



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

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Keywords:	horizon scan, teaching and learning, ecology, global challenges
Abstract:	<p>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.</p> <p>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.</p> <p>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.</p>

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3

4 **Abstract**

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7 ecologists in mitigating these challenges is arguably more important than ever. Consequently
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24 based learning and coding in the curriculum, an increased role for learned societies in teaching
25 and learning, and using new technology to enhance fieldwork studies including virtual reality,
26 artificial intelligence and real-time spoken language translation.

27

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

31

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

33

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

35

36 **Introduction**

37

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

50

51 Despite this, to our knowledge, there has been no attempt to explore the future challenges
52 that face the teaching of ecology as a discipline, and no recent review of the skills
53 requirements for future generations of ecologists. Forecasting challenges is valuable for the
54 prevention and mitigation of potential threats, but also allows the identification of potential

55 solutions, and indeed opportunities (reviewed in Sutherland and Woodroof 2009). Such an
56 exercise is particularly opportune as we move into the fourth industrial revolution, a time of
57 rapid technological advancement (Maynard et al. 2015). Shifts in teaching and skills provision
58 are expected, based on patterns of past revolutions, such as increased access to higher
59 education through the rise of online distance education, and the development of MOOCs
60 (Massive Open Online Courses) during the third industrial revolution (Penprase 2018). The
61 impact of this 4th revolution is particularly relevant to ecology teaching with shifts to more
62 sustainable industries predicted as a result of understanding product life-cycles and their
63 ecological impact on the environment (Carvalho et al. 2018).

64

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

72

73 **Materials and Methods**

74

75 We combined information from both the broader ecological community, in addition to those
76 who teach ecology. We used a combination of surveys and workshop discussions to identify
77 future issues and solutions for teaching and learning in ecology (process summarised Figure
78 1). First, we conducted a two-part Delphi survey; an efficient, inclusive, systematic approach
79 that allows a group of individuals to collectively consider complex problems with reduced
80 social pressure bias (Mukherjee et al. 2015). We sought to contact teachers of ecology at a
81 range of levels, from both formal and informal learning, students of ecology, and employers of

82 ecologists. Each survey was open for four weeks and advertised on Twitter and through
83 targeted emails, asking participants to circulate the link more broadly still. The surveys
84 received ethical approval from The Open University Ethics Committee (HREC/3170/Cooke).

85

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

94

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

- 109 • Technology and its use in ecology
- 110 • University-level issues

111

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

116

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

126

127 The ranked data formed the basis for a workshop on May 23rd, 2019, which brought ecology
128 teachers together to consider the issues and solutions that could be used to mitigate and
129 address them. Attendees comprised postgraduate students with some experience of teaching
130 ecology and a vested interest in the future of the subject, through to academics with extensive
131 teaching experience. Thirteen UK universities were represented, across all categories typically
132 used to describe UK universities, including Russell Group, pre-92, and post-92; these
133 classifications represent research-focussed institutions, other traditional UK universities, and
134 former technical colleges, respectively. All attendees are named as co-authors on this paper.
135 Although all workshop attendees were based at UK universities, this profile was not

136 unexpected given engagement required physical attendance at the workshop, and the event
137 was communicated through British Ecological Society channels. However, respondents to the
138 surveys were based in diverse countries, with most continents represented except for Africa
139 (surveys 1 and 2) and Asia (survey 2; Table S1). Indeed, a range of nationalities, backgrounds,
140 experience, and research expertise were represented, and perspectives of non-academics
141 such as schoolteachers and NGO workers were gathered via the surveys (see table S2).

142

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

157

158 The project leads attended parts of each session and collated notes during the workshop.
159 They noted that issues were routinely considered from three main perspectives: student,
160 teacher and society, and therefore we have presented the challenges in these groups,
161 mapped with the original categories under which they were discussed. Perhaps surprisingly,
162 many of the challenges raised and discussed were current, rather than the more futuristic

163 challenges we had expected. Across the day, solutions that could address multiple challenges
164 emerged, and were brought up in multiple discussion groups. These were identified by the
165 workshop organisers and are reported in the form of an evidence-based forward-thinking
166 essay. Perhaps unsurprisingly there were significant overlaps across both challenges and
167 solutions; these are mapped in Figure 2.

168

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

180

181 **Challenges**

182

183 ***Student challenges***

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

188 In recent years there has been broad recognition that there is an increasing disconnect
189 between people, particularly children and young people, and nature (reviewed in Soga and
190 Gaston 2016). Increasingly we live in suburban areas and cities

191 ([https://www.un.org/development/desa/publications/2018-revision-of-world-urbanization-
193 prospects.html](https://www.un.org/development/desa/publications/2018-revision-of-world-urbanization-
192 prospects.html)). This, in conjunction with parental fear for child safety (Carver et al. 2010), the
194 rising popularity of sedentary pastimes, and overscheduling of children's lives (Hofferth 2009),
195 means that children and young people are spending less time outdoors (Clements 2004).
196 There is now very limited practical and fieldwork learning in the UK school curricula and,
197 coupled with the disconnect with nature, the lack of experience of ecology may mean that
198 students either do not understand what ecology means, or do not appreciate its value, to the
199 extent of self-excluding from the discipline at a young age.

200 Even when students do know and understand what ecology is, a perceived lack of jobs in the
201 field may discourage students from studying ecology. This is potentially exacerbated by the
202 increasing focus on graduate income as a measure for ranking the value of degrees, as there
203 is a tendency for ecology jobs to be more poorly paid than those in other bioscience
204 professions. The importance of quantitative skills to the field may also represent a barrier to
205 young people engaging with ecology. Advanced statistics are routinely required to analyse the
206 complex datasets encountered in ecological research (Barraquand et al. 2018), yet it is well
207 documented, in the UK at least, that many bioscience students fear mathematics, and
208 students exhibit a broad range of maths-related abilities, particularly in the first year of their
209 studies (Koenig 2011, 2012). Teaching quantitative skills is therefore a challenge, and
210 concerningly, it can be tempting to remove them from the curriculum in favour of more popular
211 subjects, as these tend to receive more favourable student evaluations (Uttl and Smibert
212 2017). However, early career ecologists report that more quantitative training in both
213 theoretical and statistical modeling specifically applied to ecological problems, would have
214 been very beneficial for their career (Barraquand et al. 2018), suggesting that efforts in
215 teaching quantitative skills for ecology should be increased rather than decreased. An
216 additional factor reducing engagement with ecology is the lack of diversity in the field, which,
217 like most sciences, is not representative of broader cultural and societal diversity (e.g. Holman

218 et al. 2018, Wanelik et al. 2020). A diverse workforce is perhaps particularly important in
219 ecology, which deals with global issues; practitioners need to have diverse cultural and
220 societal norms to be able to constructively engage with those living on the frontline of where
221 the issues are being played out.

222

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

230

231 ***Teacher challenges***

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

237 There are significant institutional barriers with potential to impact on ecology teaching, if they
238 are not already doing so. Although ecology does not necessarily have to be field-based, field
239 work can be an important component. There are conflicting views as to whether there has
240 been a reduction in the amount of field teaching in UK universities in past decades (e.g. Smith
241 2004, Ashton et al. 2015), or whether it has remained stable (e.g. Mauchline et al. 2013,
242 reviewed in Goulder and Scott 2016). However, given funding challenges and increasing
243 corporatisation (Robertson 2010), there is a risk that university administration and
244 management will consider field-based teaching too expensive in both money and staff time.

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

250

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

260

261 Putting aside the challenges of teaching new ecologists, the current generation of ecology
262 practitioners themselves face problems. Ecology positions tend to be short-term and low-paid
263 contracts (Hance 2017). Many positions require prior experience, and work experience is often
264 unpaid, or in some cases demands payment, which is likely to be impacting on sector retention
265 of personnel, in addition to contributing to low diversity in the discipline (Fournier and Bond
266 2015, Wanelik et al. 2020). In the age of the UK Research Excellence Framework, and the
267 focus on 'impact' as a measure of scientific quality, there is the potential for significant barriers
268 to progression for university-based ecologists, especially as ecological research is typically
269 long-term in comparison to other STEM disciplines; for example, at least a decade of
270 consistent monitoring is needed to capture statistically significant trends in vertebrate
271 populations (White 2018) and a resulting impact case would take even longer to develop.

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

277

278 ***Societal challenges***

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

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

295

296 A related challenge is the long-term nature of ecological research. The public perceive many
297 of the problems that ecologists are trying to address, for example the impacts of climate
298 change, as distant in both time and space (Lorenzoni and Hulme 2009), which can cause a

299 barrier to engagement and understanding. Similarly, ecologists are comfortable with the
300 uncertainty of science in contrast to the public, and it has been argued that uncertainty can be
301 and has been used by the media to drive a wedge between the scientific and public
302 communities (Zehr 2000). Instances where government policy has publicly ignored ecological
303 studies, such as in the case of the UK badger cull (e.g. [https://www.bbc.co.uk/news/science-
304 environment-39418554](https://www.bbc.co.uk/news/science-environment-39418554)), damages societal perceptions of the credibility of ecology.

305

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

311

312

313 **Solutions**

314

315 The following solutions are not listed in any particular order.

316

317 ***Living labs on campus***

318

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

325 restoration of a local woodland by students from the Musahi Institute of Technology, Japan
326 (Kobori and Primack 2003).

327

328 Living labs initially gained traction in the discipline of urban sustainable development (Hossain
329 et al. 2019), but there are increasing calls to utilise such an approach in ecology teaching (e.g.
330 AASHE 2013). This is timely, as many if not all school and university campuses are seeking
331 to make the educational environment more sustainable in line with national calls (e.g.
332 McCoshan and Martin 2012). Living labs offer a multitude of benefits. At pre-school and school
333 level, encouraging children to engage with the natural world in their local area is beneficial to
334 their physical and mental wellbeing (reviewed in Louv 2006), and can also result in a more
335 positive attitude towards conserving it (e.g. Bizerril 2004, Soga et al. 2016). At higher
336 education levels, living labs can be used to engage local wildlife trusts and charities to share
337 their expertise, and to train students in working in an interdisciplinary manner with external
338 stakeholders (e.g. Evans et al. 2015). Active, inquiry-based learning and the gaining of real-
339 world experience help students develop enhanced research and employability skills (Healey
340 2005, Healey and Jenkins 2009), and such projects can be used to introduce credit-bearing
341 work experience to the curriculum, which has been shown to be beneficial to student
342 development and learning (e.g. Toledano-O’Farrill 2017). Data collected can also contribute
343 towards citizen science projects which can aid in training students to consider robust research
344 methods and data accuracy. Field work in a familiar local environment can increase
345 accessibility and inclusivity, and also helps students build confidence, for resilience in the face
346 of uncertainty of unfamiliar sites, by initiating fieldwork in a familiar setting (Leon-Beck and
347 Dodick 2012). In addition, local sites facilitate fieldwork with a limited or negligible budget
348 (Bacon and Peacock 2016) and still allow the social benefits among peers and staff-student
349 collegiality that develops during fieldwork (Peacock et al. 2018). It is notoriously difficult to
350 collect ‘real’ data on short, intensive, residential field courses. In contrast, long-term collection
351 of field data from local environs provides the opportunity to generate meaningful scientific

352 data, particularly with involvement across departments and even across institutions. Finally,
353 living labs may help mitigate increasing student concerns about the impacts of travelling for
354 fieldwork on the environment.

355

356 At the institutional level, living labs save both money and staff time, and there is also an
357 appreciable reduction in the level of health and safety risks. At society level, the living labs
358 approach can result in positive and sustainable change in the local environment, and can be
359 used to engage the general public in ecological and sustainability initiatives (e.g. Farrell et al.
360 2015, Steppe et al. 2016).

361

362 ***Teacher memberships in professional societies***

363

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

374

375 Tilling (2018) showed that, in English secondary schools, “quantity and quality of ecology
376 fieldwork has been declining in recent decades at a time when the scope, complexity, and
377 interdisciplinarity of ecological science has been growing”. Increased cross-sector sharing and
378 collaboration would make the production of teaching materials more efficient, and introduce

379 an interdisciplinary approach to help address issues of rapidly changing environments.
380 Provision of protocols for ecological experiments appropriate for specific regions (countries)
381 or environments (urban vs rural) are possible, and the rise of distance education using the
382 internet (tutor-supported paid online courses, webinars, Badged Open Courses etc.) could
383 allow efficient delivery for time-poor teachers (Kyriacou 2001). However, to ensure effective
384 use of professional societal resources, memberships likely need to be actively advertised to
385 teachers. Mentorship programs could allow strong and direct connections between ecology
386 researchers and teachers (for example Howitt et al. 2009 and the related Akres et al. 2016),
387 and increase confidence in field trips.

388

389 ***Integration of coding***

390

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

398

399 Yet despite coding being fundamental to ecological research, and to students' personal
400 development more broadly (Tu and Johnson 1990), it is still rarely taught in the UK at any level
401 of education (Koenig 2012). It has been suggested that the best way to introduce coding is to
402 start at an early age, preferably at primary school (Flórez et al. 2017). At university level,
403 strategies that have been shown to be effective in teaching coding to beginners include the
404 use of peer-peer assessment (e.g. ArchMiller et al. 2017), the use of blended learning (Cigdem
405 2015), and the development of automated e-learning and assessment systems to facilitate

406 student learning with reduced educator input (Alu-Mutka 2005). To foster collaborative
407 approaches, single platform coding across degrees is recommended, with the programme 'R'
408 (Ihaka and Gentleman 1996; R Core Team 2018) in particular gaining traction within ecology
409 (Petchey et al. 2009, Auker and Barthelmess 2019).

410

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

419

420 ***Ecological entrepreneurships***

421

422 Ecological entrepreneurship involves identifying and translating environmental concerns into
423 actionable solutions which can involve policies, technologies, products and business
424 engagement (Koch-Weser, 2015). Marsden and Smith (2005) provide examples of networks
425 which encourage development in local communities through increased quality (rather than
426 quantity) through sustainable food production and branding which identifies local produce.

427 There is an opportunity to provide ecology students with training - both the ecological
428 knowledge and skills, but also approaches from business - to allow the development and
429 participation in ecological entrepreneurial initiatives. Interdisciplinary ecology
430 projects/assessments and challenge-based learning, and also the integration of other subjects
431 could be included in the current curriculum to equip students with the necessary skills to allow
432 them to incorporate environmental responsibility into businesses (Valeryanovna 2012).

