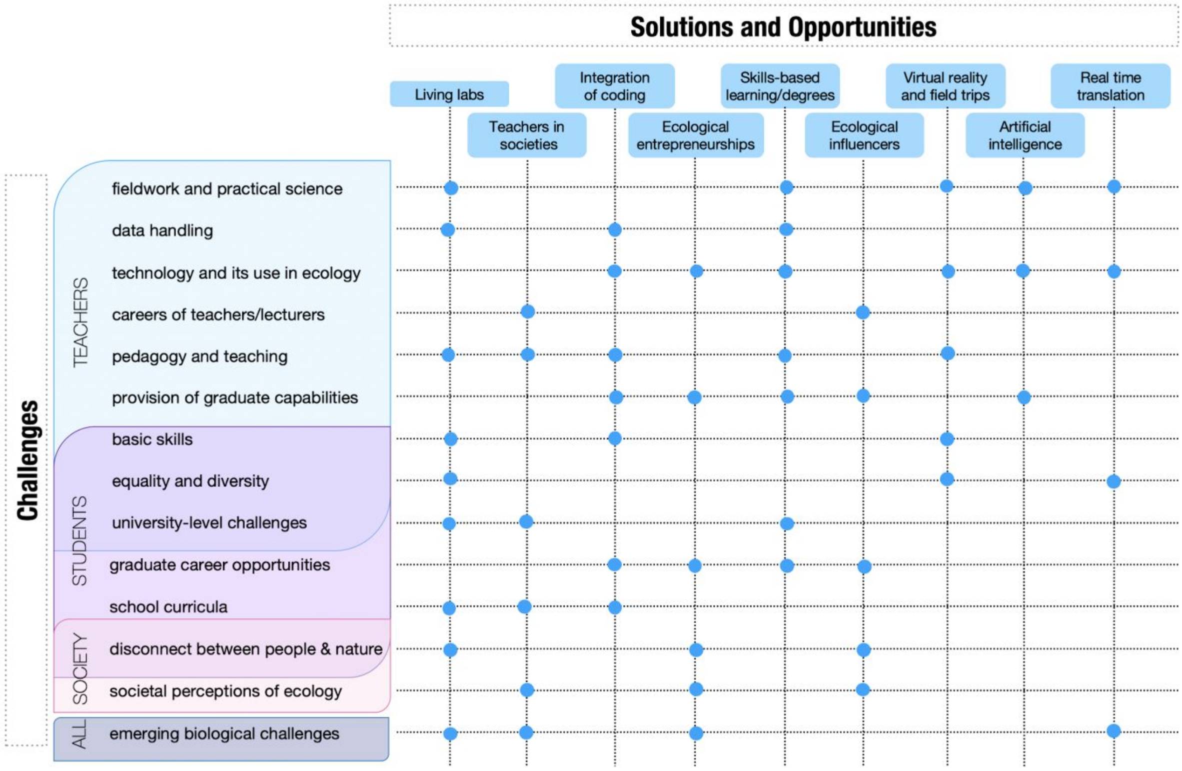

Action
Outcome
Survey 1: Participants asked "What do you think are the most important challenges we are likely to face in teaching and learning in ecology, including those associated with the employment of ecology graduates in the future?"
700 issues from 98 respondents
Issues collated, separated into broad categories that reflected main emerging themes. Duplicates removed, except where appeared in different categories
298 issues across 17 categories
Survey 2: Participants asked to rank categories and issues within each of the categories.
45-62 people ranked issues and categories
Rankings prepared as histograms by category for workshop participants.
31 ecology students and teachers from 13 UK universities recruited for workshop
Small groups discussed each category for 60 minutes, with facilitators taking notes, determining:
1) main issues, grouping similar and similar ranked issues
2) possible future solutions or innovations that could address multiple issues
Workshop organisers attended part of all sessions and identified main perspectives discussed.
Issues considered from 3 perspectives: student, teacher, society
Workshop organisers collated notes from sessions and identified solutions highlighted in workshop as they addressed multiple issues and/or were continually brought up and developed across category discussions
9 solutions identified
Manuscript prepared with ranked issues presented from the 3 main perspectives, followed by the top forward-looking solutions, with workshop participants commenting further.

Figure 2. Illustrated are the challenges, solutions, and opportunities identified in ecology teaching and learning for students, teachers, and society. The main issues identified by the participants are shown on the left. The dominant solutions and opportunities identified in this study to address the challenges are on the right, with the linkages shown by blue dots on the where the relevant horizontal and vertical lines intersect.



Supplementary Information

Table S1. Locality of survey participants. Due to rounding, the totals do not add up to 100%.

Respondent location	% respondents survey 1	% respondents survey 2
UK	84 %	83 %
Europe (but not UK)	6 %	4 %
Africa	0 %	0 %
Australasia	3 %	9 %
North America	4 %	2 %
South America	3 %	2 %
Asia	1 %	0 %
Total Respondents	97	46

Table S2. Occupations of survey participants. Due to rounding, the totals do not add up to 100%.

Respondent Occupation	% respondents survey 1	% respondents survey 2
Higher Education	58 %	76 %
Secondary Education	14 %	4 %
Primary Education	8 %	2 %
Government	6 %	0 %
NGO	6 %	4 %
Policy Development	3 %	0 %
Consultancy	12 %	2 %

Industry	2 %	2 %
Research	18 %	24 %
Post graduate student	12 %	17 %
Undergraduate student	2 %	0 %
Other	10 %	0 %
Total Respondents	97	46

Figures S1-14. Rankings of main categories and subcategories. Rankings were determined by first translating the ordering of issues, applied by each respondent, into numbers by assigning the highest ranked issue a score of n (where n = number of issues in the category), then second ranked allocated n-1 etc. For example, in the main categories, where there were 17 issues, if a respondent ranked “Disconnect between people and nature” first, it was given 17 points. The ***I don’t want to rank below this line*** option was also given a score, even if ranked last and any issues ranked below the **I don’t want to rank below this line** were automatically scored equal last. Scores were then summed for each issue across participants and these totals used to determine the overall ranking with highest scores representing the highest ranked issues. Here they are presented as relative rankings with the highest given a score of 100, and all other rankings listed in proportion to this. Rankings of subcategories not explicitly discussed at the workshop are not included.

Figure S1. Rankings of main categories

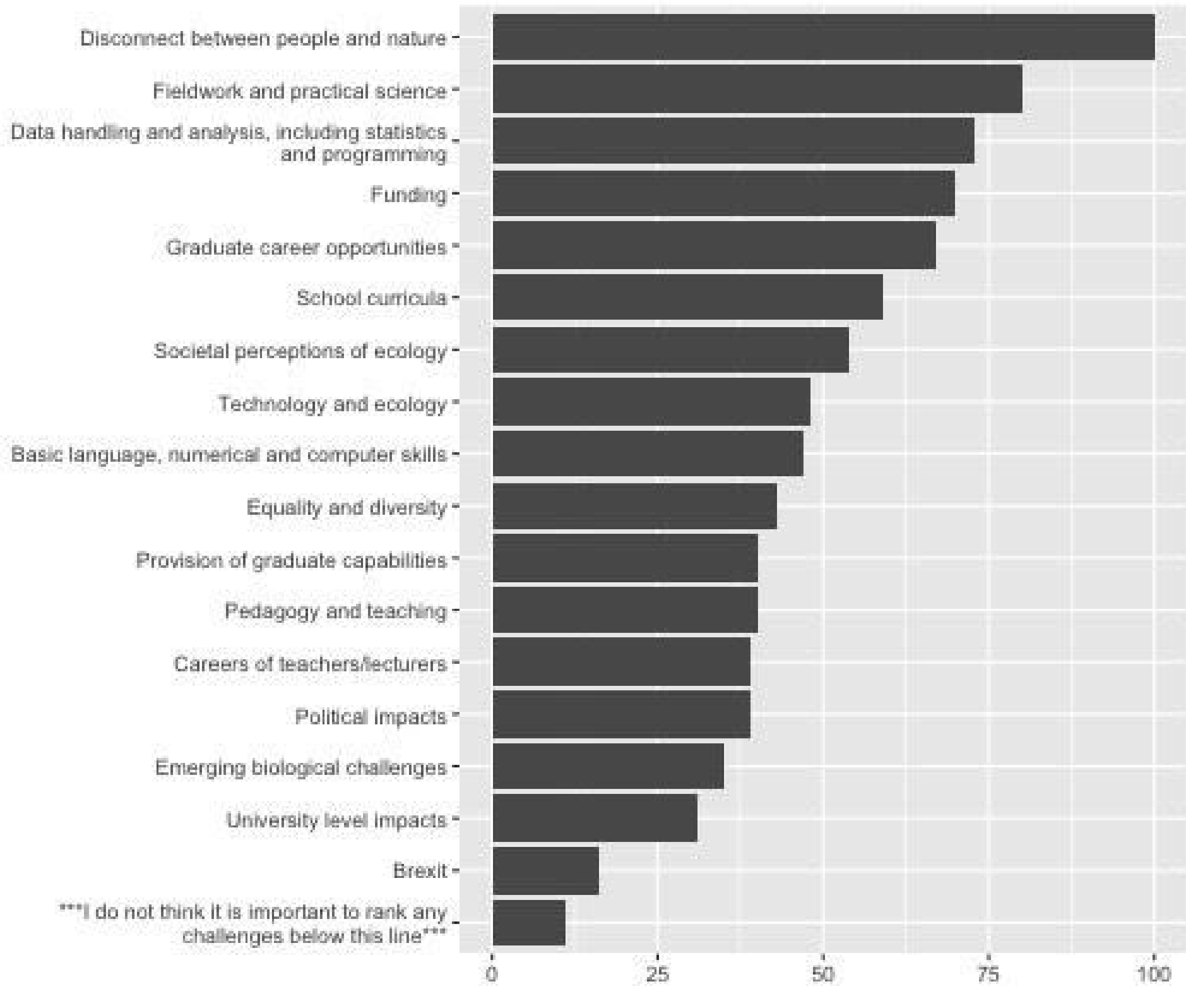


Figure S2. Rankings of issues associated with disconnect between people and nature

