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Goddard, M, Davies, Z, Guenat, S et al. (74 more authors) (2021) A global horizon scan of the future impacts of robotics and autonomous systems on urban ecosystems. Nature Ecology and Evolution.

https://doi.org/10.1038/s41559-020-01358-z

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Figure #	Figure title	Filename	Figure Legend
	One sentence only	This should be the name the file is saved as when it is uploaded to our system. Please include the file extension. i.e.: <i>Smith_ED Fig1.jpg</i>	If you are citing a reference for the first time in these legends, please include all new references in the Online Methods References section, and carry on the numbering from the main References section of the paper.
Extended Data Fig. 1	The Global North (green) and Global South (blue), with countries represented by participants in round one of the horizon scan indicated with darker shading.	Goddard MA Figure_S1.jpg	The Global North (green) and Global South (blue), with countries represented by participants in round one of the horizon scan indicated with darker shading. Countries represented from the Global North were: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Ireland, Israel, Italy, Netherlands, New Zealand, Poland, Portugal, Romania, Spain, Sweden, Switzerland, United Kingdom and United States of America. Countries represented from the Global South were: Argentina, Brazil, Chile, China, Colombia, Ethiopia, India, Malawi, Malaysia, Mexico, Nigeria, South Africa and Togo.
Extended Data Fig. 2	Opportunities associated with robotics and automated systems for urban biodiversity and ecosystems	Goddard MA Figure_S2.jpg	Opportunities associated with robotics and automated systems for urban biodiversity and ecosystems according to participants working in the (a) research sector ( <i>n</i> = 66) and (b) other sectors ( <i>n</i> = 32). The distribution of summed participant scores (range: -8 to +8) across four criteria (likelihood, impact, extent, novelty) for each of the 32 opportunities. Items are ordered according to percentage of participants in (a) who gave summed scores greater than zero. Percentage values indicate the proportion of participants giving negative,

			neutral and positive scores (left hand side, central and right hand side of the shaded bars respectively). The full wording agreed by the participants for each opportunity can be found in Supplementary Table 1: 'mm' is an abbreviation for 'monitoring and management'; item number given in parenthesis is for cross referencing between figures and tables.
Extended Data Fig. 3	Challenges associated with robotics and automated systems for urban biodiversity and ecosystems for participants working in the (a) research sector ( <i>n</i> = 66) and (b) other sectors ( <i>n</i> = 32).	Goddard MA Figure_S3.jpg	Challenges associated with robotics and automated systems for urban biodiversity and ecosystems for participants working in the (a) research sector ( <i>n</i> = 66) and (b) other sectors ( <i>n</i> = 32). The distribution of summed participant scores (range: -8 to +8) across four criteria (likelihood, impact, extent, novelty) for each of the 38 challenges. Items are ordered according to percentage of participants in (a) who gave summed scores greater than zero. Percentage values indicate the proportion of participants giving negative, neutral and positive scores (left hand side, central and right hand side of the shaded bars respectively). The full wording agreed by the participants for each challenge can be found in Supplementary Table 1: 'mm' is an abbreviation for 'monitoring and management'; item number given in parenthesis is for cross referencing between figures and tables
Extended	Opportunities	Goddard MA	Opportunities associated

Data Fig. 4	associated with robotics and automated systems for urban biodiversity and ecosystems according to participants based in (a) the Global North ( <i>n</i> = 87) and (b) the Global South ( <i>n</i> = 11).	Figure_S4.jpg	with robotics and automated systems for urban biodiversity and ecosystems according to participants based in (a) the Global North ( <i>n</i> = 87) and (b) the Global South ( <i>n</i> = 11). The distribution of summed participant scores (range: -8 to +8) across four criteria (likelihood, impact, extent, novelty) for each of the 32 opportunities. Items are ordered according to percentage of participants in (a) who gave summed scores greater than zero. Percentage values indicate the proportion of participants giving negative, neutral and positive scores (left hand side, central and right hand side of the shaded bars respectively). The full wording agreed by the participants for each opportunity can be found in Supplementary Table 1: 'mm' is an abbreviation for 'monitoring and management'; item number given in parenthesis is for cross referencing between figures and tables.
Extended Data Fig. 5	Challenges associated with robotics and automated systems for urban biodiversity and ecosystems according to participants based in (a) the Global North ( $n =$ 87) and (b) the Global South ( $n =$ 11).	Goddard MA Figure_S5.jpg	Challenges associated with robotics and automated systems for urban biodiversity and ecosystems according to participants based in (a) the Global North ( <i>n</i> = 87) and (b) the Global South ( <i>n</i> = 11). The distribution of summed participant scores (range: -8 to +8) across four criteria (likelihood, impact, extent, novelty) for each of the 38 challenges. Items are ordered according to percentage of participants in (a) who gave summed scores greater than