433

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

441

442 ***Developing skills-based learning and skills-based degrees***

443

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

457

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

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

478

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

485

486 One of the challenges identified was that the diversity of topics and skills required (both new
487 and traditional) is difficult to fit into an ecology curriculum. One solution to this would be to

488 offer skills based degrees embedded in a specific field of ecological knowledge (e.g. ecological
489 engineering, ecological microbiology). Such degrees could have the benefit of equipping
490 students with good ecological understanding (or another field), but also well-developed and
491 specific, but transferable skills. Co-teaching of modules in such a degree would allow subject
492 specialists to contribute key concepts and knowledge to students, while their skills would be
493 developed by specialist practitioners. In this way graduates would have in-depth ecological
494 knowledge, but highly developed specific skills, with degrees in science communication
495 (ecology), microbiology (ecology), field studies (ecology), engineering (ecology) or data
496 analysis/science (ecology) as examples.

497

498 ***Ecological influencers***

499

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

514 public identity that is singularly charismatic and responsive to the needs and interests of target
515 audiences” (Khamis et al. 2017).

516

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

527

528 ***Virtual reality and field trips***

529

530 Virtual reality is the replacement of the real world with a simulated version, while augmented
531 reality is a simulation enhanced with additional perceptual information. Both technologies have
532 the potential to revolutionise ecology teaching, and indeed have already gained traction,
533 particularly in the geographical sciences (e.g. Bursztyn et al. 2017, Friess et al. 2016). Virtual
534 reality is a tool to complement traditional ecology teaching, both in the classroom and in the
535 field, rather than a replacement, but with potential to increase accessibility and remove some
536 of the barriers associated with field teaching. Virtual resources that can supplement more
537 traditional ecology teaching range from simple virtual guides and resources (reviewed in
538 France et al. 2015), through to fully immersive virtual reality experiences (e.g. Tarng et al.
539 2015). For example, Markowitz et al. (2018) used a virtual reality underwater experience to
540 teach school and university students about the effects of climate change on seawater acidity.

541

542 Using virtual or augmented technologies in teaching has several benefits. In the Markowitz
543 (2018) study, virtual reality resulted in the students developing more positive attitudes about
544 the environment. Student use of digital video technology in the field can develop employability
545 skills (Fuller and France 2016), while virtual or augmented technologies can enable remote
546 fieldwork for students with mobility impairments (e.g. Stokes et al. 2012), or overcome financial
547 barriers to a field course (Cliffe 2017) and allow students an experience of inaccessible
548 locations such the ocean floor (Whitelock 1999). Virtual introductions to field sites pre-field trip
549 can enhance student confidence and allay fears of the unknown. However, while evidence
550 shows benefits of virtual or augmented reality technologies as additional teaching resource to
551 traditional field courses, students suggest that they should not replace them (Spicer and
552 Stratford 2001). It is worth noting that some studies show immersive virtual reality can be
553 detrimental to learning (e.g. Makransky et al. 2017), while others demonstrate no additional
554 benefits to learning compared to non-immersive virtual reality technology (e.g. Moreno and
555 Mayer 2002).

556

557 ***Artificial intelligence***

558

559 Artificial intelligence (AI), defined as the capacity of computers or other machines to exhibit or
560 simulate intelligent behaviour (Oxford English Dictionary), is a burgeoning field. It has many
561 applications for ecology, including the identification of individual animals from video data (eg.
562 Sherley et al. 2010), investigating complex animal behaviours (Kunz and Hemelrijk 2012) and
563 to collate complex information from multiple sources, including feedback loops, to facilitate
564 decision making in natural research management decision making (eg. Liu et al. 2018).
565 Computer programs are already routinely used in both ecology teaching and research to help
566 identify vegetation communities from field data (eg. MATCH and MAVIS facilitate using the
567 National Vegetation Classification system), and online keys aid species identification using

568 known or available features (eg. EUCLID for Eucalyptus identification), hence using AI in
569 teaching is a logical next step. This scan identified that employers are concerned future
570 graduates should have species identification skills (See supplementary Table/Figure). There
571 is potential to use AI to assist species identification (MacLeod et al. 2010), while teaching the
572 limitations of technology (such as the impressive but imperfect Seek by iNaturalist) will serve
573 to maintain an appreciation for the role and value of traditional species identification skills. For
574 example, in arthropod species identification, the frequent requirement to use minute external
575 or internal morphological traits makes it unlikely that a photo-based AI app identification
576 system could replace human experts.

577

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

586

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

595 their employability. Including machine learning specialists in course and curriculum
596 development could serve to form a link between consumers versus producers of technology,
597 as well as facilitate the enhanced employability.

598

599 ***Real time spoken language translation***

600

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

617

618 This technology, however, is currently far from ready for the applications outlined above, not
619 least for localised, indigenous languages. Text translation is increasingly sophisticated for
620 more common languages, but automated translations from audio still often render problematic
621 results for all languages, as algorithms struggle to include correct punctuation, frequently fail

622 to recognise uncommon words (including scientific terminology) and cannot interpret speakers
623 with accents on which the program has not been trained (Heer 2019). In addition, for functional
624 real-time language translation, cadence, intonation and expression will need to be
625 incorporated, adding another layer of complexity. However, automated translation is an active
626 area of technological development, and increasingly common in computer programs and
627 social media platforms. Programs are beginning to use artificial intelligence to predict the
628 likelihood of the next spoken word to enable real time translations for widely spoken languages
629 ([https://www.technologyreview.com/f/612730/google-assistant-now-comes-with-a-real-time-
630 translator-for-27-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
631 aspirational for field teaching, it is noteworthy that various forms of translation technologies
632 are already used to increase accessibility for students in STEM, such as speech-to-text and
633 text-to-speech (Lee and Templeton 2008), sonograms (visual displays of sound waves e.g.
634 Huffling et al. 2018) and sonification (audible versions of data e.g. Vines et al. 2019).

635

636 **Discussion and Conclusions**

637

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

647

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

662

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

675

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

683

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

693

694

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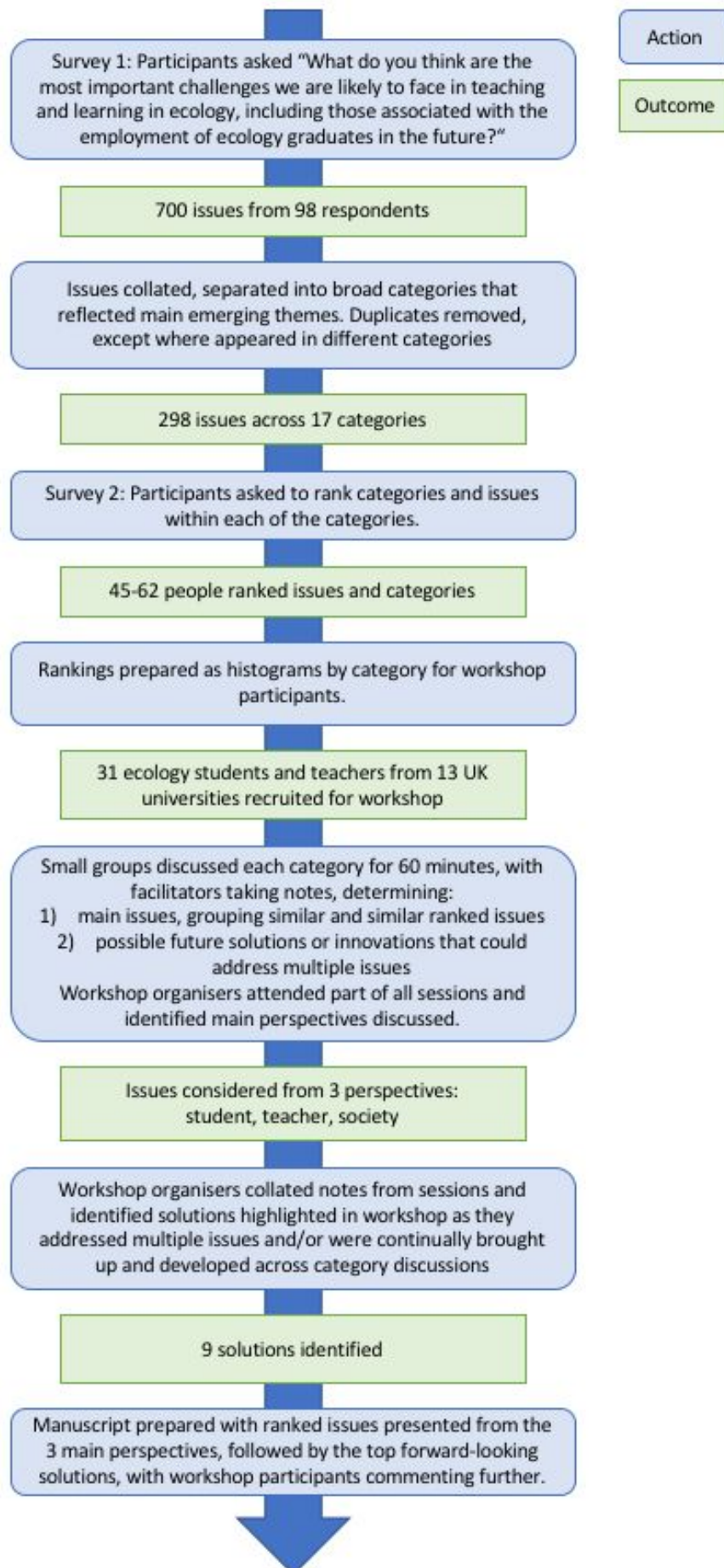
1159 **Tables and Figures**

1160

1161 **Figure 1. Schematic diagram of the horizon scan process and main outcomes.**

1162

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1164 **Figure 2. Illustrated are the challenges, solutions, and opportunities identified in**
 1165 **ecology teaching and learning for students, teachers, and society.** The main issues
 1166 identified by the participants are shown on the left. The dominant solutions and opportunities
 1167 identified in this study to address the challenges are on the right, with the linkages shown by
 1168 blue dots on the where the relevant horizontal and vertical lines intersect.



1169

1170 **Supplementary Information**

1171

1172 **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

1173

1174 **Table S2. Occupations of survey participants.** Due to rounding, the totals do not add up to
1175 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 %
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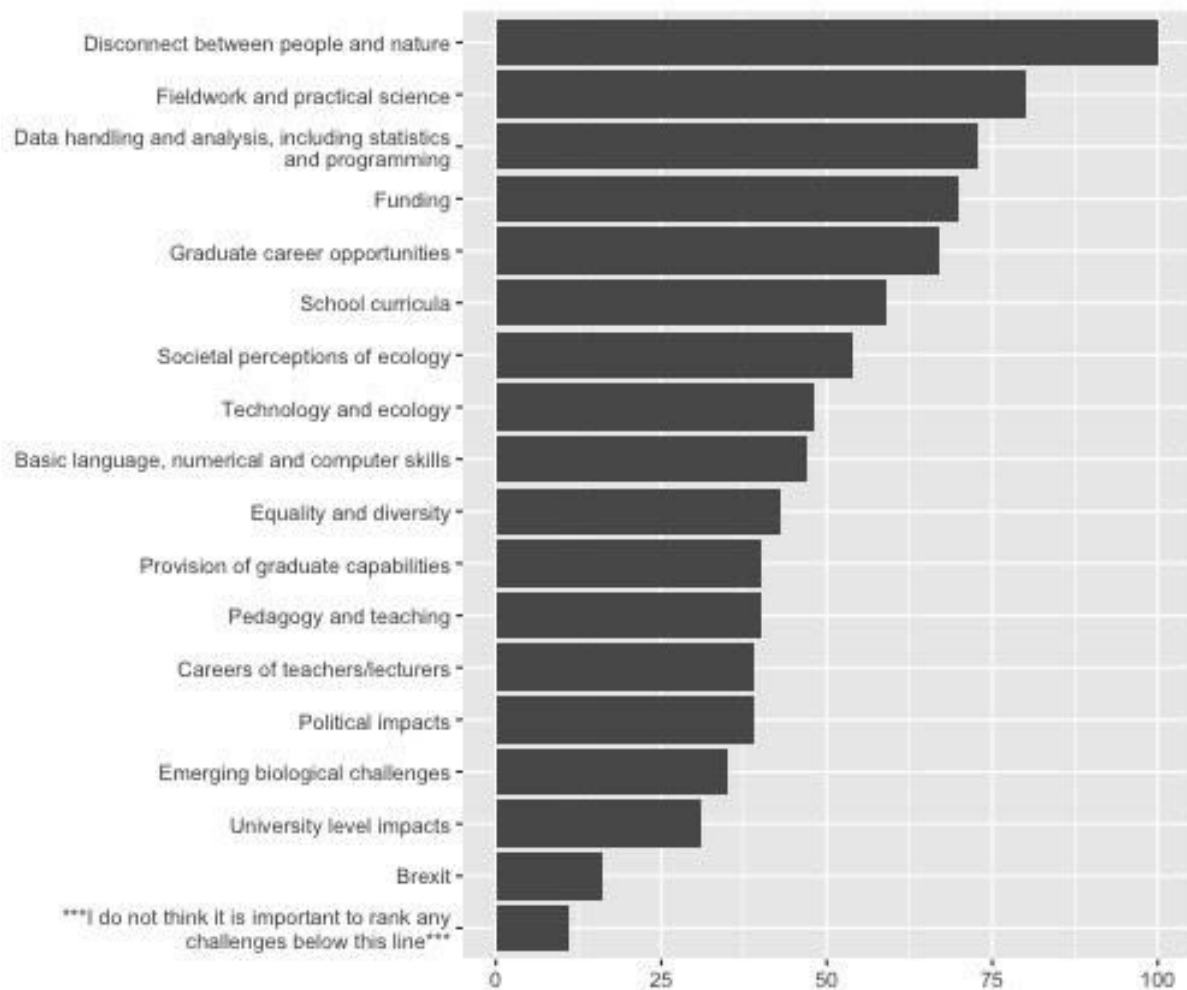
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1178 **Figures S1-14. Rankings of main categories and subcategories.** Rankings were
 1179 determined by first translating the ordering of issues, applied by each respondent, into
 1180 numbers by assigning the highest ranked issue a score of n (where n = number of issues in
 1181 the category), then second ranked allocated n-1 etc. For example, in the main categories,
 1182 where there were 17 issues, if a respondent ranked “Disconnect between people and nature”
 1183 first, it was given 17 points. The ***I don’t want to rank below this line*** option was also given
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 1185 line** were automatically scored equal last. Scores were then summed for each issue across
 1186 participants and these totals used to determine the overall ranking with highest scores
 1187 representing the highest ranked issues. Here they are presented as relative rankings with the
 1188 highest given a score of 100, and all other rankings listed in proportion to this. Rankings of
 1189 subcategories not explicitly discussed at the workshop are not included.