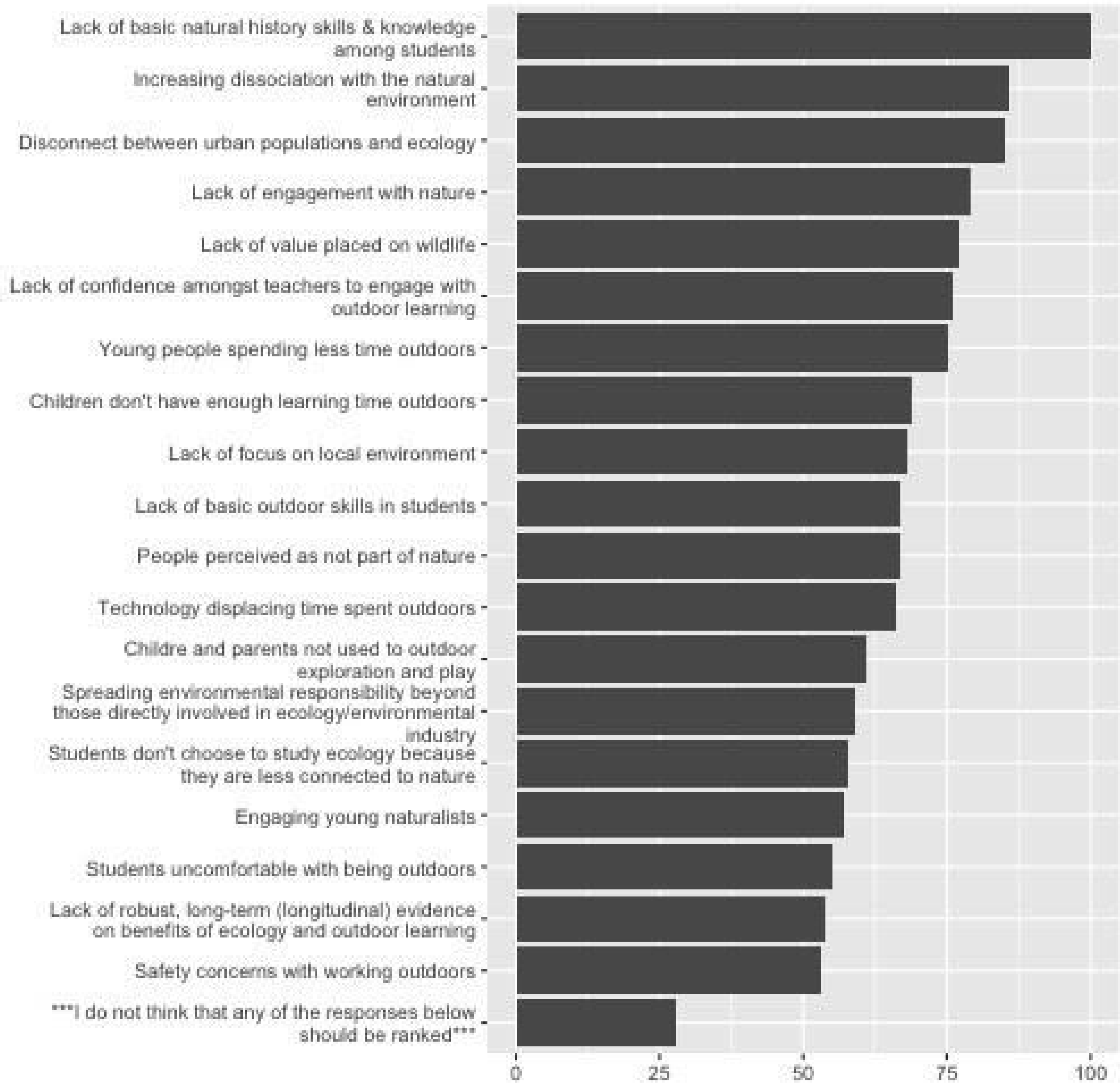


Figure S3. Rankings of issues associated with fieldwork and practical science


Costs of field courses relative to other forms of teaching
Restricted budgets for field-based teaching
Costs to students of fieldwork
Finding time for field work
Limited number of practitioners to support training
Teaching skills to large groups in the field
Decline of field-based teaching
Making the case for fieldwork in general
Time required for fieldwork administration
Restricted budgets for field equipment
Access to quality field equipment
Making the case for local/regional fieldwork
Restricted budgets for field-based teaching in schools
Delivering field-based teaching generally
Teaching field sampling techniques
Equality and diversity issues for field-based teaching
Conflict between increasing online delivery and need for field-based teaching
Building links with communities and organisations
Increased mental health issues of students, particularly in the field
Increasing administrative burden on educators
Health and safety issues as a barrier to fieldwork
Physical demands of fieldwork for students
Access to field sites especially in urban areas
Time & self-directed learning required for acquiring field skills
Health and safety issues as a barrier to fieldwork in schools
Lack of focus on urban ecology
Reduction in interest in students studying the field
Lack of interest in fieldwork by students
Work-life balance for students doing fieldwork (eg early morning and late night surveys)
Access to quality lab equipment (eg. microscopes)
****I do not think it is important to rank any challenges below this line****
Emotional demands of fieldwork for students
Greater reliance on team based approaches to problems
0
25
50
75
100

1199

Figure S4. Rankings of issues associated with data handling and analysis, including statistics and programming