			zero. Percentage values indicate the proportion of participants giving negative, neutral and positive scores (left hand side, central and right hand side of the shaded bars respectively). Boxes and * indicate a significant difference between the proportions of participants in (a) and (b) scoring the item greater than zero. The full wording agreed by the participants for each challenge can be found in Supplementary Table 1: 'mm' is an abbreviation for 'monitoring and management'; item number given in parenthesis is for cross referencing between figures and tables.
Extended Data Fig. 6	Opportunities associated with robotics and automated systems for urban biodiversity and ecosystems according to participants with (a) environmental expertise ( <i>n</i> = 65) and those with (b) non-environmental expertise ( <i>n</i> = 33).	Goddard MA Figure_S6.jpg	Opportunities associated with robotics and automated systems for urban biodiversity and ecosystems according to participants with (a) environmental expertise ( <i>n</i> = 65) and those with (b) non-environmental expertise ( <i>n</i> = 33). The distribution of summed participant scores (range: -8 to +8) across four criteria (likelihood, impact, extent, novelty) for each of the 32 opportunities. Items are ordered according to percentage of participants in (a) who gave summed scores greater than zero. Percentage values indicate the proportion of participants giving negative, neutral and positive scores (left hand side, central and right hand side of the shaded bars respectively). Boxes and * indicate a significant difference between the

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Extended Data Fig. 7	Challenges associated with robotics and automated systems for urban biodiversity and ecosystems according to participants with (a) environmental expertise ( <i>n</i> = 65) and those with (b) non-environmental expertise ( <i>n</i> = 33).	Goddard MA Figure_S7.jpg	Challenges associated with robotics and automated systems for urban biodiversity and ecosystems according to participants with (a) environmental expertise ( <i>n</i> = 65) and those with (b) non-environmental expertise ( <i>n</i> = 33). The distribution of summed participant scores (range: -8 to +8) across four criteria (likelihood, impact, extent, novelty) for each of the 38 challenges. Items are ordered according to percentage of participants in (a) who gave summed scores greater than zero. Percentage values indicate the proportion of participants giving negative, neutral and positive scores (left hand side, central and right hand side of the shaded bars respectively). Boxes and * indicate a significant difference between the proportions of participants in (a) and (b) scoring the item greater than zero. The full wording agreed by the participants for each challenge can be found in Supplementary Table 1: 'mm' is an abbreviation for 'monitoring and management';

	item number given in parenthesis is for cross referencing between figures and tables.

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Supplementary Information	Yes	Goddard RAS Supplementary Info Oct 2020 No Figures.pdf	Supplementary Table 1
Reporting Summary	Yes	nr-reporting-summary Goddard et al Oct 2020.pdf	

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A global horizon scan of the future impacts of robotics and autonomous
 systems on urban ecosystems

6

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134 Technology is transforming societies worldwide. A significant innovation is the 135 emergence of robotics and autonomous systems (RAS), which have the potential to 136 revolutionise cities for both people and nature. Nonetheless, the opportunities and 137 challenges associated with RAS for urban ecosystems have yet to be considered 138 systematically. Here, we report the findings of an online horizon scan involving 170 139 expert participants from 35 countries. We conclude that RAS are likely to transform 140 land-use, transport systems and human-nature interactions. The prioritised 141 opportunities were primarily centred on the deployment of RAS for monitoring and 142 management of biodiversity and ecosystems. Fewer challenges were prioritised. 143 Those that were emphasised concerns surrounding waste from unrecovered RAS, 144 and the quality and interpretation of RAS-collected data. Although the future impacts 145 of RAS for urban ecosystems are hard to predict, examining potentially important 146 developments early is essential if we are to avoid detrimental consequences, but fully 147 realise the benefits.