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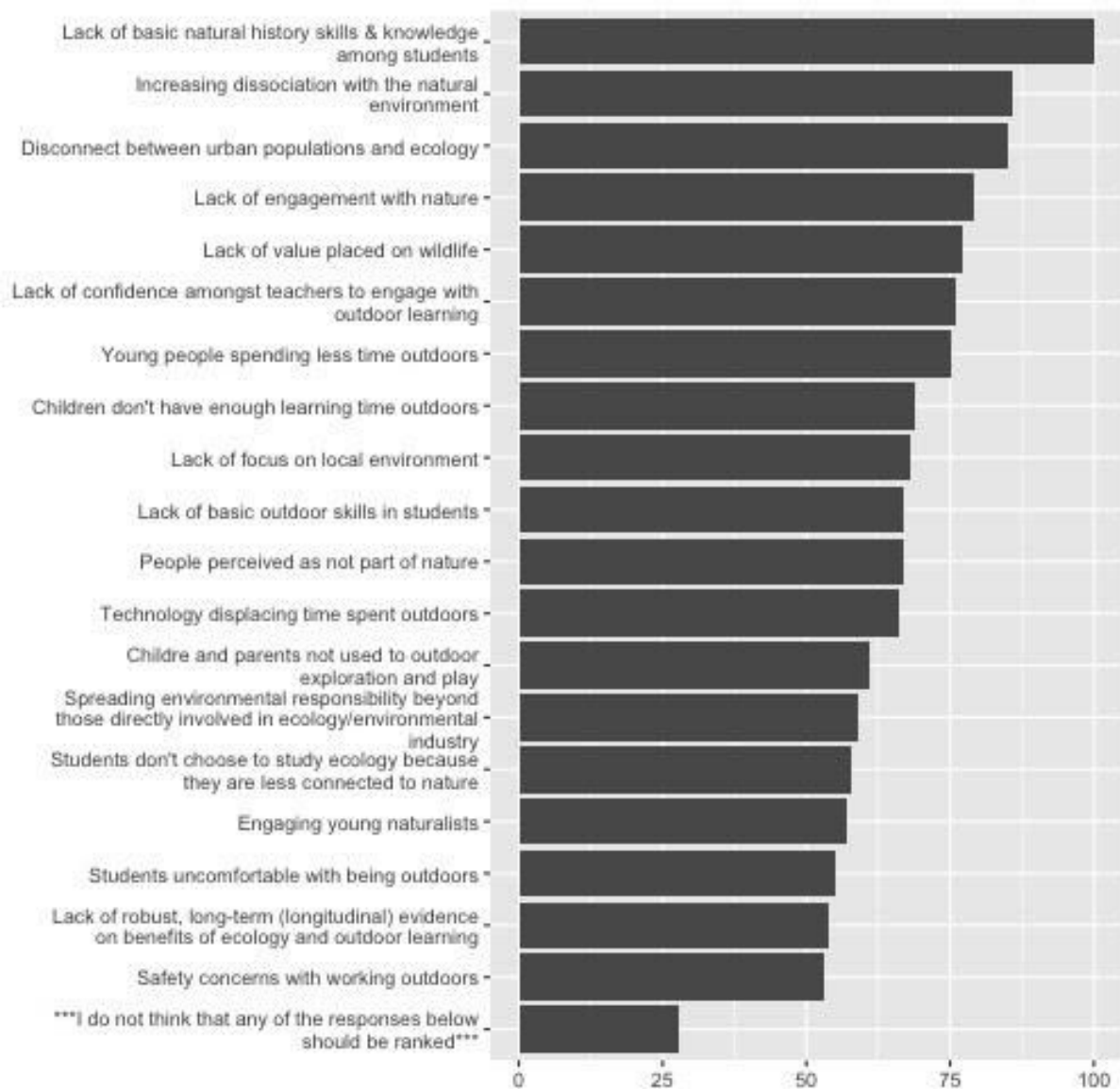
1191 Figure S1. Rankings of main categories



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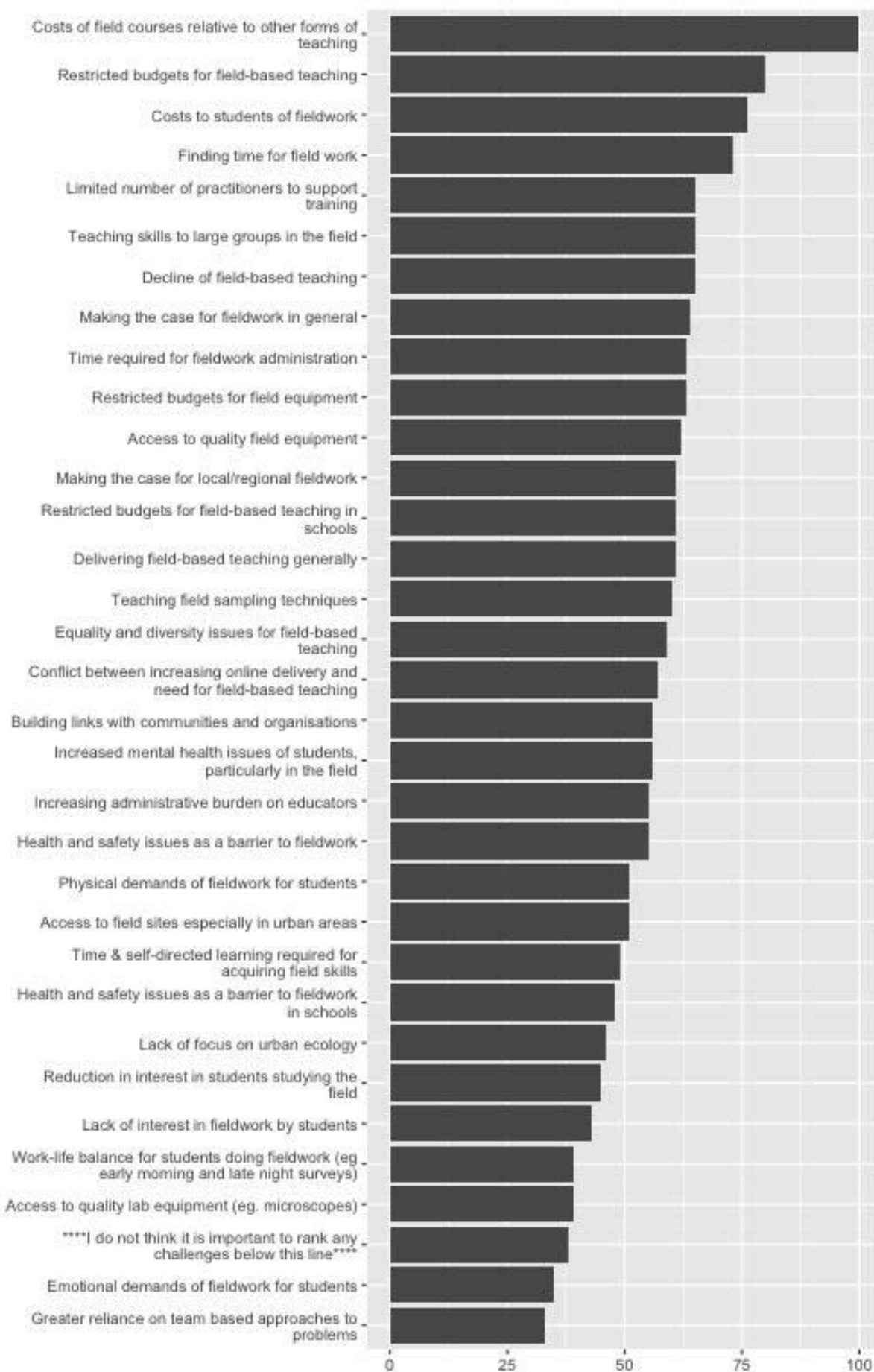
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1194 Figure S2. Rankings of issues associated with disconnect between people and nature



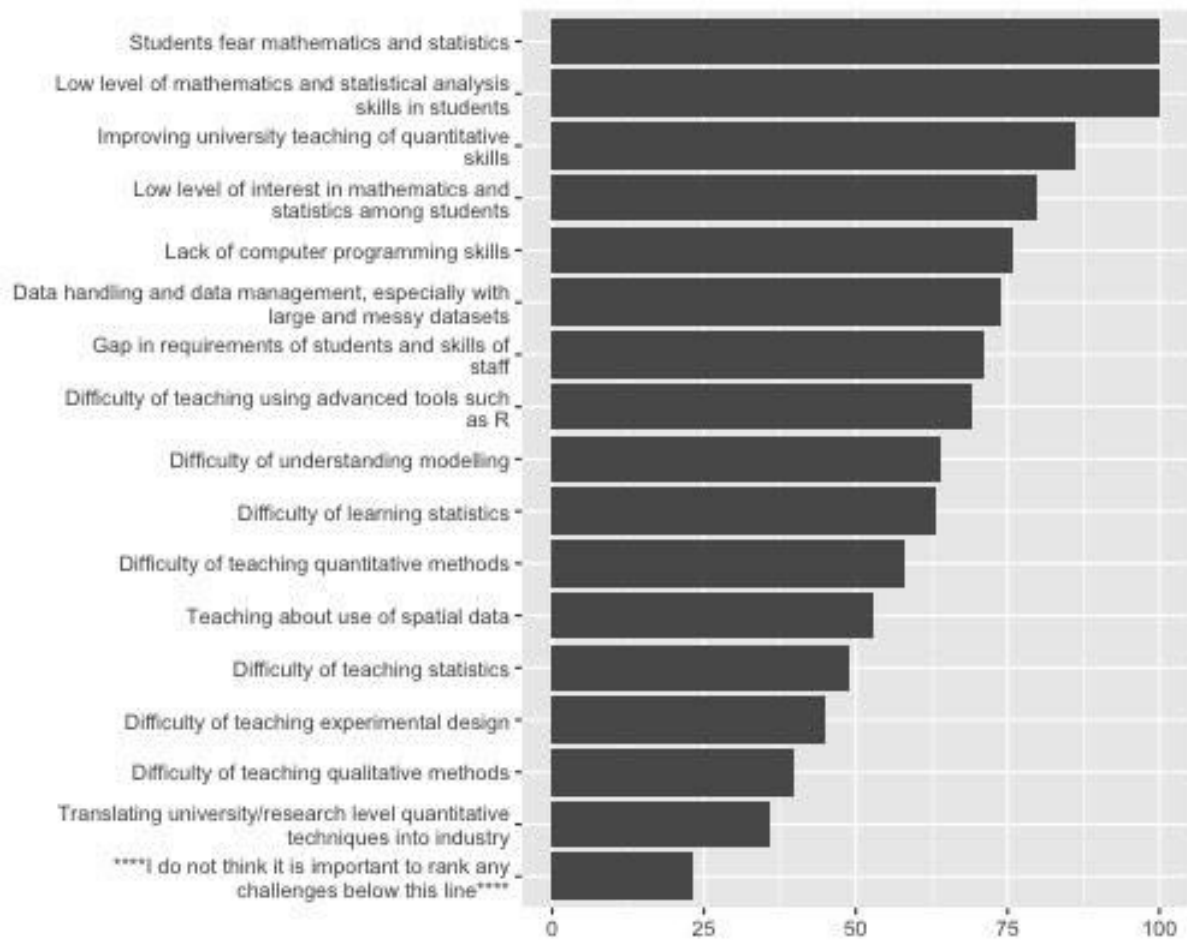
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Figure S3. Rankings of issues associated with fieldwork and practical science



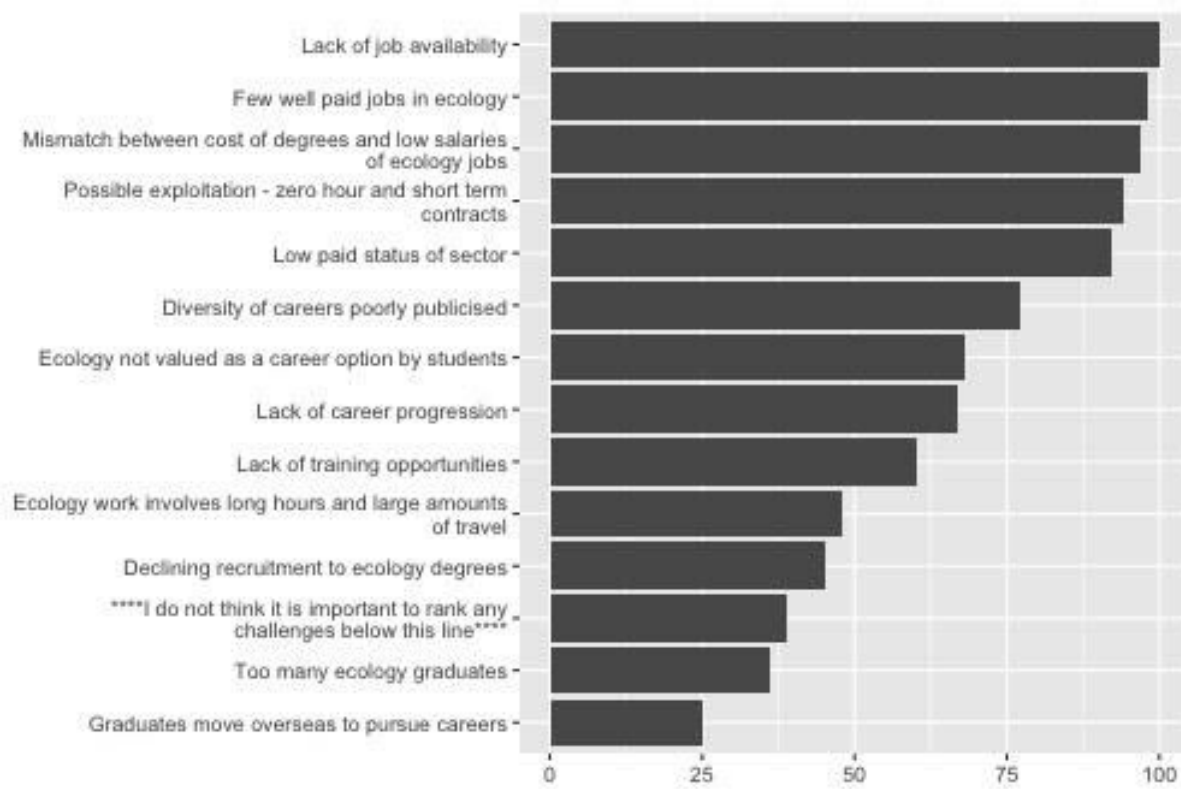
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Figure S4. Rankings of issues associated with data handling and analysis, including statistics and programming