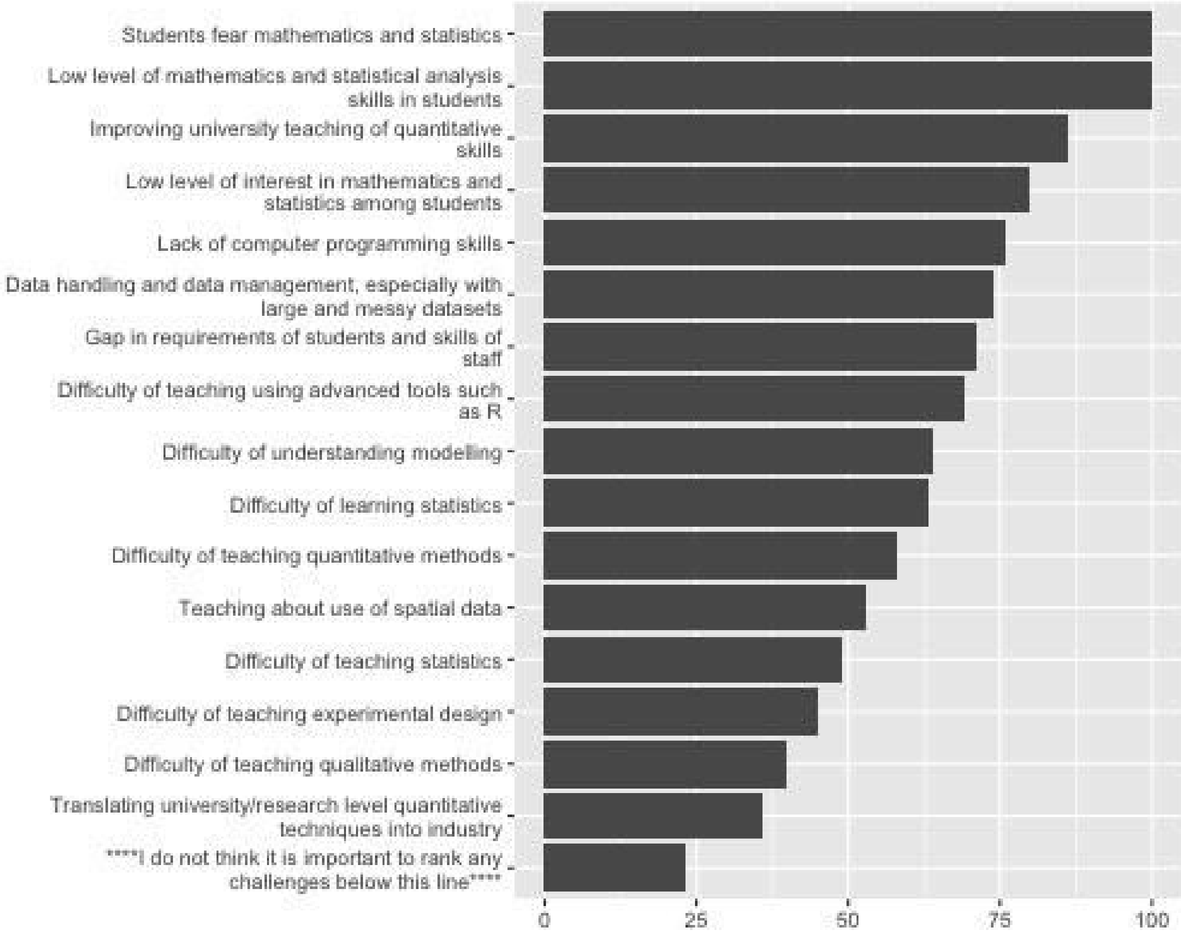


Figure S5. Rankings of issues associated with graduate career opportunities

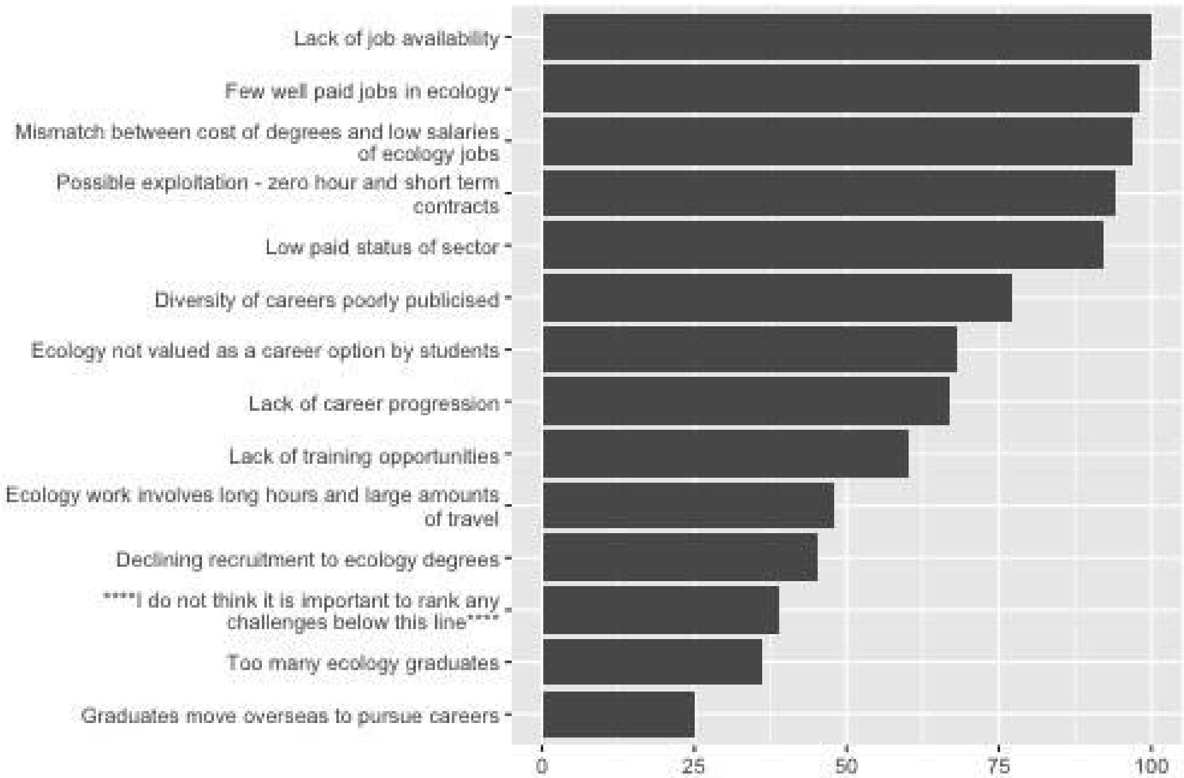


Figure S6. Rankings of issues associated with school curricula

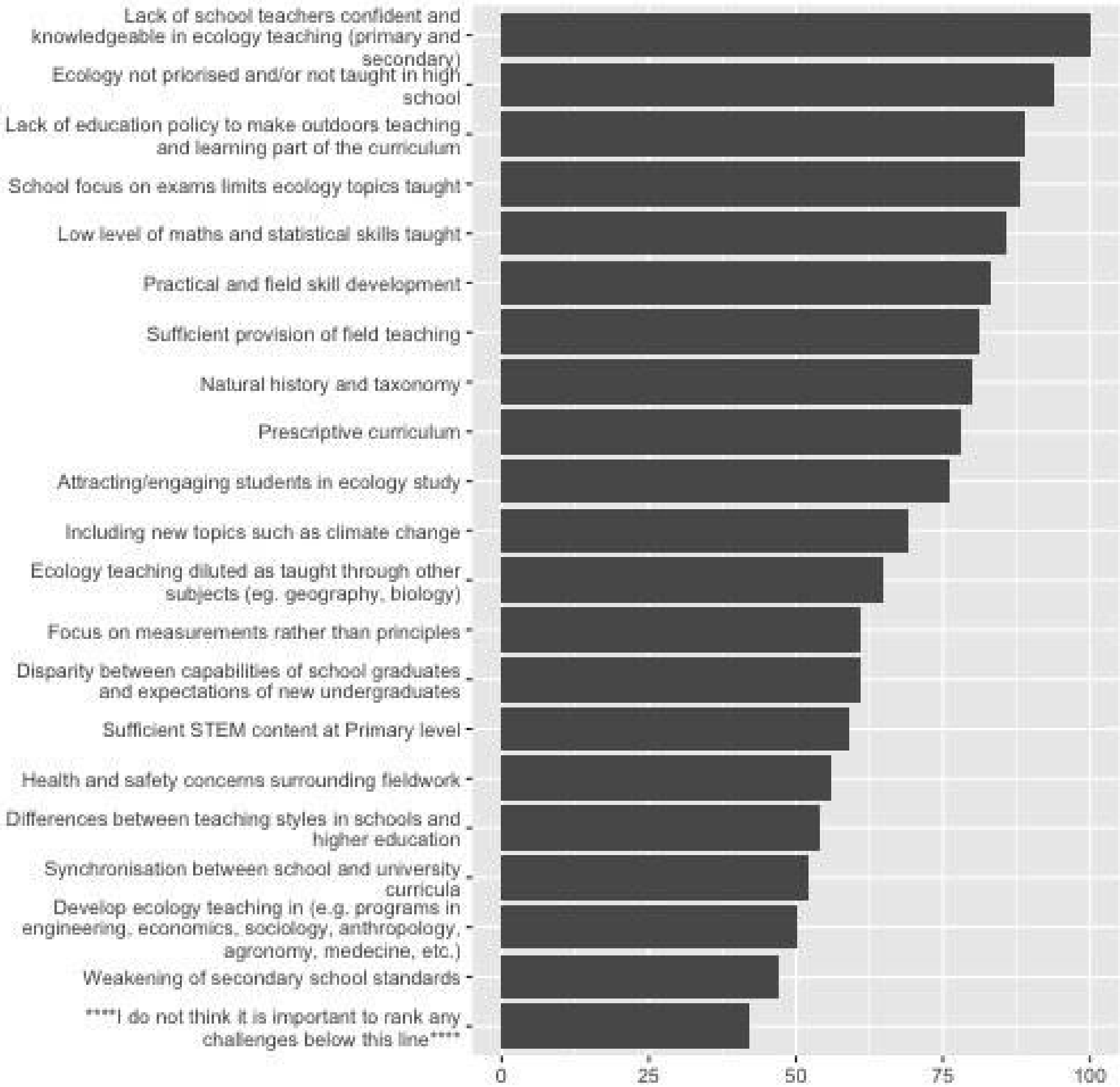


Figure S7. Rankings of issues associated with society perceptions

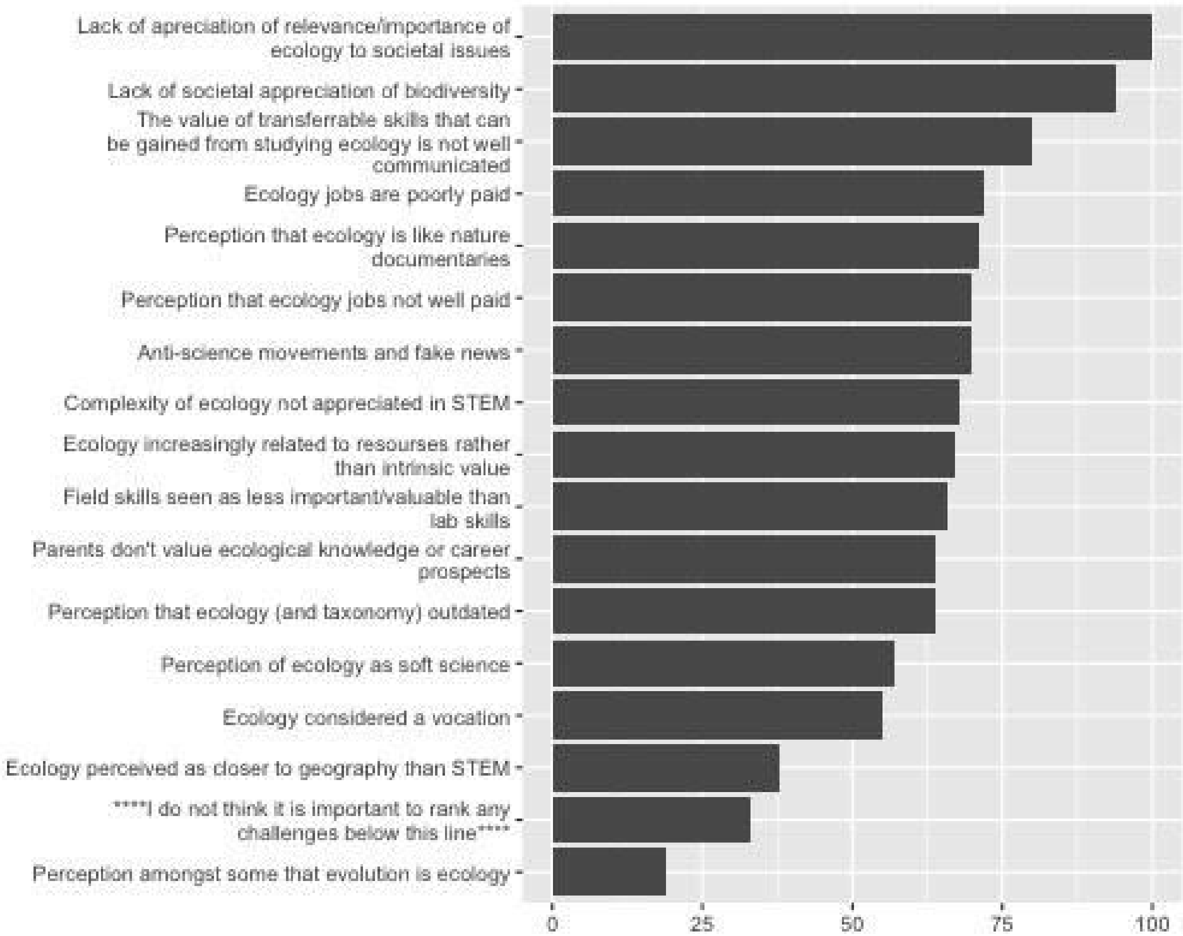


Figure S8. Rankings of issues associated with technology and ecology

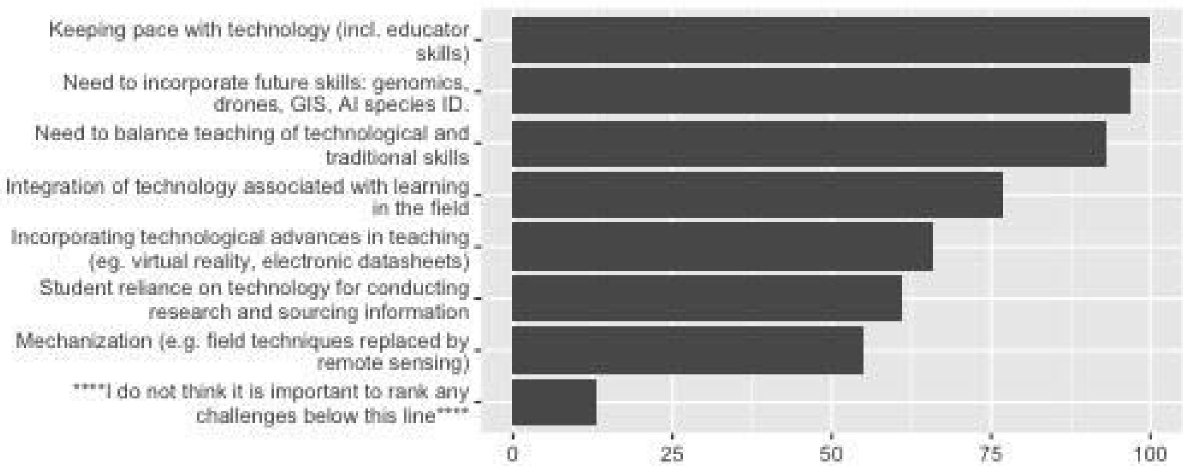


Figure S9. Rankings of issues associated with basic language, numerical and computer skills