148

149 We are currently witnessing the fourth industrial revolution<sup>1</sup>. Technological innovations have 150 altered the way in which economies operate, and how people interact with built, social and 151 natural environments. One area of transformation is the emergence of robotics and 152 autonomous systems (RAS), defined as technologies that can sense, analyse, interact with 153 and manipulate their physical environment<sup>2</sup>. RAS include unmanned aerial vehicles 154 (drones), self-driving cars, robots able to repair infrastructure, and wireless sensor networks 155 used for monitoring. RAS therefore have a large range of potential applications, such as autonomous transport, waste collection, infrastructure maintenance and repair, policing<sup>2,3</sup>, 156 and precision agriculture<sup>4</sup> (Figure 1). RAS have already revolutionised how environmental 157 data are collected<sup>5</sup>, and species populations are monitored for conservation<sup>6</sup> and/or control<sup>7</sup>. 158 159 Globally, the RAS market is projected to grow from \$6.2 billion in 2018 to \$17.7 billion in 2026<sup>8</sup>. 160

162 Concurrent with this technological revolution, urbanisation continues at an unprecedented 163 rate. By 2030, an additional 1.2 million km<sup>2</sup> of the planet's surface will be covered by towns 164 and cities, with ~90% of this development happening in Africa and Asia. Indeed, 7 billion 165 people will live in urban areas by 2050<sup>9</sup>. Urbanisation causes habitat loss, fragmentation and 166 degradation, as well as alters local climate, hydrology and biogeochemical cycles, resulting in novel urban ecosystems with no natural analogs<sup>10</sup>. When poorly planned and executed, 167 168 urban expansion and densification can lead to substantial declines in many aspects of 169 human well-being<sup>11</sup>.

170

171 Presently, we have little appreciation of the pathways through which the widespread uptake and deployment of RAS could affect urban biodiversity and ecosystems<sup>12,13</sup>. To date, 172 173 information on how RAS may impact urban biodiversity and ecosystems remains scattered 174 across multiple sources and disciplines, if it has been recorded at all. The widespread use of RAS has been proposed as a mechanism to enhance urban sustainability<sup>14</sup>, but critics have 175 guestioned this techno-centric vision<sup>15,16</sup>. Moreover, while RAS are likely to have far-176 177 reaching social, ecological, and technological ramifications, these are often discussed only in 178 terms of the extent to which their deployment will improve efficiency and data harvesting, and the associated social implications<sup>17-19</sup>. Such a narrow focus will likely overlook 179 180 interactions across the social-ecological-technical systems that cities are increasingly thought to represent<sup>20</sup>. Without an understanding of the opportunities and challenges RAS 181 182 will bring, their uptake could cause conflict with the provision of high quality natural 183 environments within cities<sup>13</sup>, which can support important populations of many species<sup>21</sup>, and are fundamental to the provision of ecosystem services that benefit people<sup>22</sup>. 184

185

186 Here we report the findings of an online horizon scan to evaluate and prioritise future 187 opportunities and challenges for urban biodiversity and ecosystems, including their structure, 188 function and service provision, associated with the emergence of RAS. Horizon scans are 189 not conducted to fill a knowledge gap in the conventional research sense, but are used to 190 explore arising trends and developments, with the intention of fostering innovation and 191 facilitating proactive responses by researchers, managers, policymakers and other 192 stakeholders<sup>23</sup>. Using a modified Delphi technique, which is a structured and iterative 193 survey<sup>23-25</sup> (Figure 2), we systematically collated and synthesised knowledge from 170 194 expert participants based in 35 countries (Extended Data Fig.). We designed the exercise to involve a large range of participants and incorporate a diversity of perspectives<sup>26</sup>. 195

196

## 197 **Results and Discussion**

198 Following two rounds of online questionnaires, the participants identified 32 opportunities 199 and 38 challenges for urban biodiversity and ecosystems associated with RAS (Figure 2). 200 These were prioritised in Round Three, with participants scoring each opportunity and 201 challenge according to four criteria, using a 5-point Likert scale: (i) likelihood of occurrence; 202 (ii) potential impact (i.e. the magnitude of positive or negative effects); (iii) extensiveness (i.e. 203 how widespread the effects will be); and (iv) degree of novelty (i.e. how well known or 204 understood the issue is). Opportunities that highlighted how RAS could be used for 205 environmental monitoring scored particularly highly (Figure 3; Supplementary Table 1). In 206 contrast, fewer challenges received high scores. Those that did emphasised concerns 207 surrounding waste from unrecovered RAS, and the quality and interpretation of RAS-208 collected data (Figure 4; Supplementary Table 1).