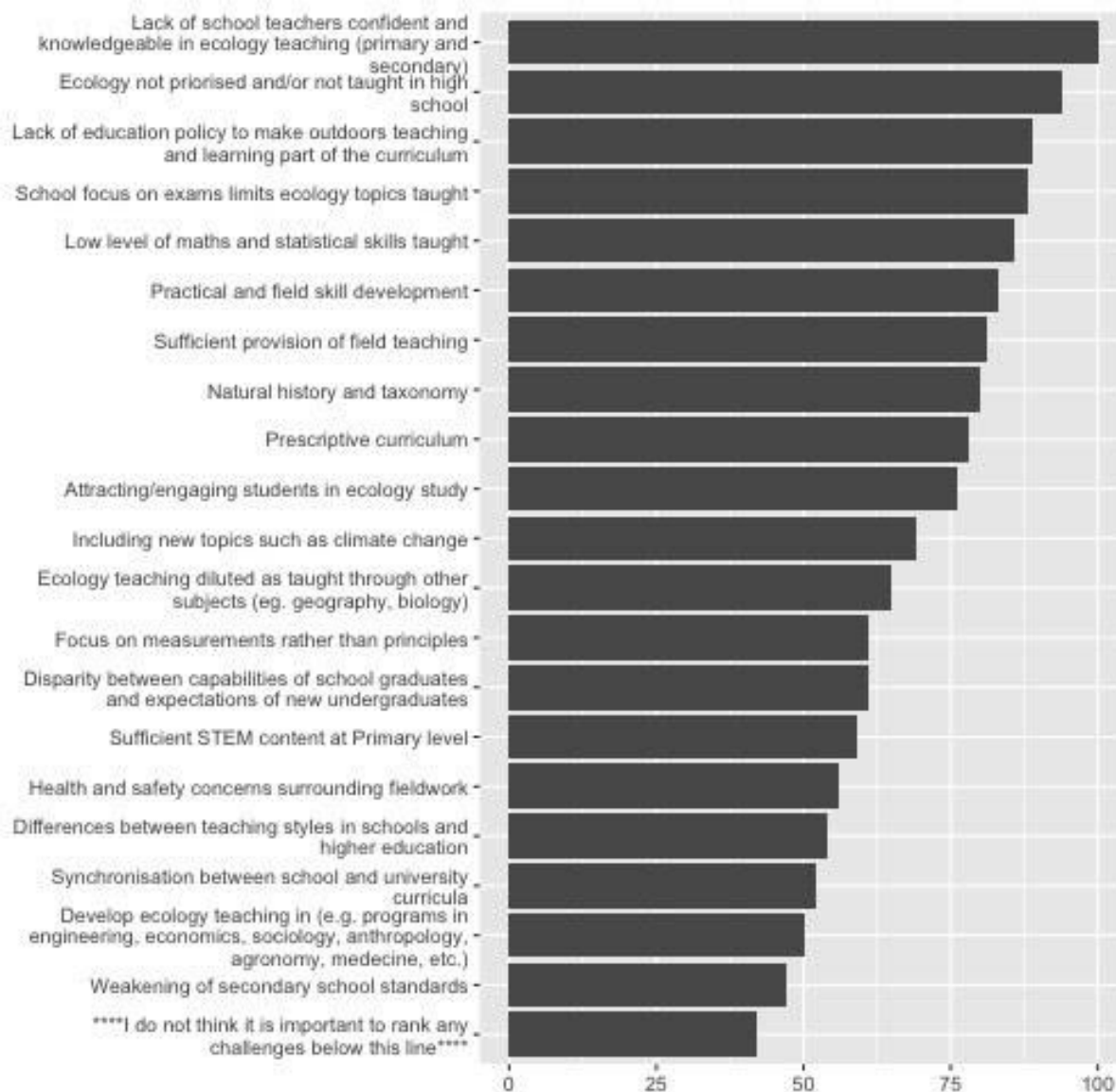
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Figure S5. Rankings of issues associated with graduate career opportunities



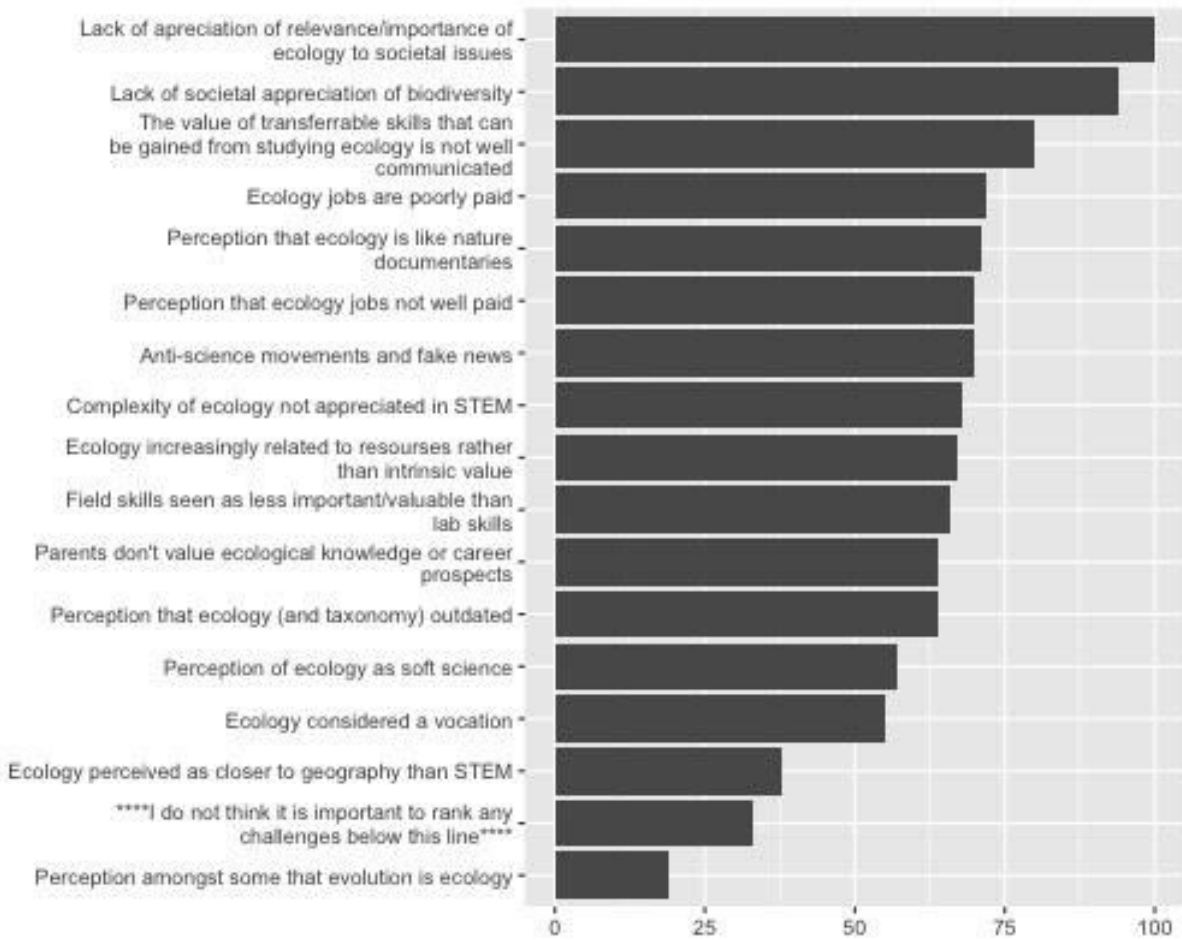
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Figure S6. Rankings of issues associated with school curricula



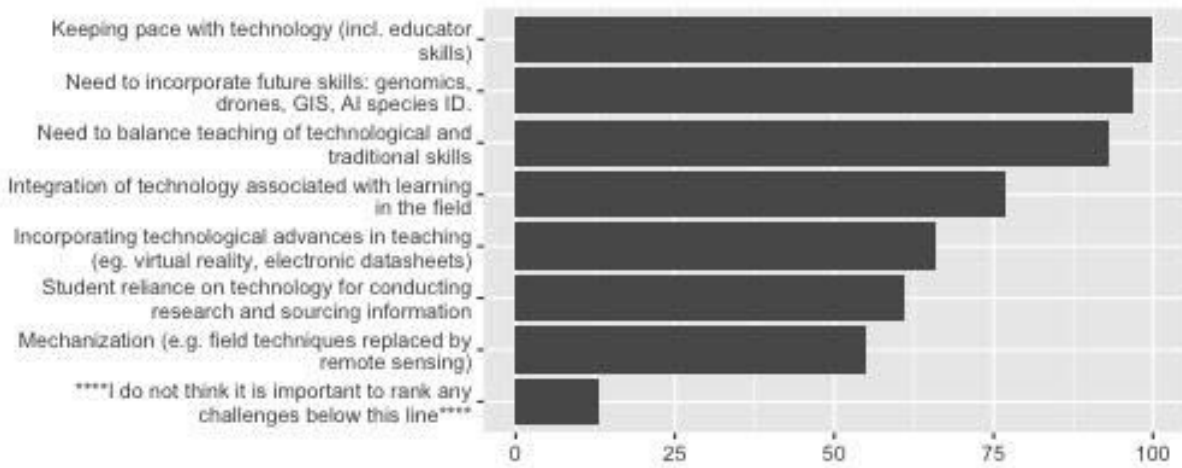
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Figure S7. Rankings of issues associated with society perceptions



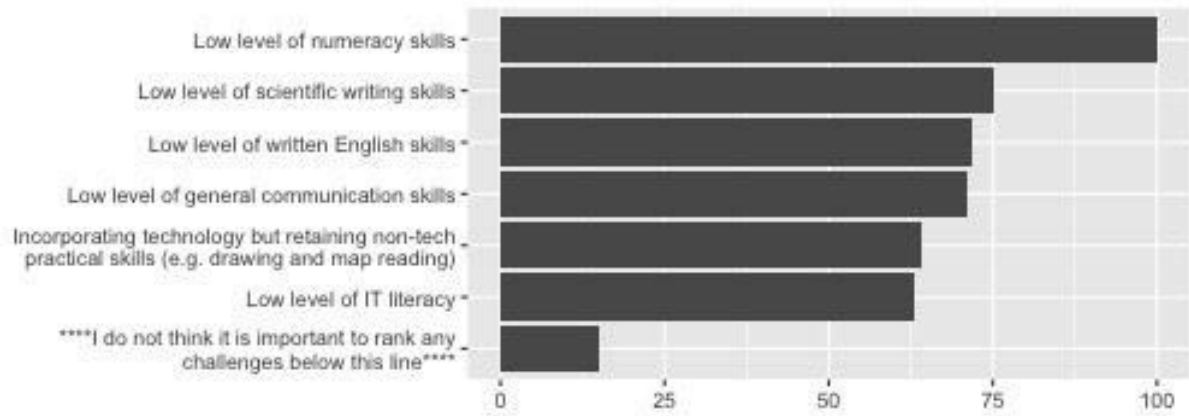
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Figure S8. Rankings of issues associated with technology and ecology



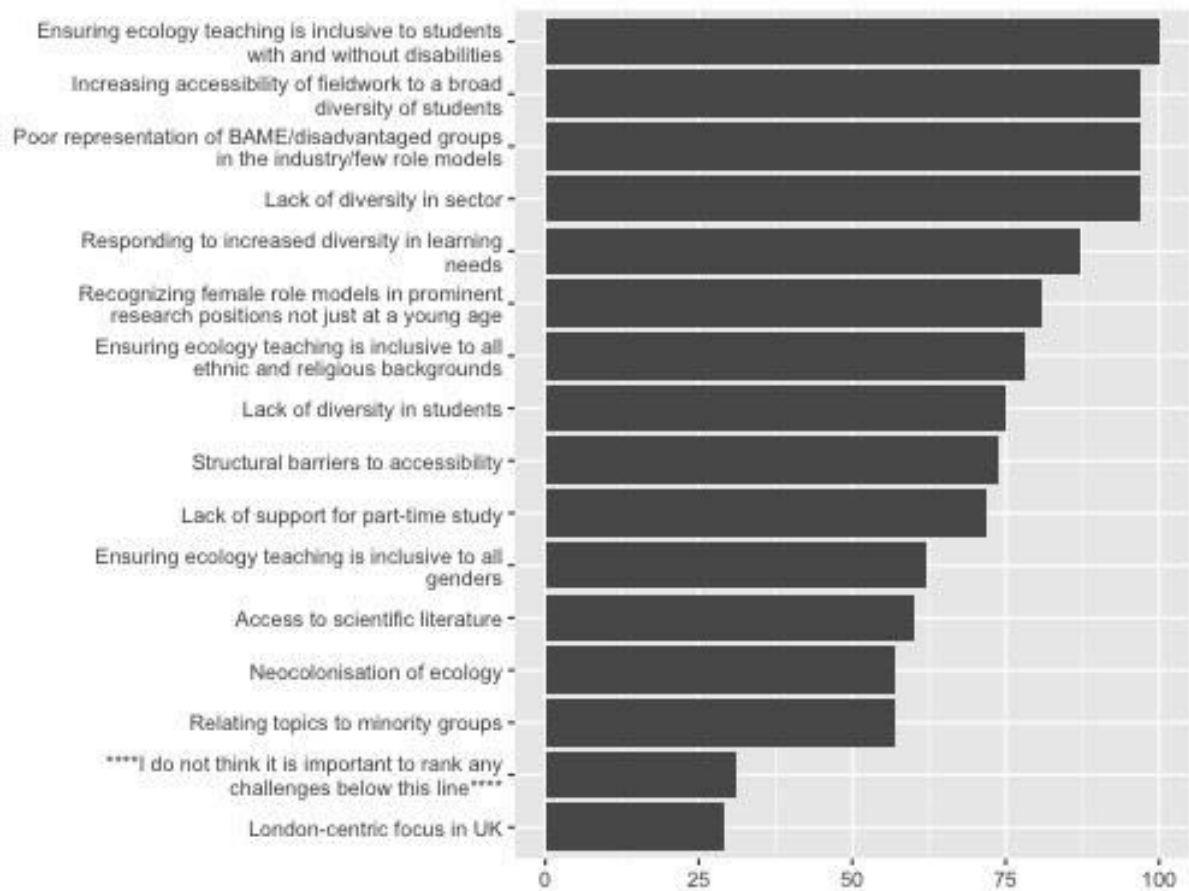
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Figure S9. Rankings of issues associated with basic language, numerical and computer skills