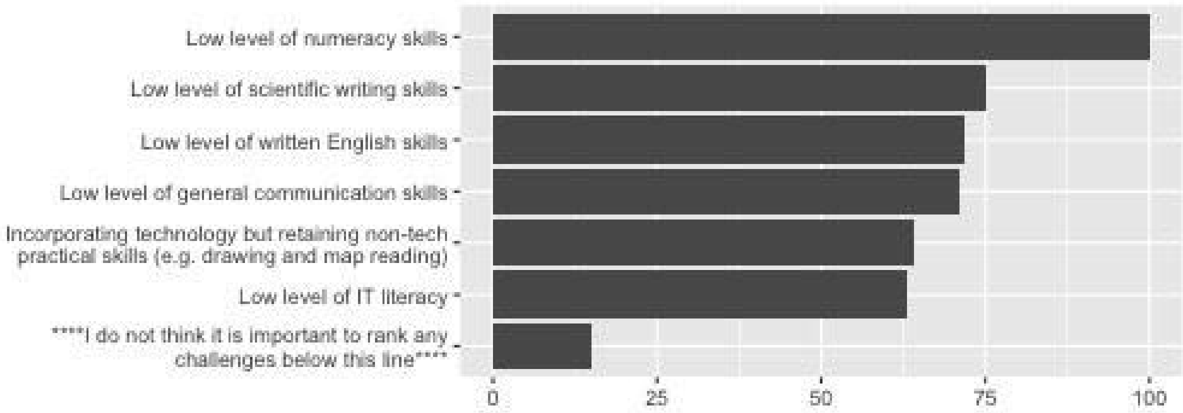


Figure S10. Rankings of issues associated with equality and diversity

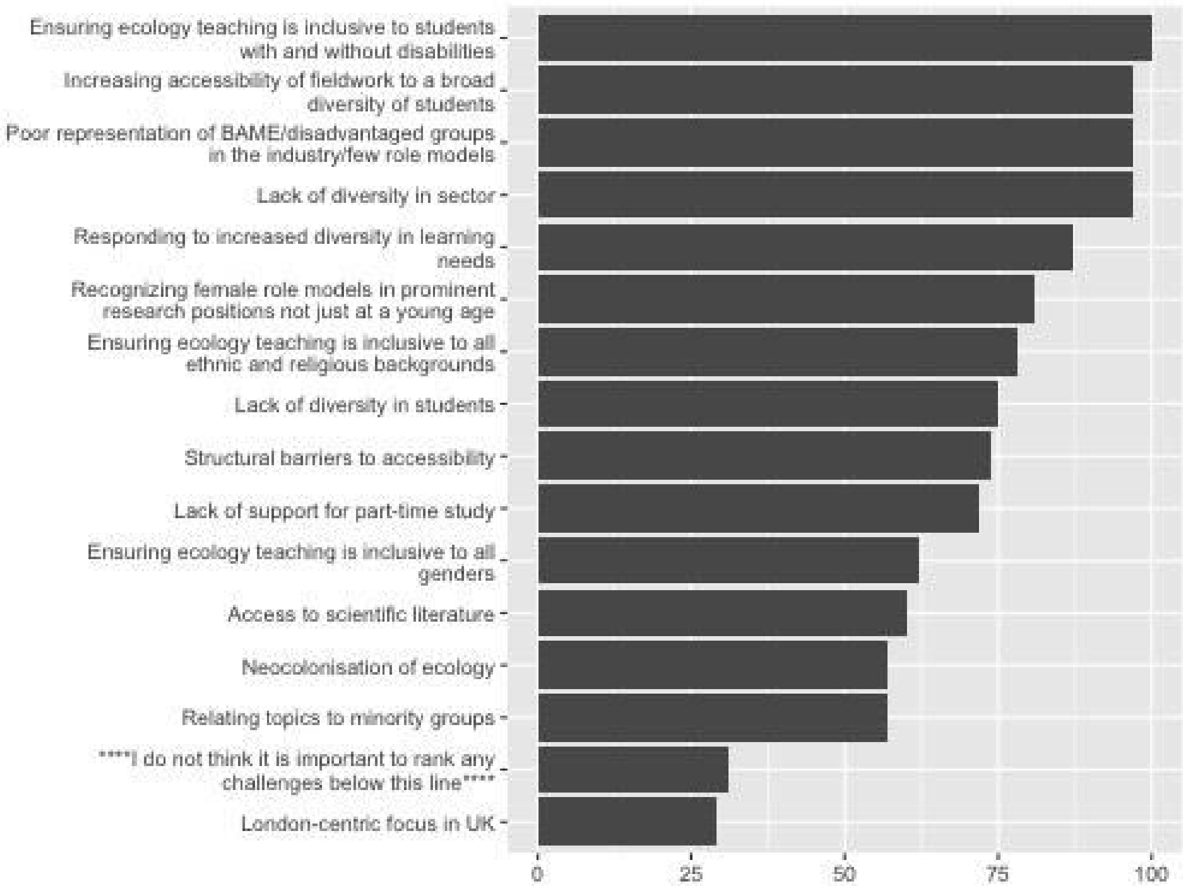


Figure S11. Rankings of issues associated with the provision of graduate capabilities

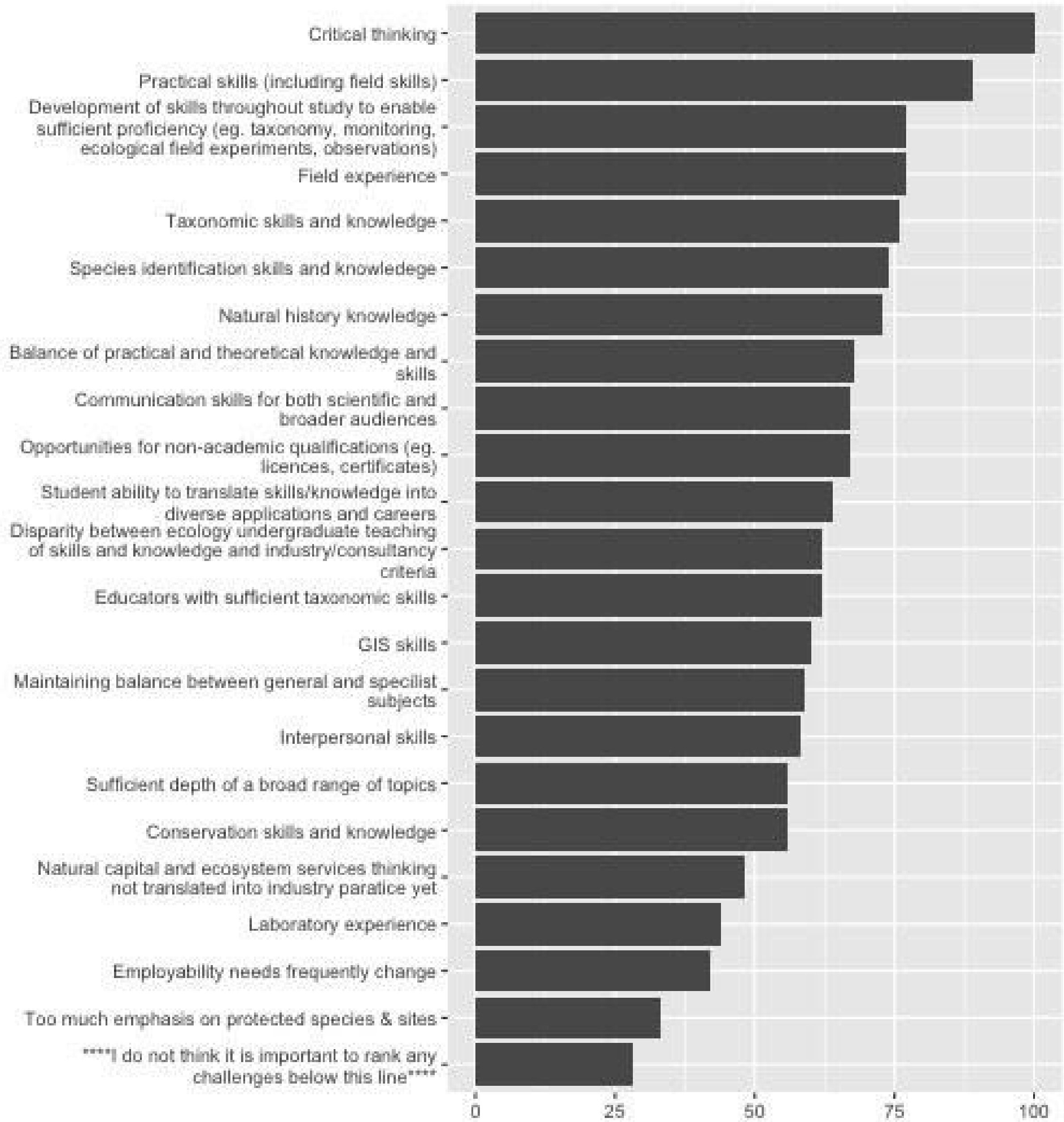
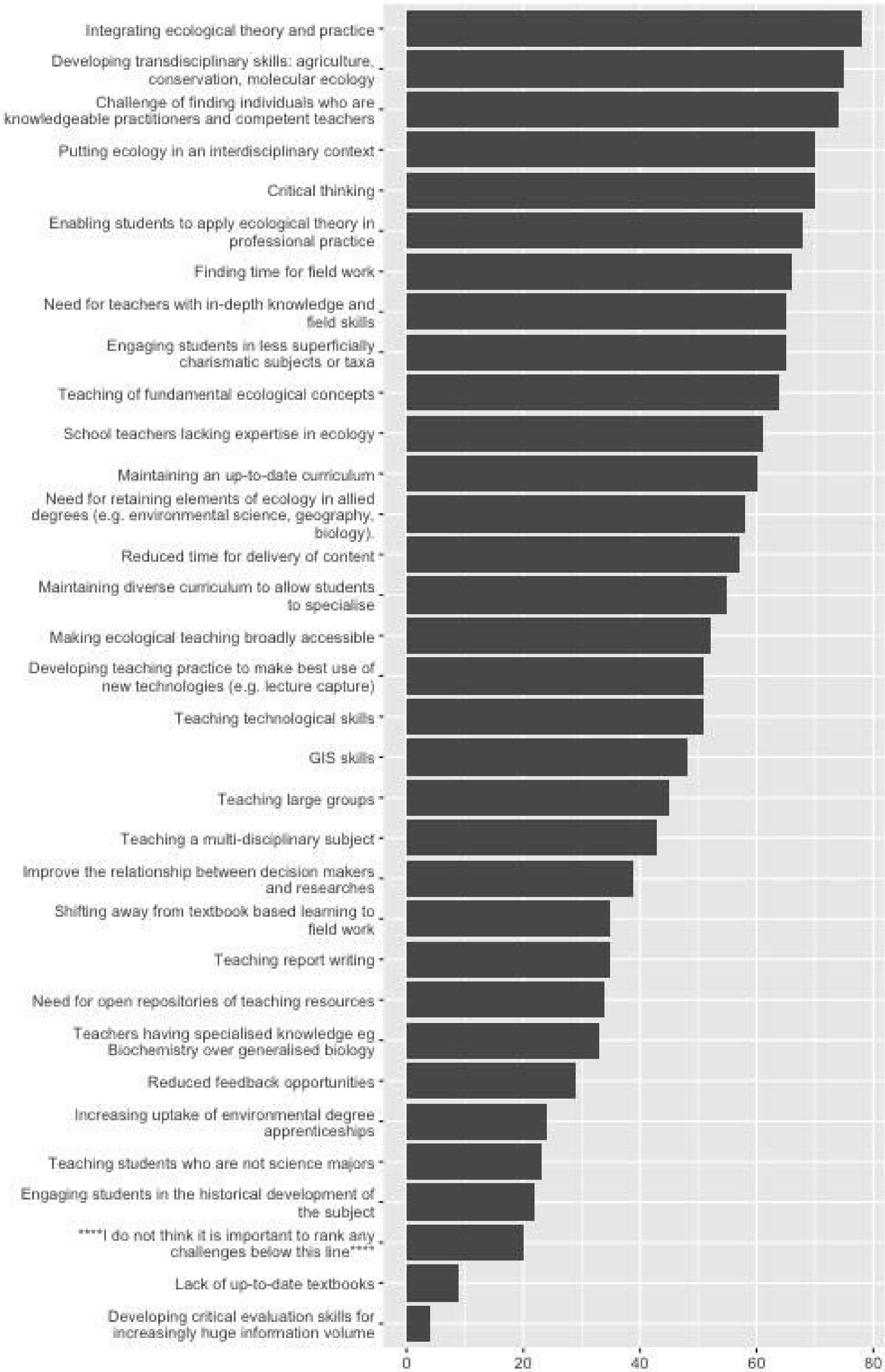