209

- 210 These patterns from the whole dataset masked heterogeneity between groups of
- 211 participants, which could be due to at least three factors: (i) variation in

background/expertise; (ii) variation in which opportunities and challenges are considered
important in particular contexts; and (iii) variation in experience and, therefore, perspectives.
We found variation according to participants' country of employment and area of expertise
(Extended Data Fig. 2 and 3). However, we found no significant disagreement between
participants working in different employment sectors. This broad consensus suggests that
the priorities of the research community and practitioners are closely aligned.

218

## 219 Country of employment

Of our 170 participants, 11% were based in the Global South, suggesting that views from that region might be under-represented. Nevertheless, this level of participation is broadly aligned with the numbers of researchers working in different regions. For instance, urban ecology is dominated by Global North researchers<sup>27,28</sup>.

224

225 There were significant divergences between the views of participants from the Global North 226 and South (Extended Data Fig. 4 and 5). Over two thirds (69%; n=44/64) of Global North 227 participants indicated that the challenge "Biodiversity will be reduced due to generic, 228 simplified and/or homogenised management by RAS" (item 11 in Supplementary Table 1) 229 would be important, assigning scores greater than zero. Global South participants expressed 230 much lower concern for this challenge, with only one participant assigning it a score above 231 zero (Fisher's Exact Test: odds ratio=19.04 (95% CI 2.37-882.61), p=0.0007; Extended 232 Data Fig. 2). The discussions in Rounds Four and Five (Figure 2) revealed that participants 233 thought RAS management of urban habitats was not imminent in cities of the Global South, 234 due to a lack of financial, technical and political capacity.

235

236 All Global South participants (100%; n=11) in Round Three assigned scores greater than 237 zero to the opportunities "Monitoring for rubbish and pollution levels by RAS in water sources 238 will improve aquatic biodiversity" (item 35) and "Smart buildings will be better able to 239 regulate energy usage and reduce heat loss (e.g. through automated reflectors), reducing 240 urban temperatures and providing less harsh microclimatic conditions for biodiversity under 241 ongoing climate change" (item 10). Both items would tackle recognised issues in rapidly 242 expanding cities. Discussions indicated that Global South participants prioritised the 243 opportunities for RAS in mitigating pollution and urban heat island effects more than their 244 Global North counterparts, even though 80% (n= 60/75) of Global North participants also 245 assigned positive scores to these items.

246

#### 247 Area of expertise

248 There was considerable heterogeneity in how opportunities and challenges were prioritised 249 by participants with environmental and non-environmental expertise (Extended Data Fig. 6 250 and 7). Significantly more participants with non-environmental expertise gave scores above 251 zero to opportunities that were about the use of RAS for the maintenance of green 252 infrastructure. The largest difference was for the opportunity "An increase in RAS" 253 maintenance will allow more sites to become 'wild', as the landscape preferences of human 254 managers is removed" (item 9), which 76% (n=22/29) of participants with non-environmental 255 expertise scored above zero compared to 38% (n=20/52) of those with environmental 256 expertise (Fisher's Exact Test: odds ratio=0.20 (95% CI 0.06-0.6), p=0.02). More participants 257 with non-environmental expertise (82%, n=23/28) scored the opportunity "RAS to enable 258 self-repairing built infrastructure will reduce the impact of construction activities on 259 ecosystems" (item 57) greater than zero compared to those with environmental expertise 260 (58%; n=26/45) (Fisher's Exact Test: odds ratio=0.30 (95% CI 0.08-1.02, p=0.04).