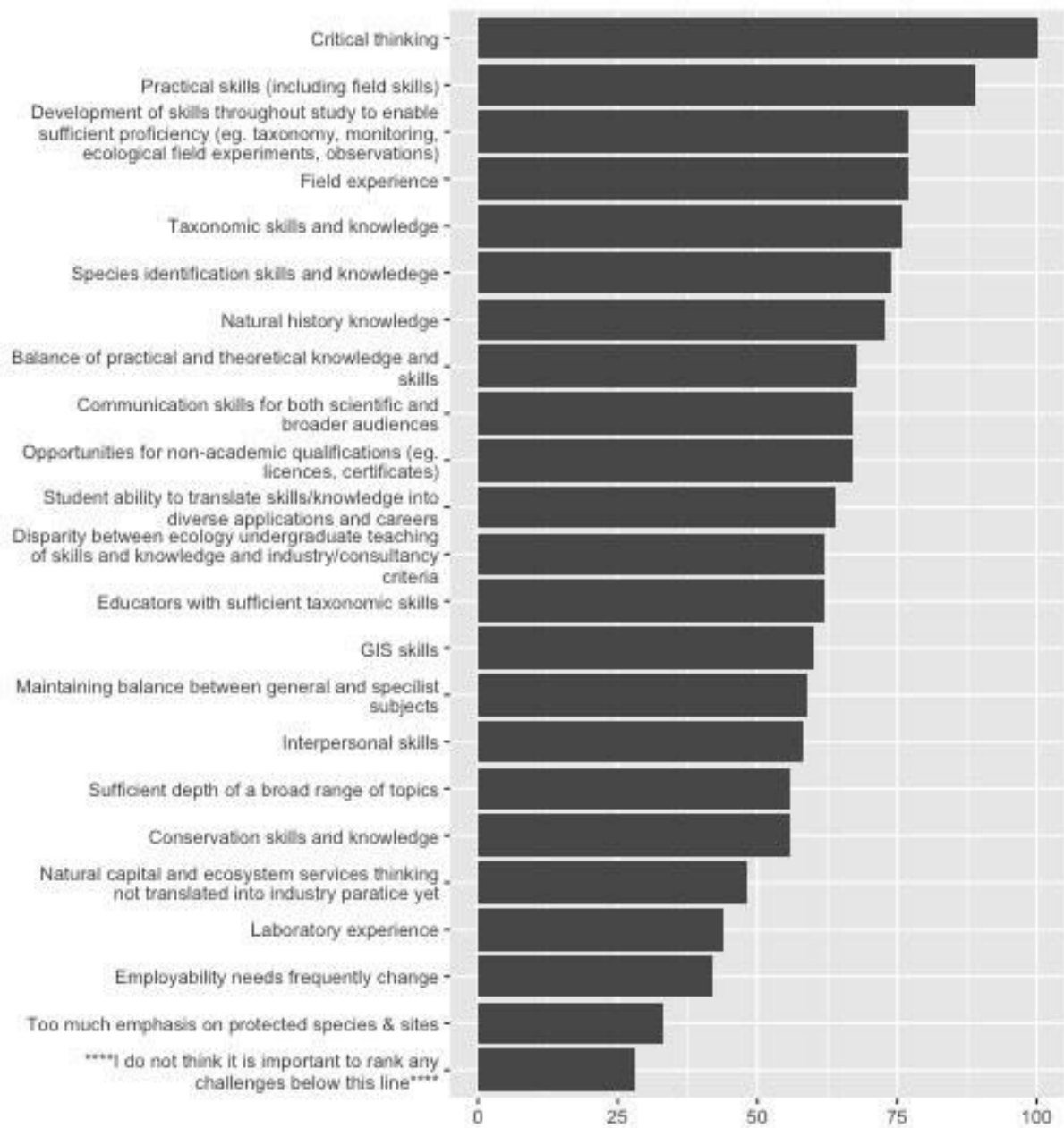
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Figure S10. Rankings of issues associated with equality and diversity



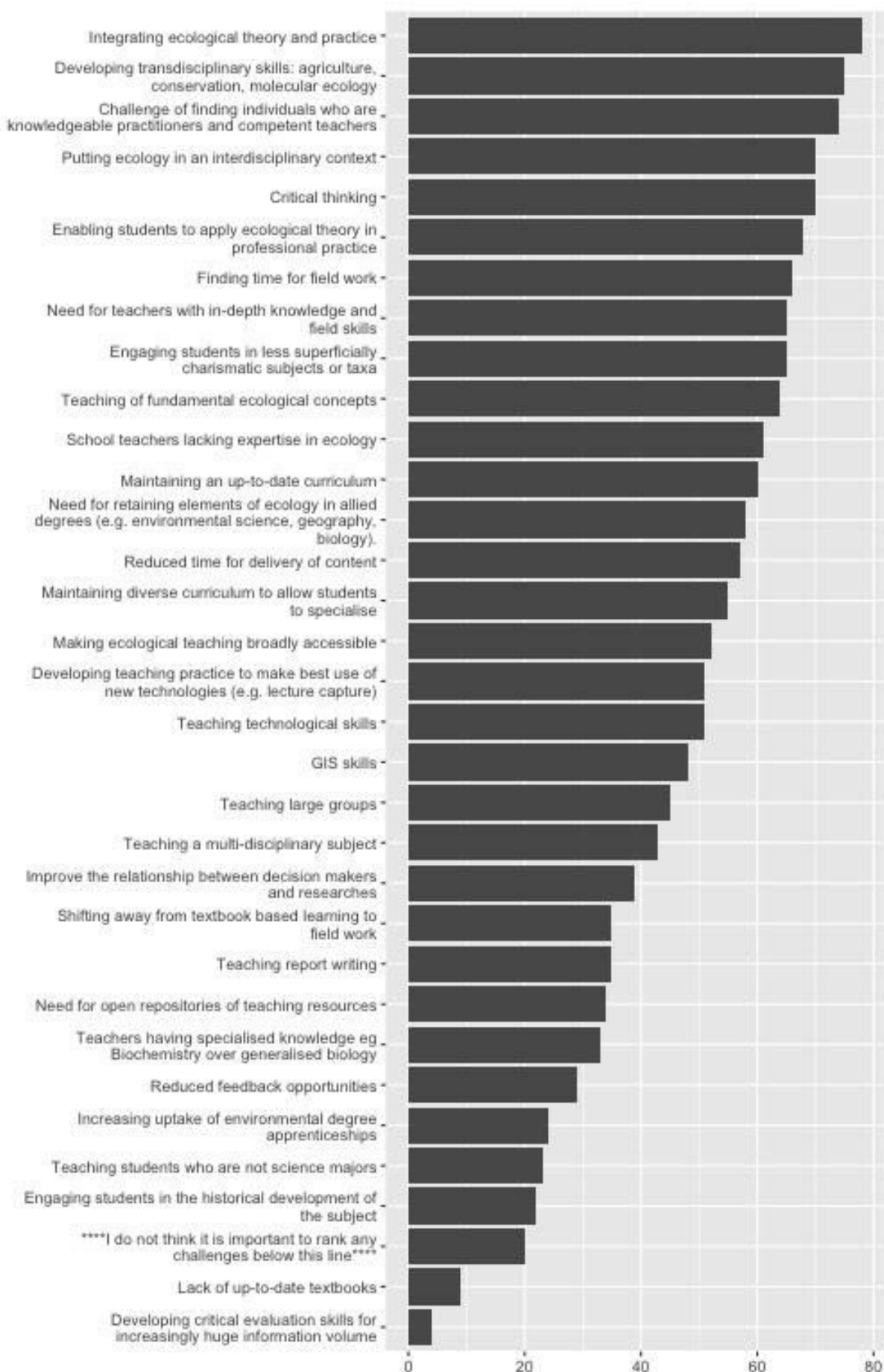
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Figure S11. Rankings of issues associated with the provision of graduate capabilities



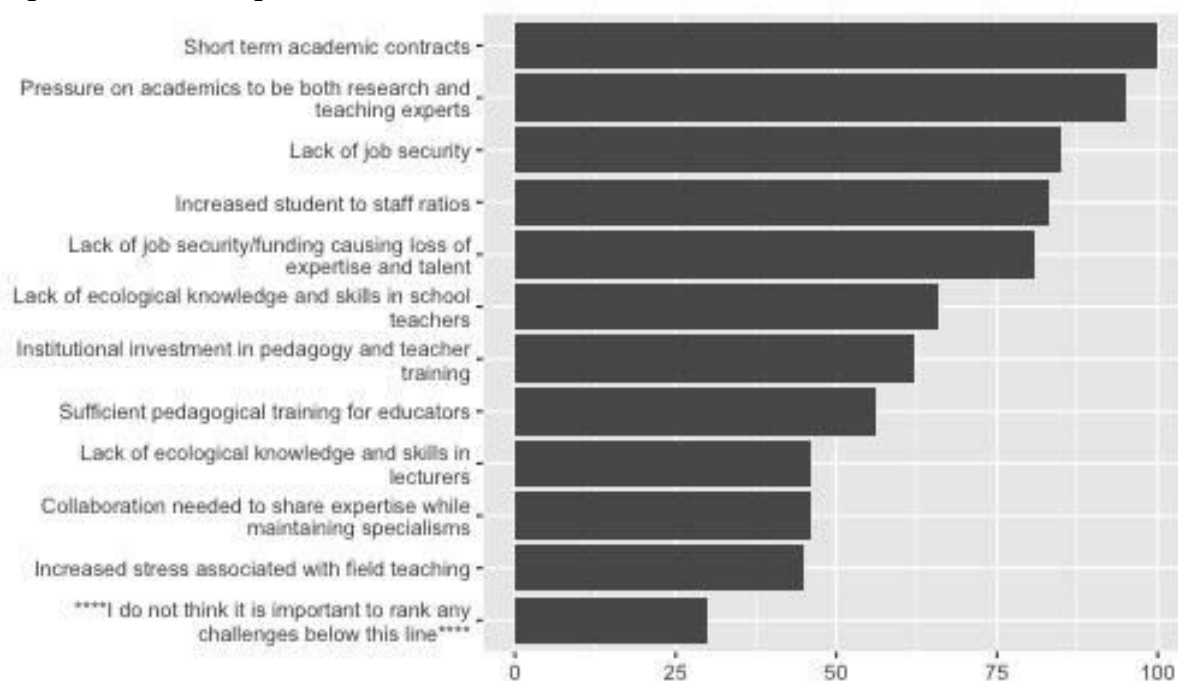
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Figure S12. Rankings of issues associated with pedagogy and teaching



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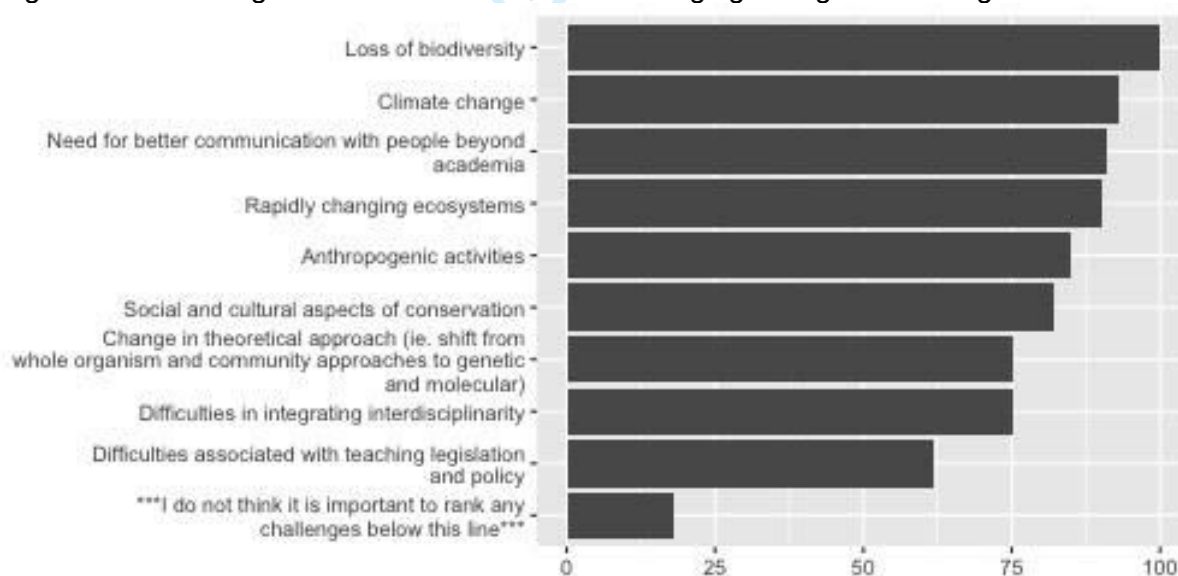
1231 Figure S13. Rankings of issues associated with the careers of teachers/lecturers



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1234 Figure S14. Rankings of issues associated with emerging biological challenges