Figure S12. Rankings of issues associated with pedagogy and teaching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Reduced feedback opportunities
Increasing uptake of environmental degree apprenticeships
Teaching students who are not science majors
Engaging students in the historical development of the subject
****I do not think it is important to rank any challenges below this line****
Lack of up-to-date textbooks
Developing critical evaluation skills for increasingly huge information volume
0
20
40
60
80

1229

Figure S13. Rankings of issues associated with the careers of teachers/lecturers

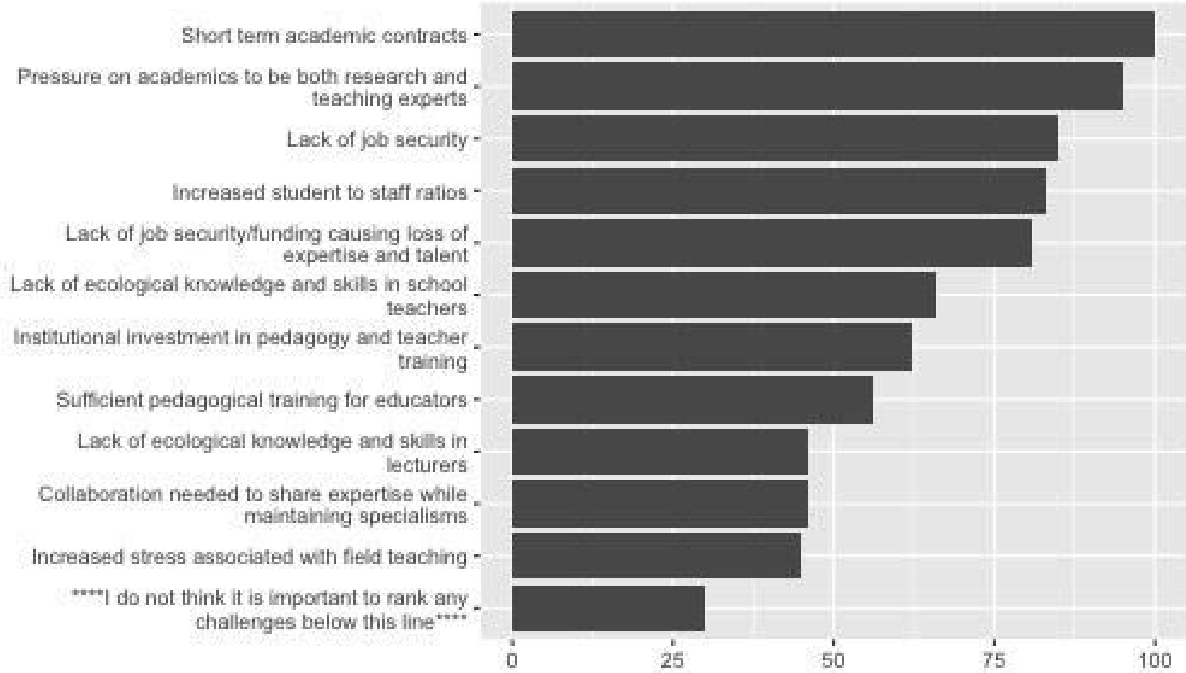
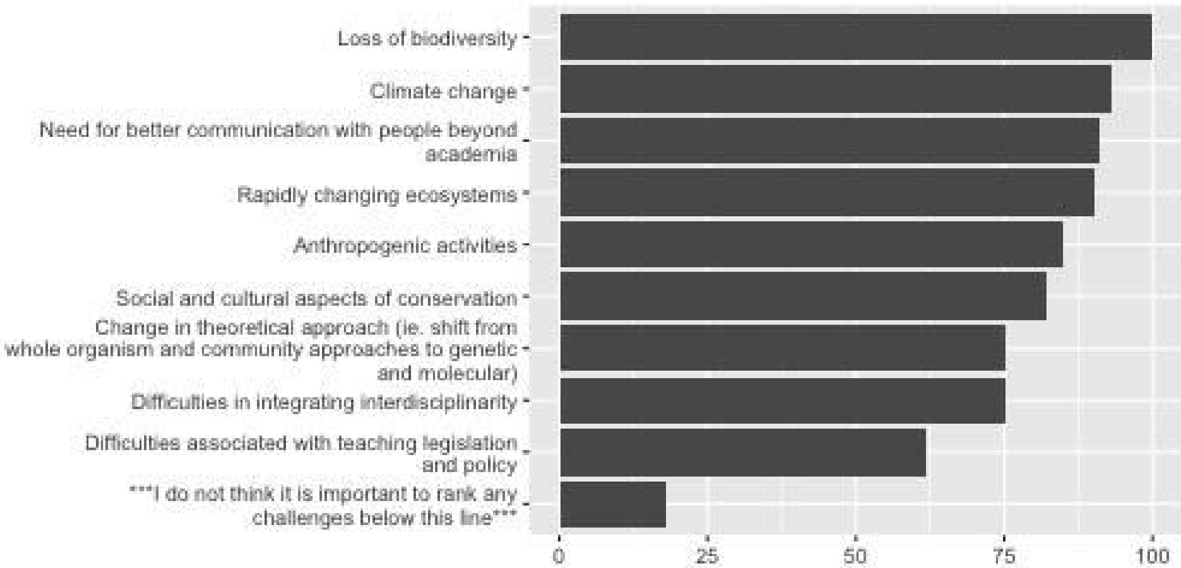


Figure S14. Rankings of issues associated with emerging biological challenges



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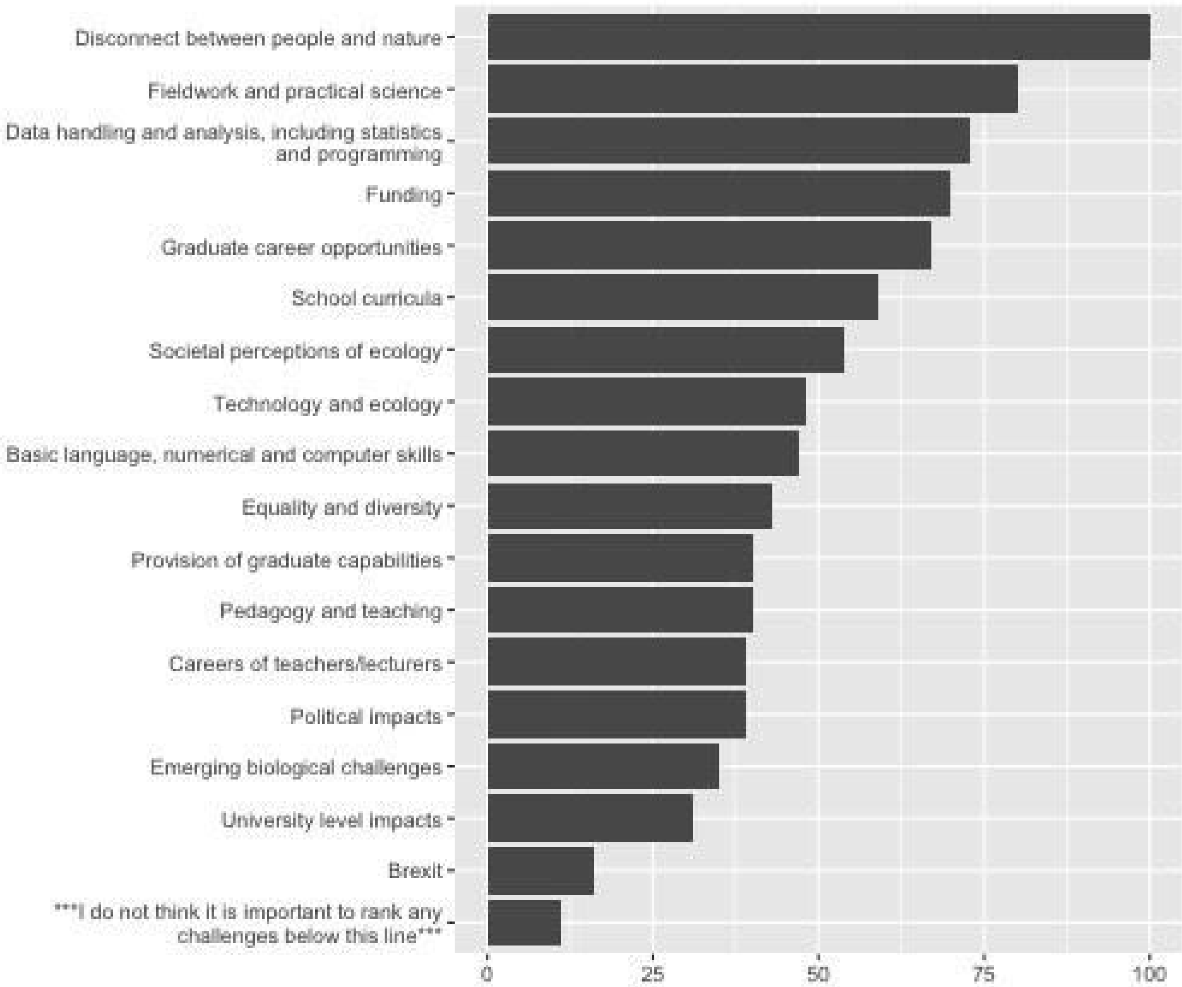