261

262 For the challenges, there was universal consensus among participants with non-

263 environmental expertise that "Unrecovered RAS and their components (e.g. batteries, heavy

- 264 *metals, plastics) will be a source of hazardous and non-degradable waste*" (item 31) will
- pose a major problem. All (n=29) scored the item above zero, compared to 73% (n=40/55)
- for participants with environmental expertise (Fisher's Exact Test: odds ratio=0, 95% CI 0-
- 267 0.43, p=0.002). A greater proportion of non-environmental participants (76% n=22/29) also
- scored challenge "*Pollution will increase if RAS are unable to identify or clean-up accidents*
- 269 (e.g. spillages) that occur during automated maintenance/construction of infrastructure" (item
- 270 32) above zero compared to those with environmental expertise (45% n=22/29) (Fisher's
- Exact Test: odds ratio=0.26 (95% CI 0.08-0.79), p=0.01). Again, a similar pattern was
- 272 observed for item 38 "RAS will alter the hydrological microclimate (e.g. temperature, light),
- 273 altering aquatic communities and encouraging algal growth". A significantly greater

274 proportion of non-environmental compared to environmental participants (60% n=12/20 and

275 26% n=11/42 respectively) allocated scores above zero (Fisher's Exact Test: odds

276 ratio=0.24 (95% CI 0.07–0.84), p=0.013).

277

278 The mismatch in opinions of environmental and non-environmental participants in Round 279 Three indicate that the full benefits for urban biodiversity and ecosystem of RAS may not be 280 realised. Experts responsible for the development and implementation of RAS could 281 prioritise opportunities and challenges that do not align well with environmental concerns, 282 unless an interdisciplinary outlook is adopted. This highlights the critical importance of 283 reaching a consensus in Rounds Four and Five of the horizon scan with a diverse set of 284 experts (Figure 2). A final set of 13 opportunities and 15 challenges were selected by the 285 participants, which were grouped into eight topics (Table 1).

286

## 287 Topic one: Urban land-use and habitat availability

288 The emergence of autonomous vehicles in cities seems inevitable, but the scale and speed 289 of their uptake is unknown and could be hindered by financial, technological and 290 infrastructural barriers, public acceptability, or privacy and security concerns<sup>29,30</sup>. 291 Nevertheless, participants anticipated wide-ranging impacts for urban land-use and 292 management, with implications for habitat extent, availability, guality and connectivity, and the stocks and flows of ecosystem services<sup>31</sup>, not least because alterations to the amount 293 and guality of green space affects both species<sup>32</sup> and people's well-being<sup>33</sup>. Participants 294 highlighted that urban land-use and transport planning could be transformed<sup>34,35</sup> if the uptake 295 296 of autonomous vehicles is coupled with reduced personal vehicle ownership through vehicle sharing or public transport<sup>36-38</sup>Participants argued that, if less land is required for transport 297 298 infrastructure (e.g. roads, car parks, driveways)<sup>39</sup>, this could enable increases in the extent 299 and quality of urban green space. Supporting this view, research suggests that the need for 300 parking could be reduced by 80-90%<sup>40</sup>.

301

302 Conversely, participants highlighted that autonomous vehicles could raise demand for 303 private vehicle transport infrastructure, leading to urban sprawl and habitat 304 loss/fragmentation as people move further away from centres of employment because 305 commuting becomes more efficient<sup>41,42</sup>. Urban sprawl has a major impact on biodiversity<sup>43</sup>. 306 Participants also noted that autonomous transport systems will require new types of 307 infrastructure (e.g. charging stations, maintenance and control facilities, vehicle depots)<sup>44</sup> 308 that could result in additional loss/fragmentation of green spaces. Furthermore, road 309 systems may require even larger amounts of paved surface to facilitate the movement of autonomous vehicles, potentially to the detriment of roadside trees and vegetated margins<sup>39</sup>. 310

311

## 312 Topic two: Built and green infrastructure maintenance and management

313 A specific RAS application within urban green infrastructure (the network of green/blue 314 spaces and other environmental features within an urban area) that was strongly supported 315 by our participants was the use of automated irrigation of vegetation to mitigate heat stress, 316 thereby optimising water use and the role trees can play in cooling cities. For example, 317 sensors to monitor soil moisture, an integral component in automated irrigation systems, are deployed for urban trees in the Netherlands<sup>12</sup>, and similar applications are available for 318 319 urban gardening<sup>45</sup>. This is likely to be particularly important in arid cities as irrigation can be 320 informed by weather data and measures of evapotranspiration<sup>46</sup>. Resilience to climate 321 change could also be improved by smart buildings that are better able to regulate energy usage and reduce heat loss<sup>47</sup>, through the use of technology like light sensing blinds and 322 323 reflectors<sup>48</sup>. This could help reduce urban heat island effects and moderate harsh microclimates<sup>49</sup>. 324