1235

Supplementary Information

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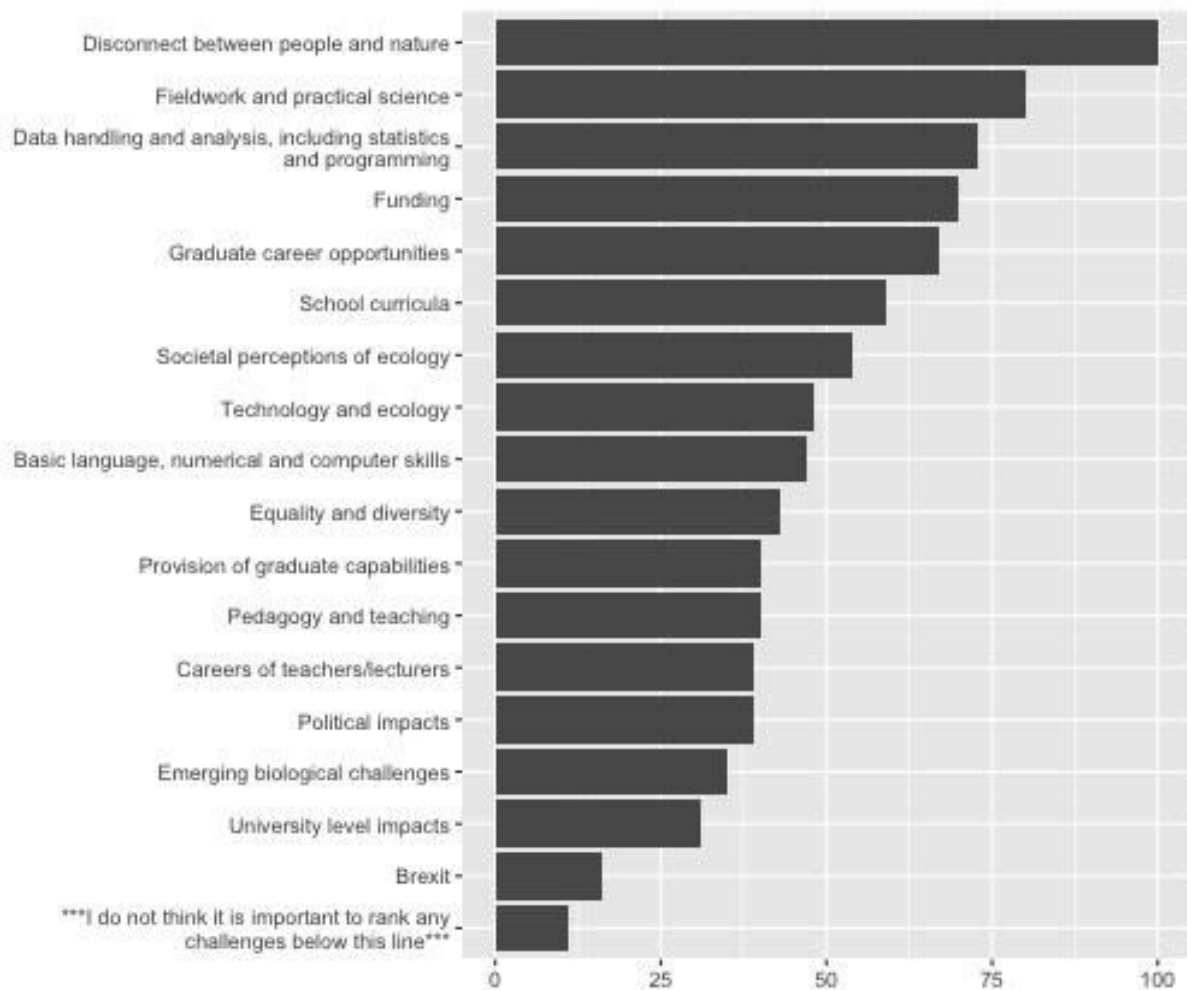


Figure S2. Rankings of issues associated with disconnect between people and nature

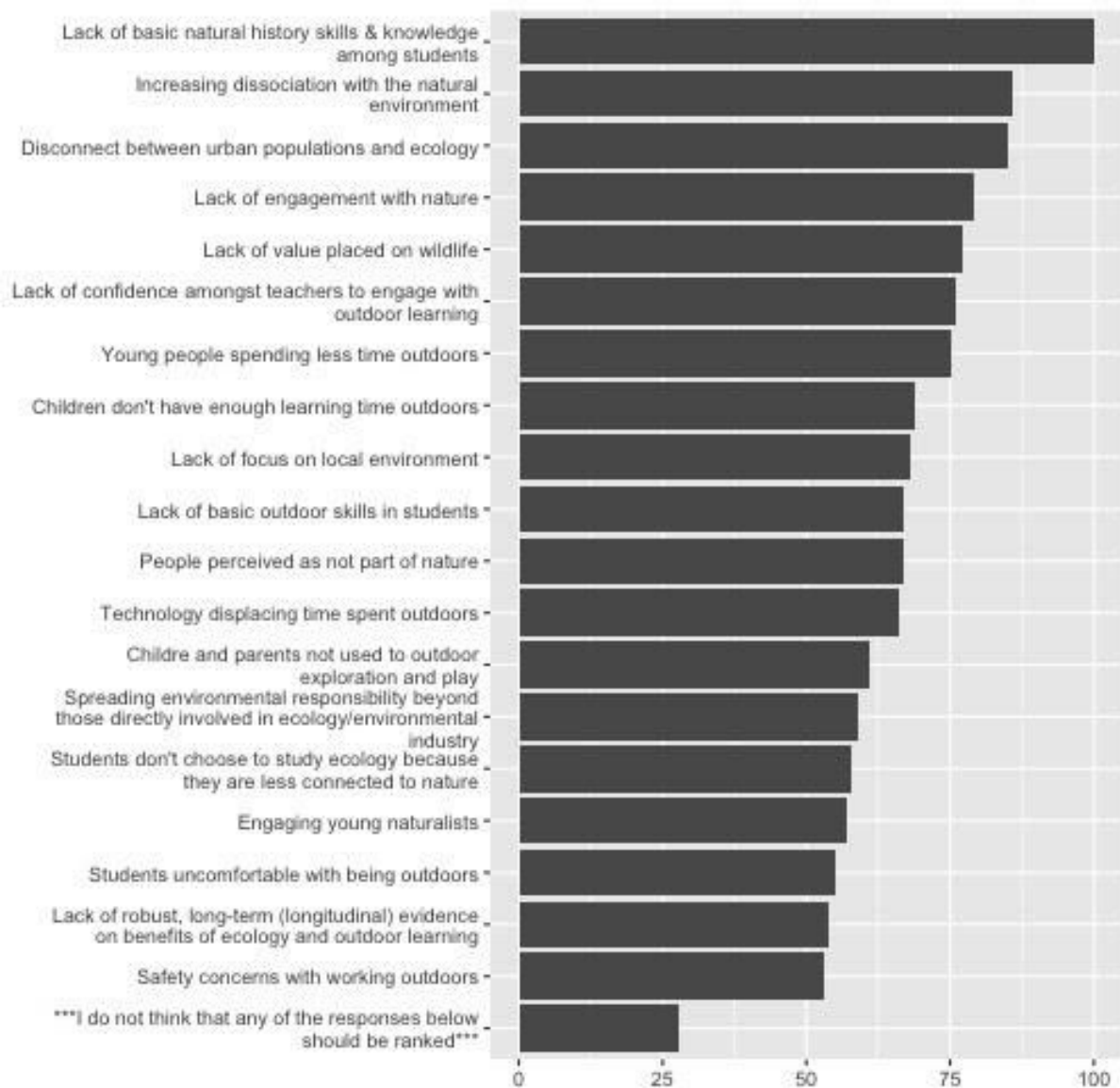


Figure S3. Rankings of issues associated with fieldwork and practical science

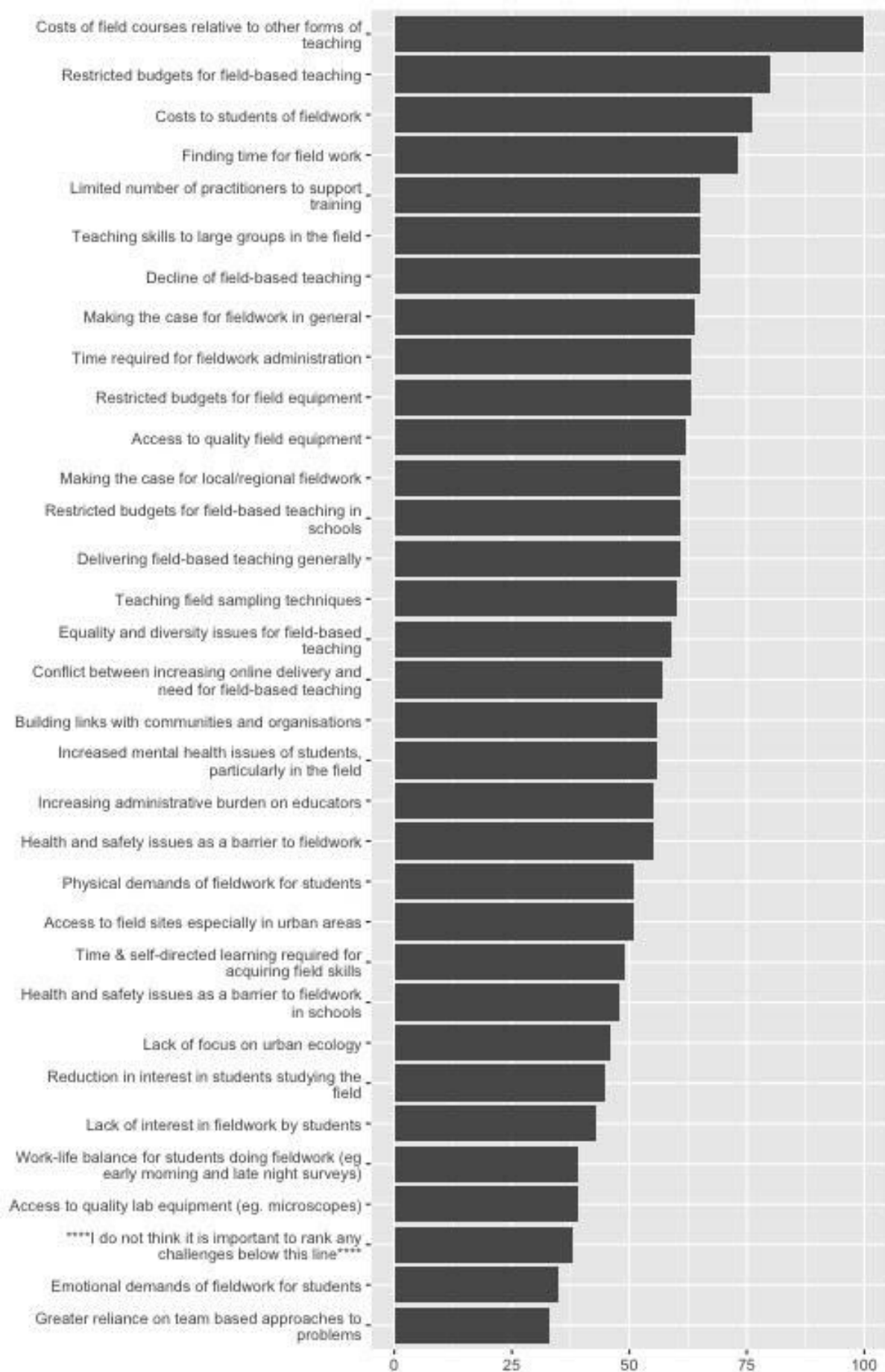


Figure S4. Rankings of issues associated with data handling and analysis, including statistics and programming