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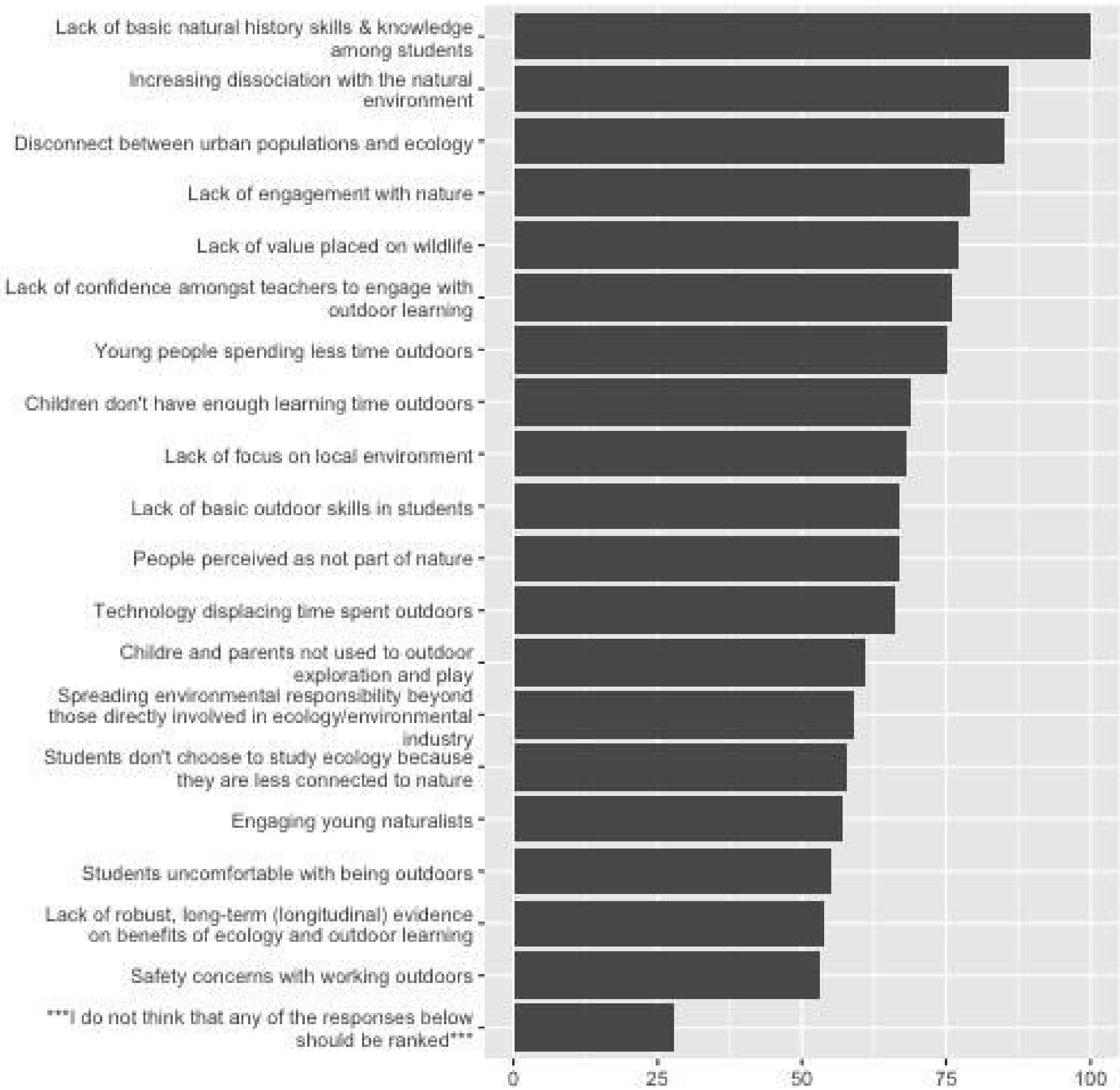

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100

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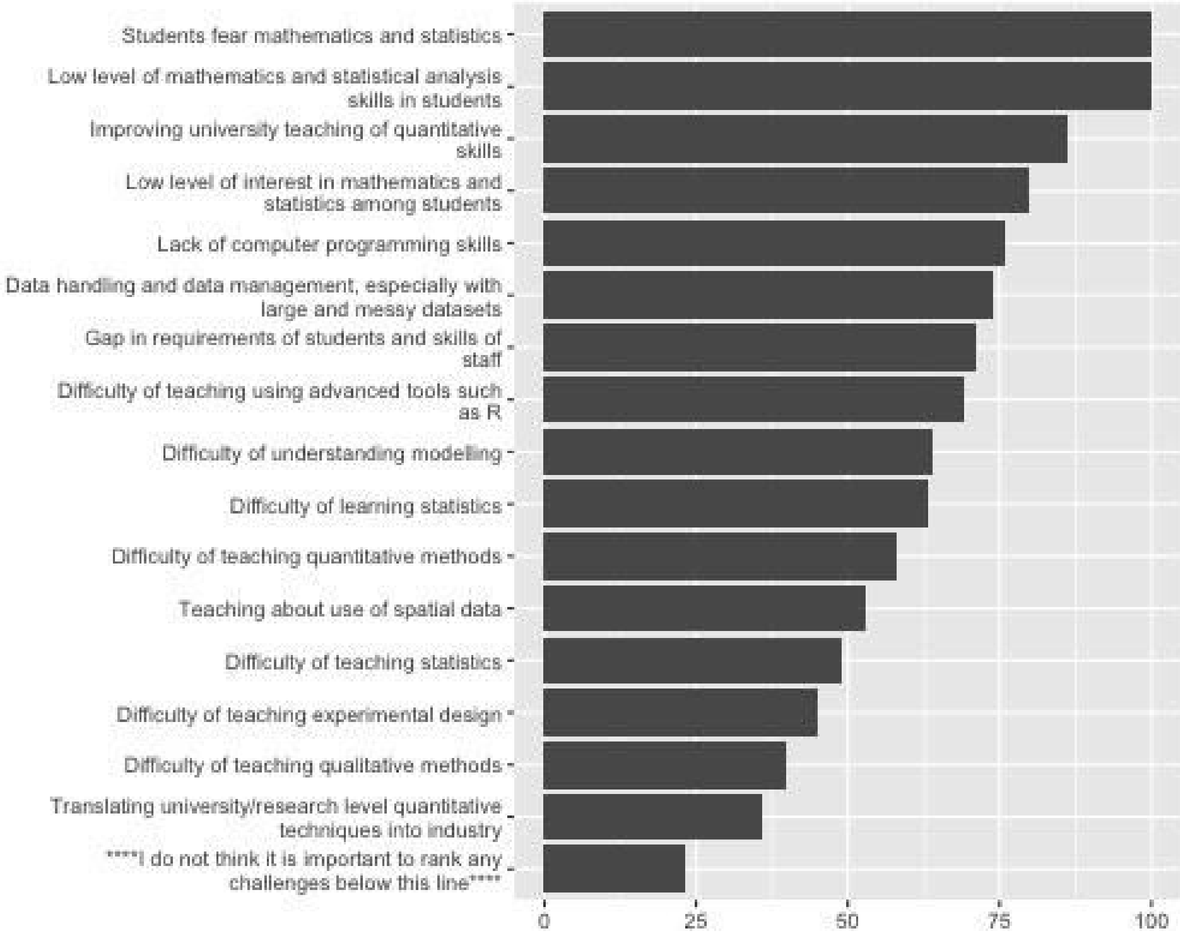

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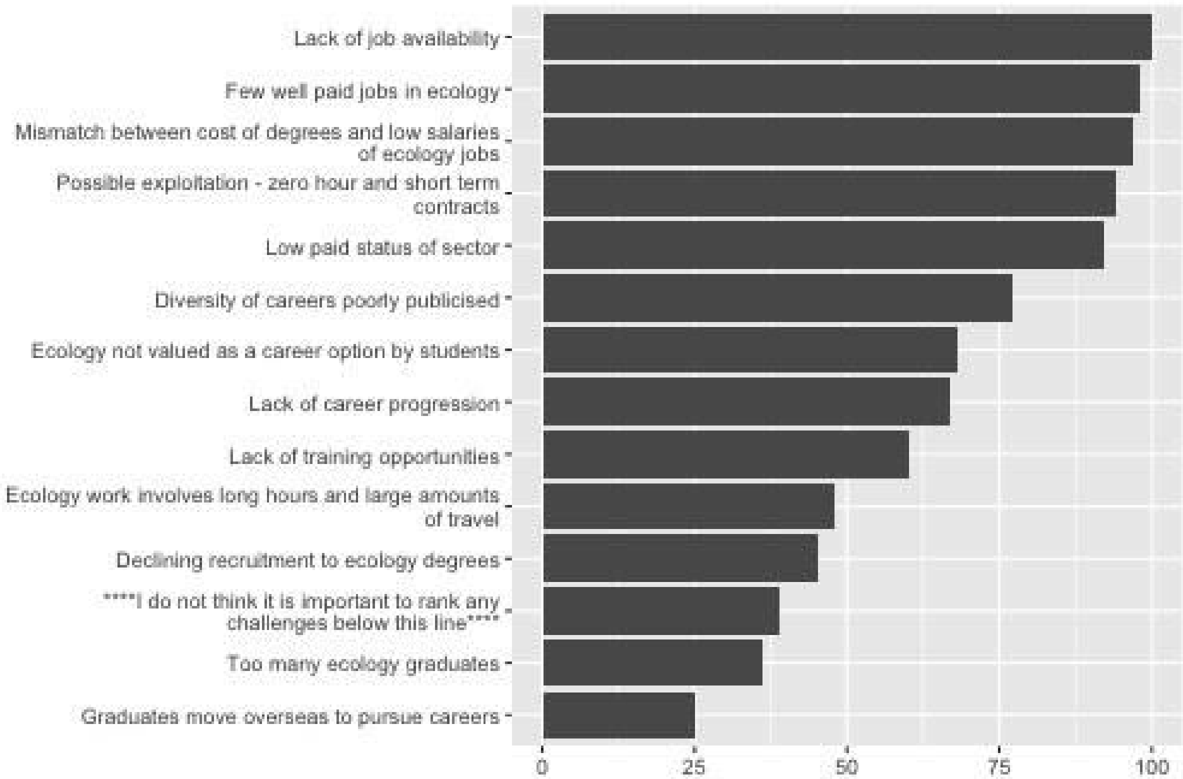

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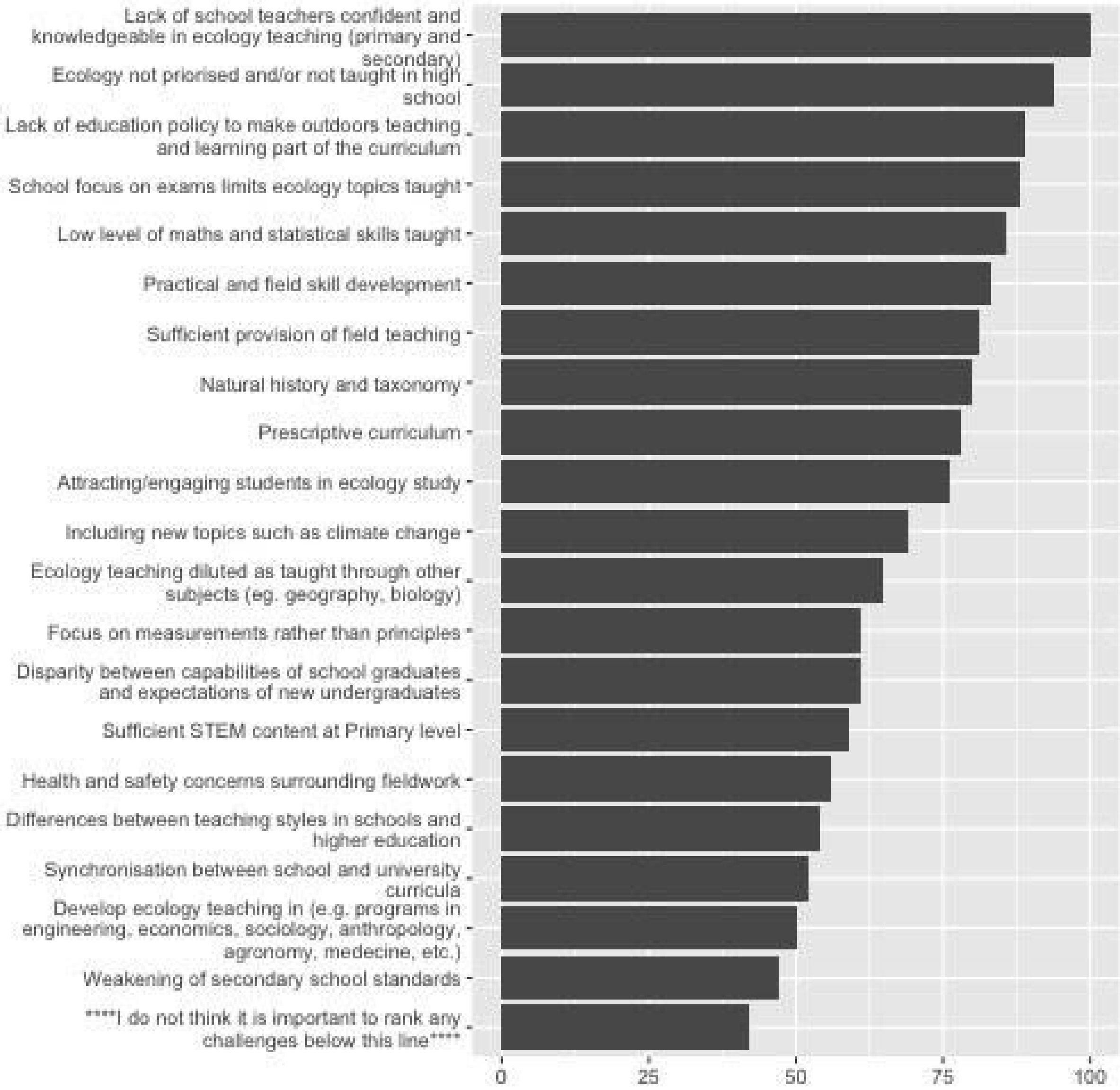