325

326 Landscape management is a major driver of urban ecosystems<sup>50</sup>, which can be especially 327 complex, due to the range of habitat types and the variety of stakeholder requirements<sup>51</sup>. 328 Participants highlighted that autonomous care of green infrastructure could lead to the 329 simplification of ecosystems, with negative consequences for biodiversity<sup>13</sup>. This would be 330 the likely outcome if RAS make the removal of 'weeds', leaf litter and herbicide application 331 significantly cheaper and quicker, such as through the widespread uptake of robotic lawn 332 mowers or tree-climbing robots for pruning<sup>52</sup>. Urban ecosystems can be heterogeneous in habitat type and structure<sup>51</sup> and phenology<sup>53</sup>. RAS, therefore, may be unable to respond 333 334 adequately to species population variation and phenology, or when species that are 335 protected or of conservation concern are encountered. For hydrological systems in 336 particular, participants noted that automated management could result in the 337 homogenisation of water currents and timings of flow, which are known to disrupt the 338 lifecycles of flow-sensitive species<sup>54</sup>. Similarly, improved building maintenance could lead to

the loss of nesting habitats and shelter (e.g. for house sparrows *Passer domesticus*<sup>55</sup>),

340 especially for cavity and ground-nesting species.

341

## 342 **Topic three: Human-nature interactions**

343 RAS will inevitably alter the ways in which people experience, and gain benefits from, urban 344 biodiversity and ecosystems. However, it is less clear what changes will occur, or how 345 benefits will be distributed across sectors of society. Environmental injustice is a feature of 346 most cities worldwide, with residents in lower income areas typically having less access to green space and biodiversity<sup>56-58</sup>, while experiencing greater exposure to environmental 347 hazards such as air pollution<sup>59,60</sup> and extreme temperatures<sup>61</sup>. RAS have the potential to 348 349 mitigate, but also compound such inequalities, and the issues we highlight here will manifest 350 differently according to political and social context. RAS could even lead to novel forms of 351 injustice by exacerbating a digital divide or producing additional economic barriers, whereby those without access to technology become increasingly digitally marginalised<sup>13,15</sup> from 352 353 interacting with, and accessing, the natural world.

354

355 Experiencing nature can bring a range of human health and well-being benefits<sup>62</sup>.

356 Participants suggested that RAS will fundamentally alter human-nature interactions, but this

357 could manifest itself in contrasting ways. On the positive side, RAS have the potential to

358 reduce noise and air pollution<sup>63-65</sup> through, for example, automated infrastructure repairs

359 leading to decreased vehicle emissions from improved traffic flow and/or reduced

360 construction. In turn, this could make cities more attractive for recreation, encouraging

361 walking and cycling in green spaces, with positive outcomes for physical<sup>66</sup> and mental

362 health<sup>67</sup>. Changes in noise levels could also improve experiences of biophonic sounds such

363 as bird song<sup>68</sup>. Driving through green, rather than built, environments can provide human

364 health benefits<sup>69</sup>. These could be further enhanced if autonomous transport systems were

365 designed to increase people's awareness of surrounding green space features, or if navigation algorithms preferentially choose greener routes<sup>70</sup>. Autonomous vehicles could 366 367 alter how disadvantaged groups such as children, elderly and disabled travel<sup>71</sup>. Participants 368 felt that this might mean improved access to green spaces, thus reducing environmental 369 inequalities. Finally, community (or citizen) science is now a component of urban biodiversity research and conservation<sup>72</sup> that can foster connectedness to nature<sup>73</sup>. Participants 370 371 suggested RAS could provide a suite of different ways to engage and educate the public 372 about biodiversity and ecosystems such as through easier access to and input into real-time data on species<sup>74</sup>. 373

374

375 Alternatively, participants envisaged scenarios whereby RAS reduce human-nature 376 interactions. One possibility is that autonomous deliveries to households may minimise the 377 need for people to leave their homes, decreasing their exposure to green spaces while 378 travelling. In addition, walking and cycling could decline as new modes of transport 379 predominate<sup>75</sup>. RAS that mimic or replace ecosystem service provision (e.g. Singapore's cyborg supertrees<sup>76</sup>, robotic pollinators<sup>77</sup>) may reduce people's appreciation of ecological 380 381 functions<sup>78</sup>, potentially undermining public support for, and values associated with, green 382 infrastructure and biodiversity conservation<sup>79</sup>. This is in line with what is thought to be 383 occurring as people's experience of nature is increasingly dominated by digital media<sup>80</sup>.