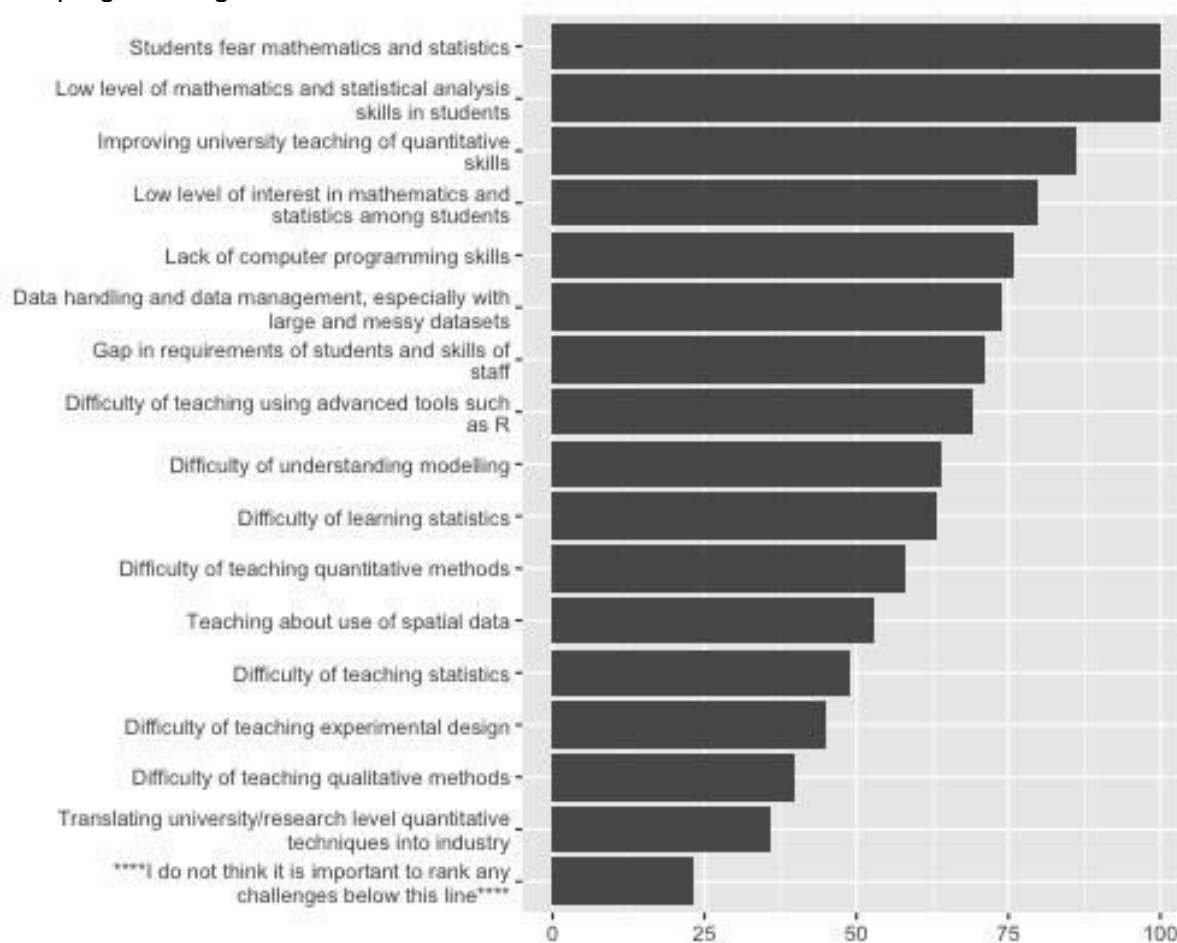


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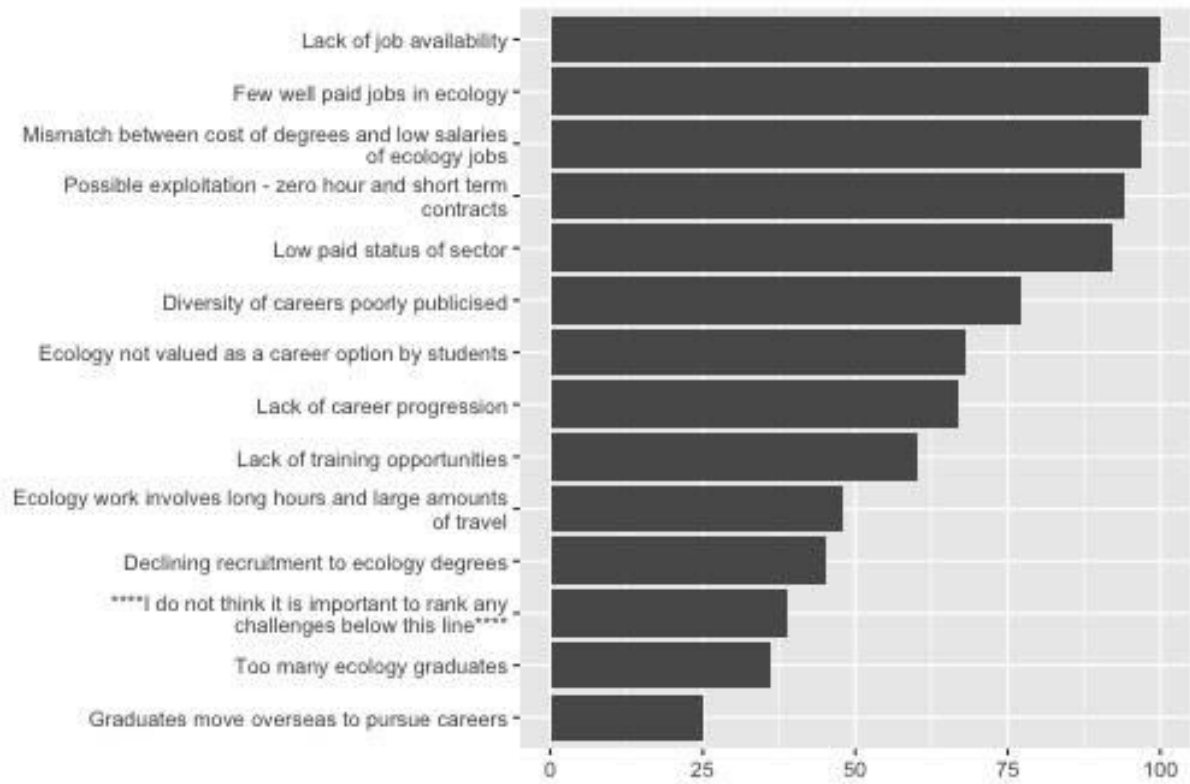


Figure S6. Rankings of issues associated with school curricula

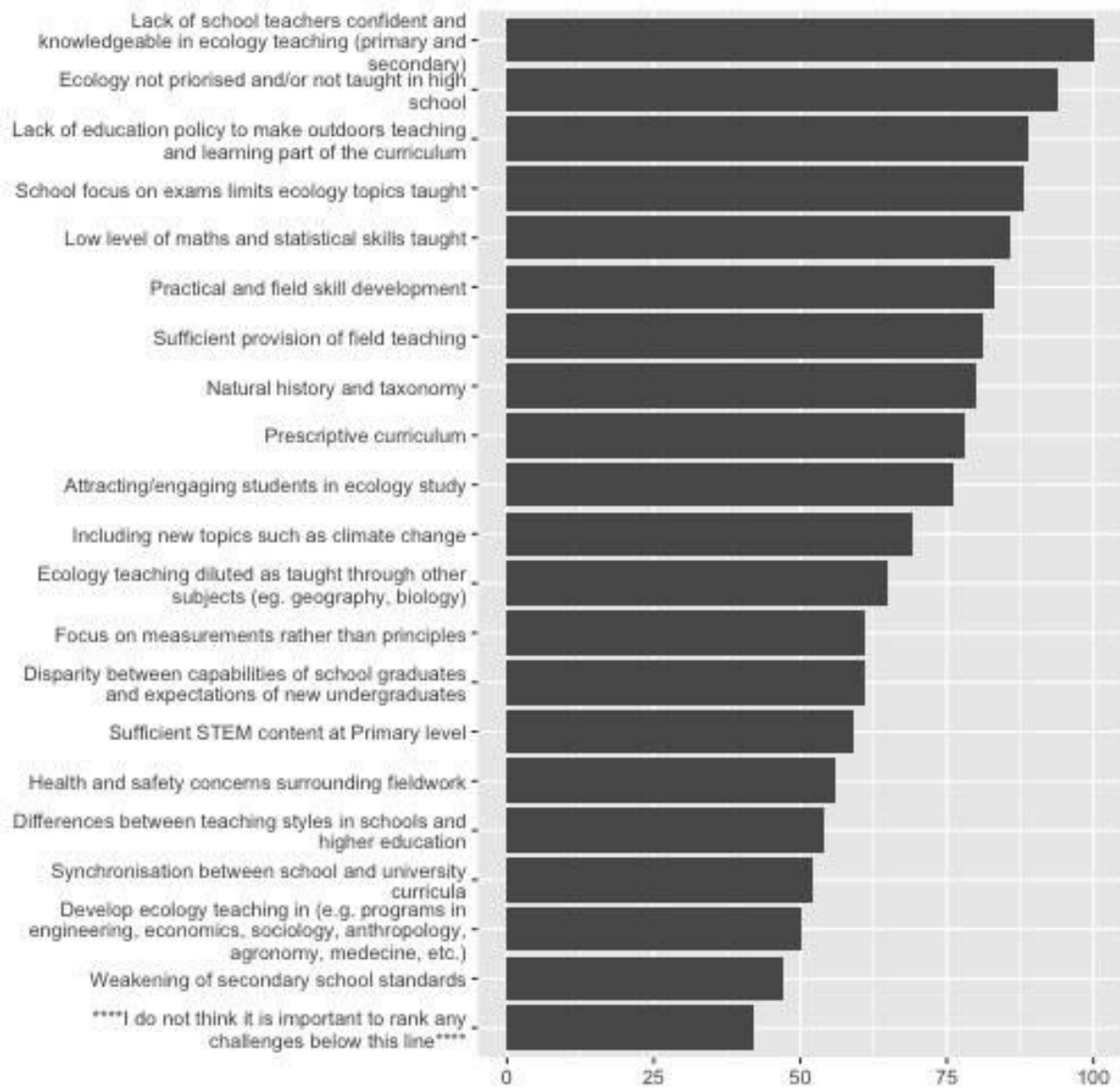


Figure S7. Rankings of issues associated with society perceptions

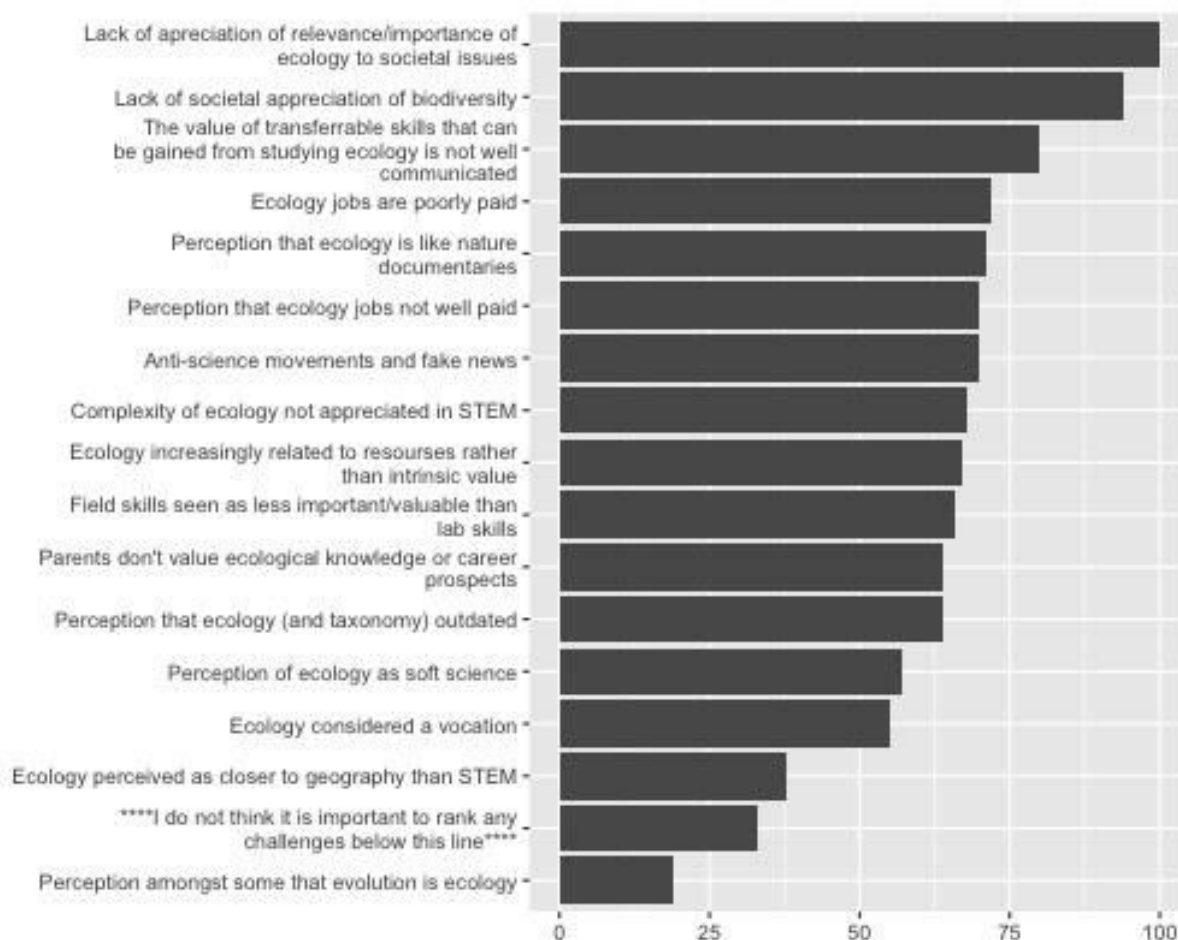


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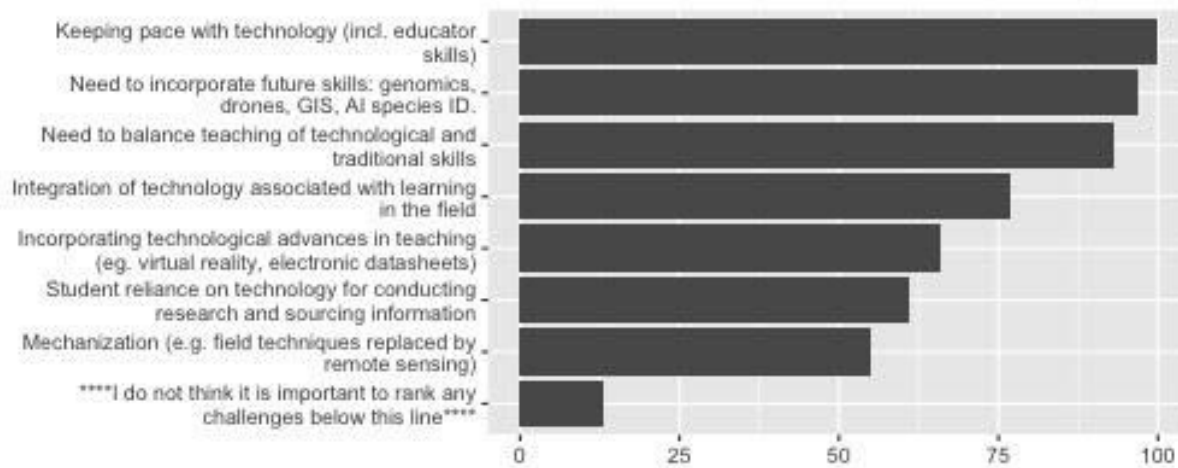


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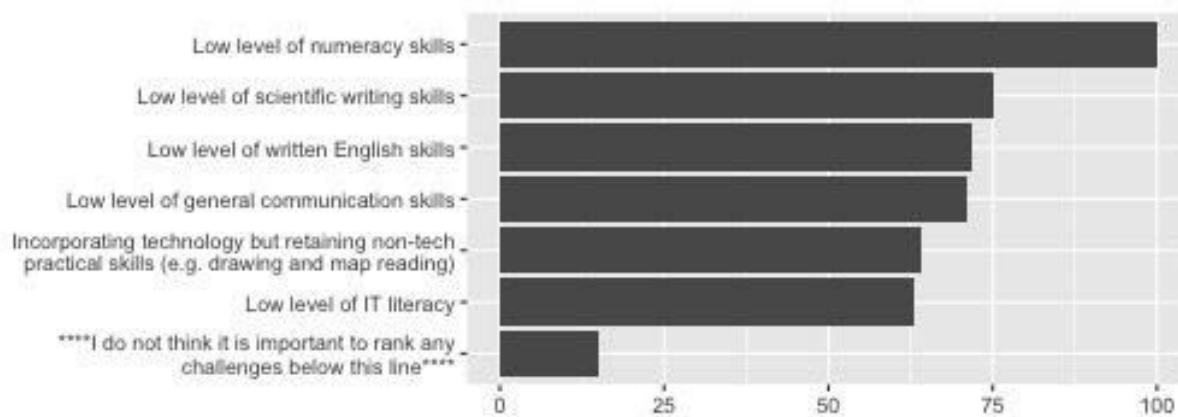