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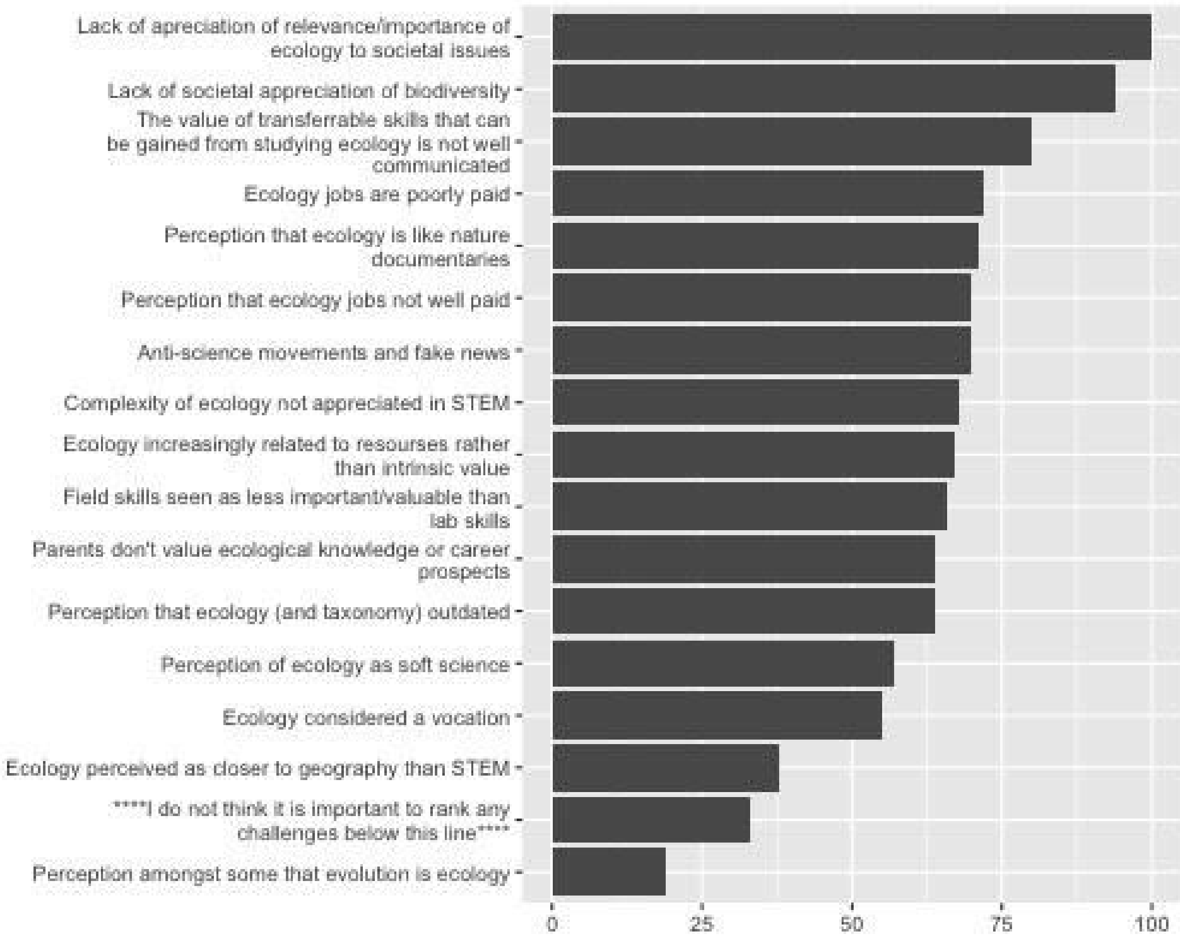

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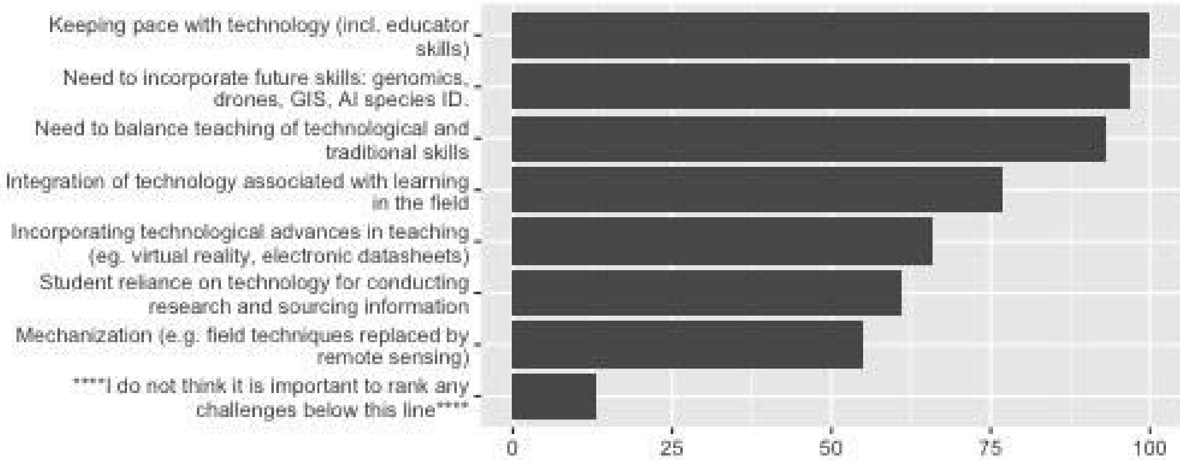

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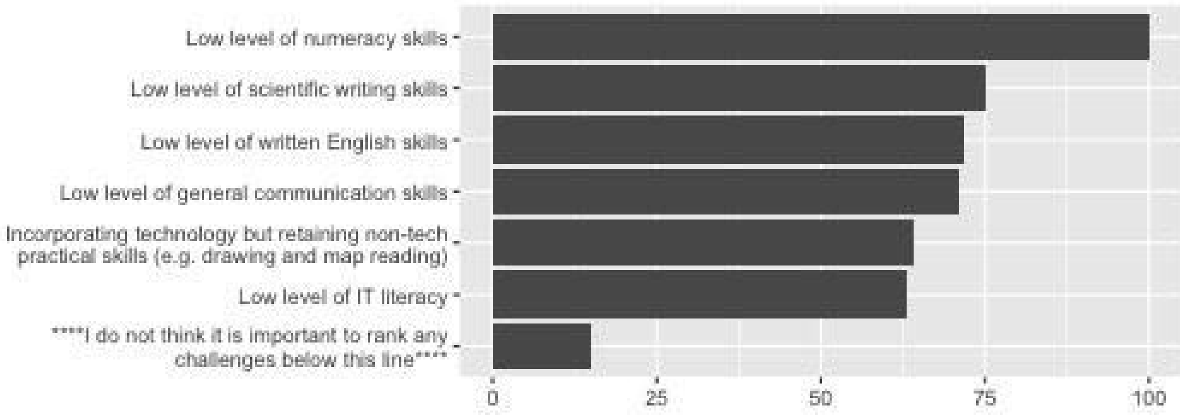

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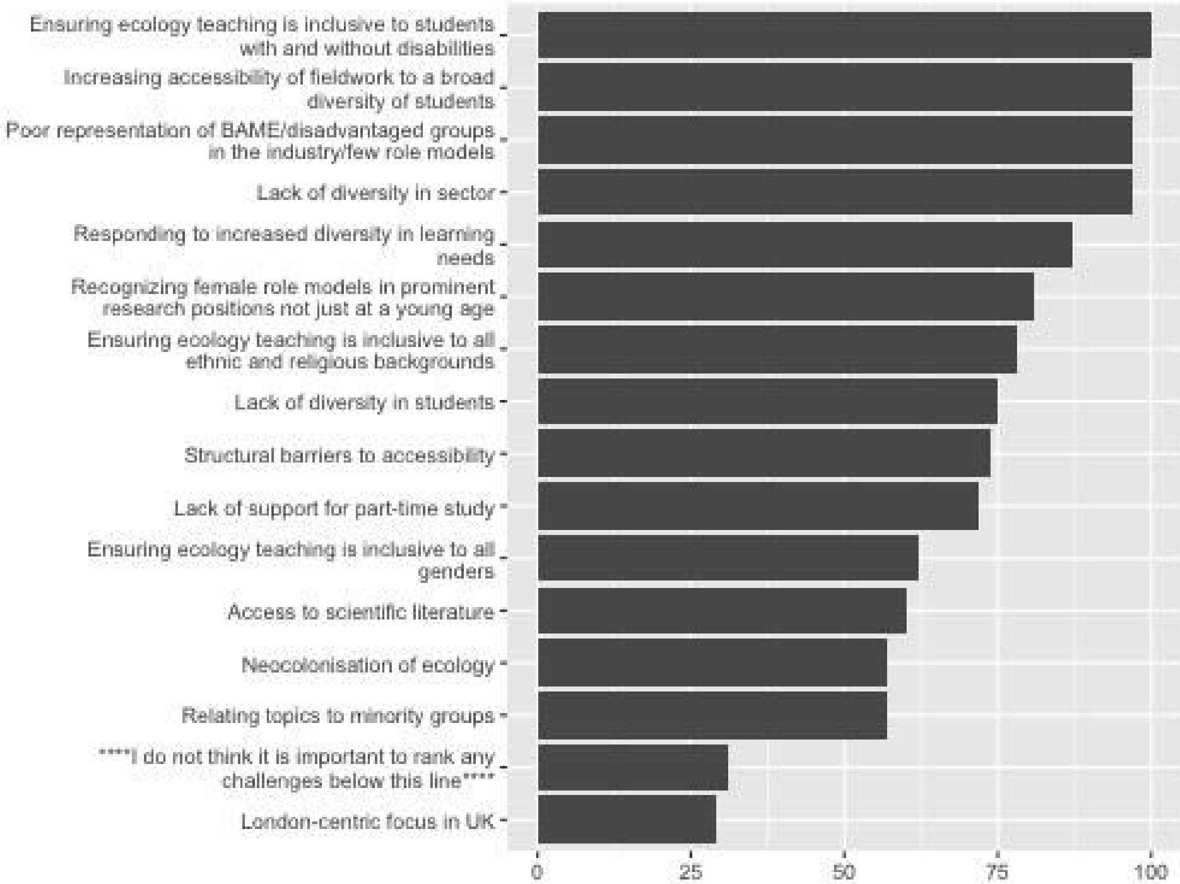

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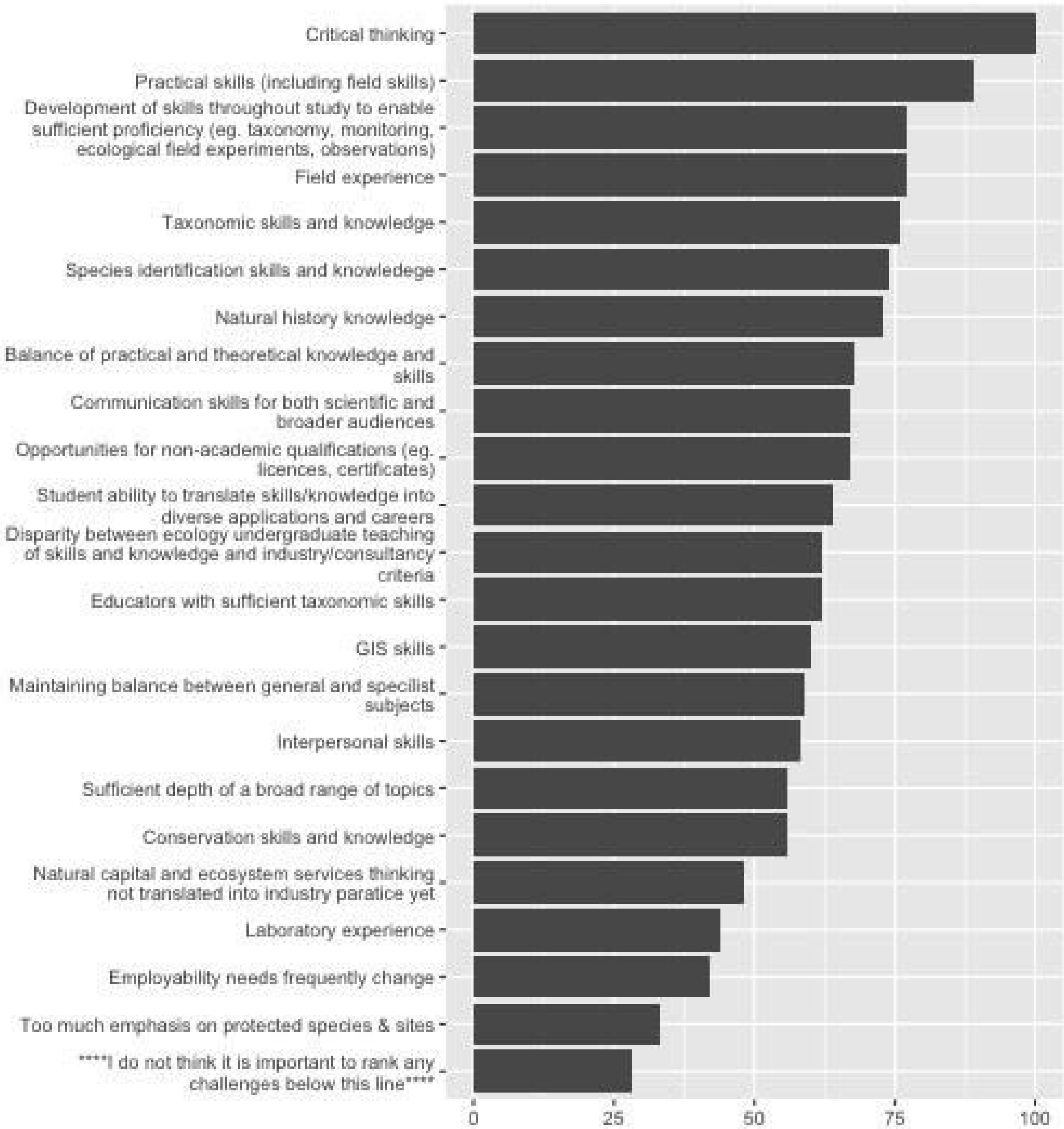

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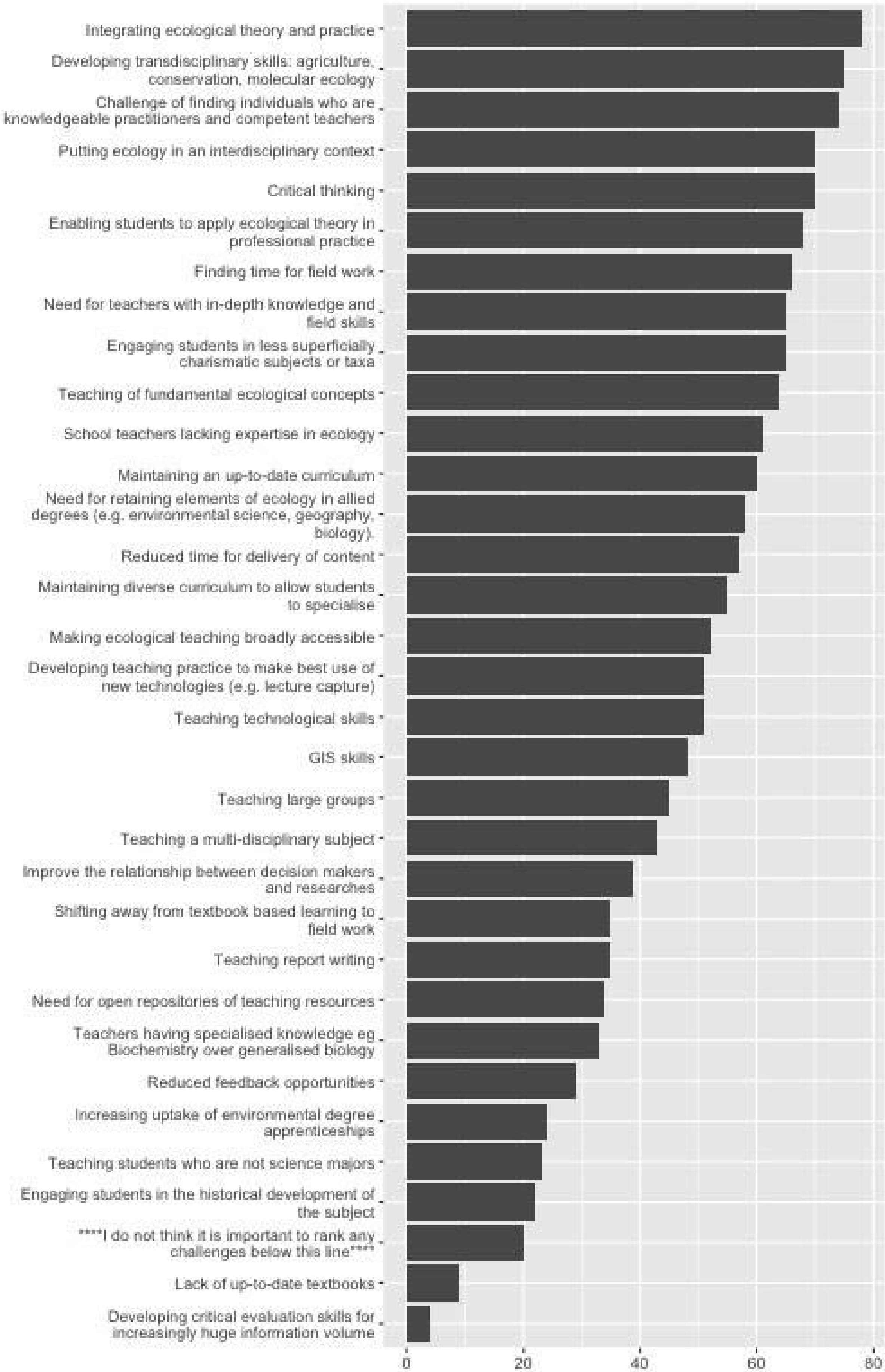
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40
60
80

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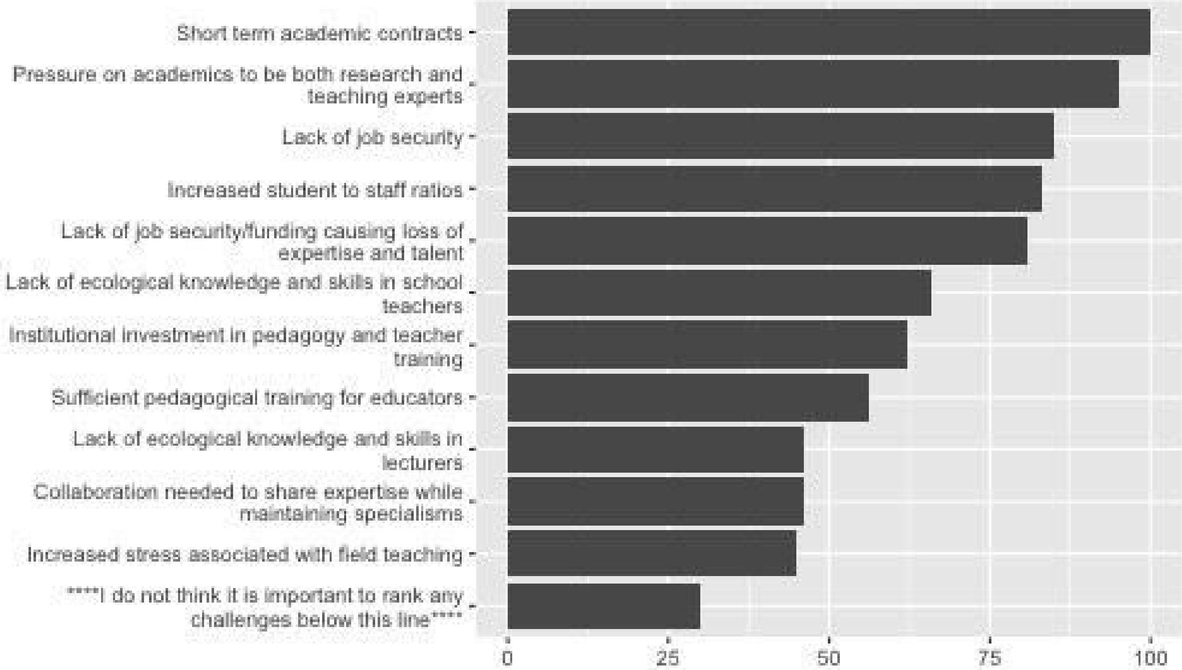

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