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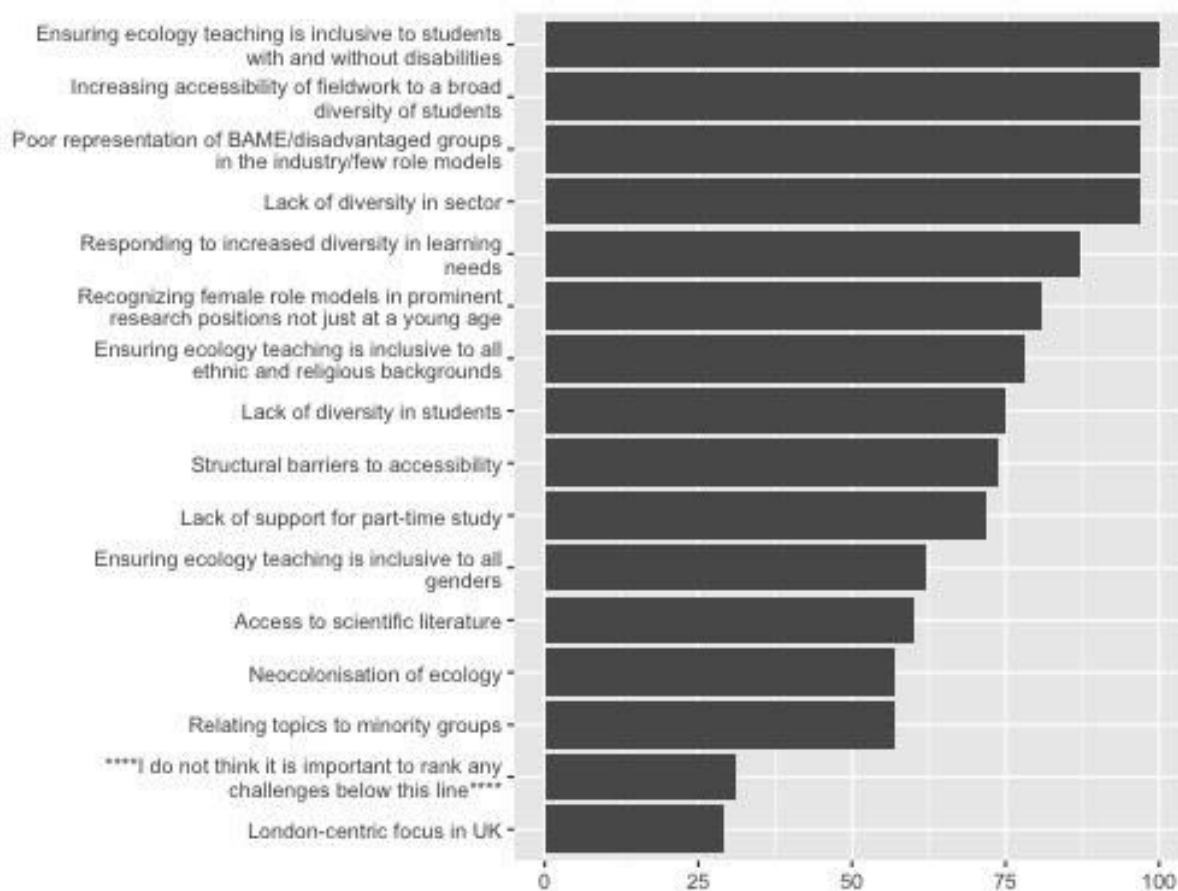


Figure S11. Rankings of issues associated with the provision of graduate capabilities

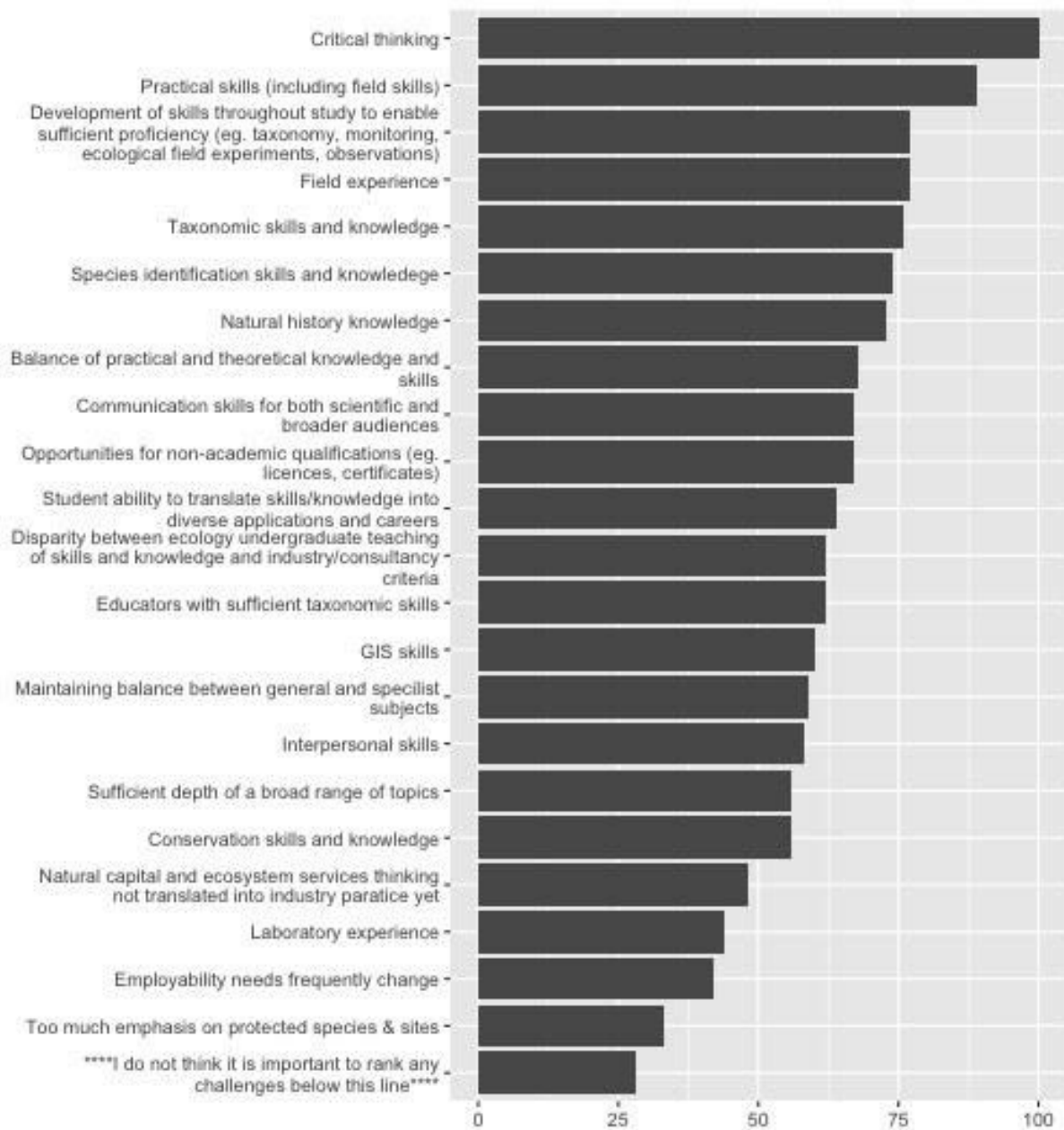


Figure S12. Rankings of issues associated with pedagogy and teaching

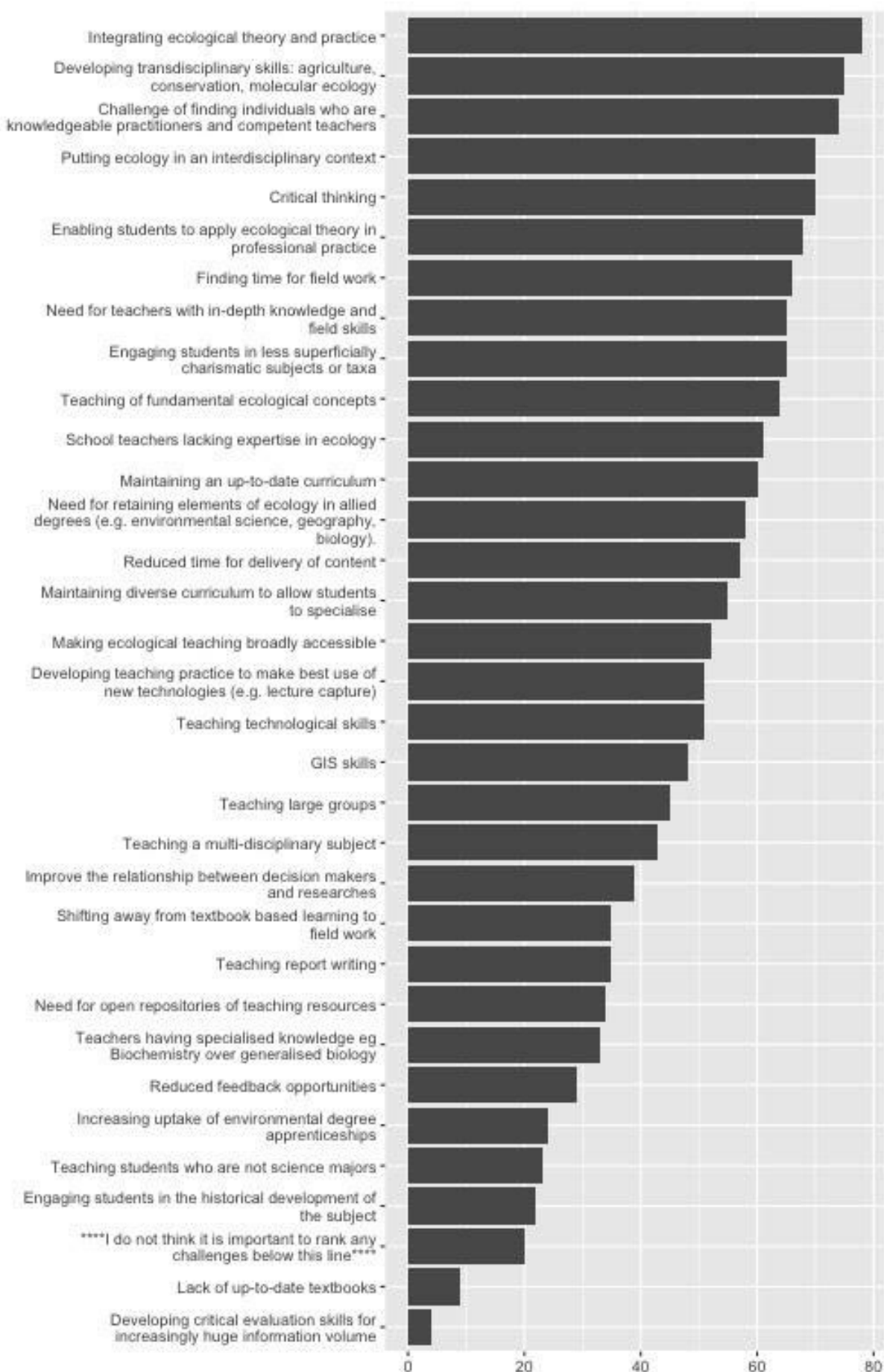


Figure S13. Rankings of issues associated with the careers of teachers/lecturers

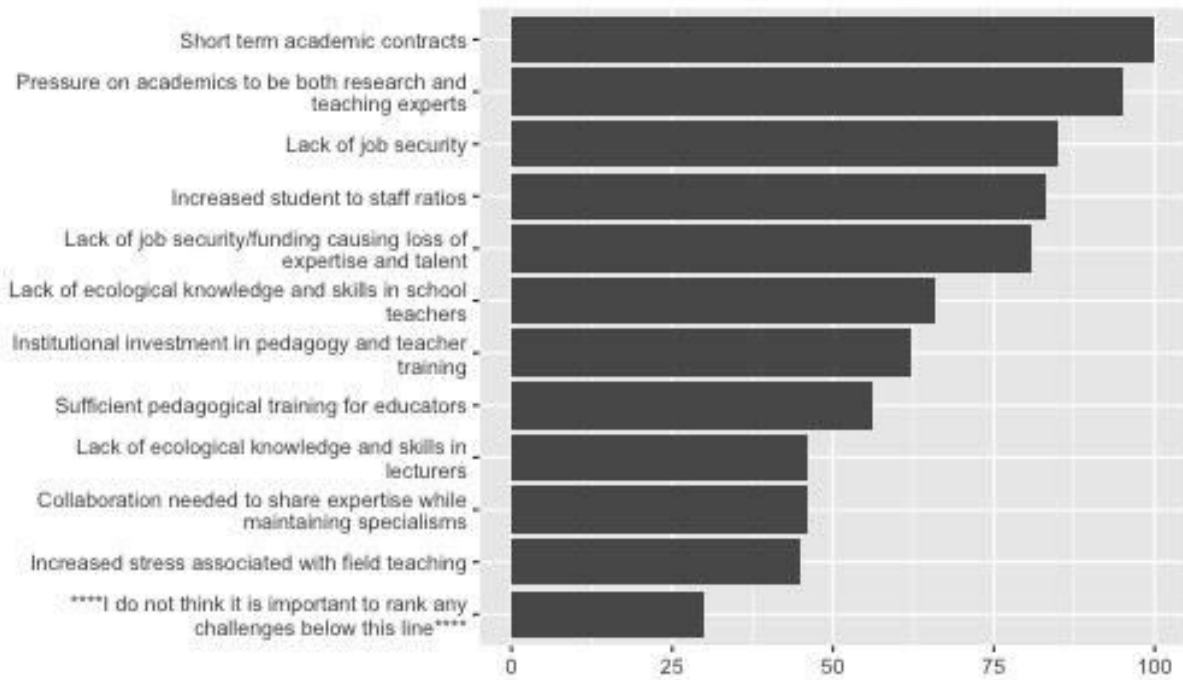


Figure S14. Rankings of issues associated with emerging biological challenges