384

## 385 Topic four: Biodiversity and environmental data and monitoring

RAS are already widely used for the automated collection of biodiversity and environmental
monitoring data in towns and cities<sup>81</sup>. This has the potential to greatly enhance urban
planning and management decision-making<sup>12</sup>. Continuing to expand such applications would
be a logical step and one that participants identified as an important opportunity<sup>82</sup>. RAS will
allow faster and cheaper data collection over large spatial and temporal scales, particularly

391 across inaccessible or privately owned land. Ecoacoustic surveying and automated sampling

392 of environmental DNA (eDNA) is already enabling the monitoring of hard to detect

393 species<sup>83,84</sup>. RAS also offer potential to detect plant diseases in urban vegetation and,

394 subsequently inform control measures<sup>85,86</sup>.

395

396 Nevertheless, our participants highlighted that the technology and baseline taxonomy 397 necessary for the identification of the vast majority of species autonomously is currently 398 unavailable. If RAS cannot reliably monitor cryptic, little-known or unappealing taxa, the 399 existing trend for conservation actions to prioritise easy to identify and charismatic species in 400 well-studied regions could intensify<sup>87</sup>. Participants emphasised that easily collected RAS 401 data, such as tree canopy cover, could serve as surrogates for biodiversity and ecosystem 402 structure/function without proper evidence informing their efficacy. This would mirror current 403 practices, rather than offering any fundamental improvements in monitoring. Moreover, there 404 is a risk that subjective or intangible ecosystem elements (e.g. landscape, aesthetic, spiritual 405 benefits) that cannot be captured or quantified autonomously may be overlooked in decisionmaking<sup>88</sup>. Participants expressed concern that the quantity, variety and complexity of big 406 407 data gathered by RAS monitoring could present new barriers to decision-makers when coordinating citywide responses<sup>89</sup>. 408

409

## 410 **Topic five: Managing invasive and pest species**

The abundance and diversity of invasive and pest species are often high in cities<sup>90</sup>. One priority concern identified by the participants is that RAS could facilitate new introduction pathways, dispersal opportunities or different niches that could help invasive species to establish. Participants noted that RAS offer clear opportunities for earlier and more efficient pest and invasive species detection, monitoring and management<sup>91,92</sup>. However, participants were concerned the implementation of such novel approaches, citing the potential for error,

417 whereby misidentification leads to accidentally controlling non-target species. Likewise,

418 RAS-mediated pest control could threaten unpopular taxa, such as wasps or termites, if the

419 interventions are not informed by knowledge of the important ecosystem functions such

420 species underpin.

421

## 422 **Topic six: RAS interactions with animals**

The negative impact of unmanned aerial vehicles on wildlife is well-documented<sup>93</sup>, but 423 424 evidence from some studies in non-urban settings suggest this impact may not be universal<sup>94,95</sup>. Nevertheless, participants highlighted that RAS activity at new heights and 425 426 locations within cities will generate novel threats, particularly for raptors that may perceive 427 drones as prey or competitors. Concentrating unmanned aerial vehicle activity along 428 corridors is a possible mitigation strategy. However, participants noted that this could further 429 fragment habitat by creating a 3-dimensional barrier to animal movement, which might disproportionately affect migratory species. Similarly, ground-based or tree-climbing robots<sup>96</sup> 430 431 may disturb nesting and non-flying animals.

432

## 433 Topic seven: Managing pollution and waste

Air<sup>97,98</sup>, noise<sup>99</sup> and light<sup>100,101</sup> pollution can substantially alter urban ecosystem function. 434 435 Participants believed that RAS would generate a range of important opportunities for 436 reducing and mitigating such pollution. For instance, automated transport systems and road repairs could reduce vehicle numbers and improve traffic flow<sup>36</sup>, leading to lower emissions 437 and improved air quality<sup>64,65</sup>. If increased autonomous vehicle use reduced noise from traffic, 438 439 species that rely on acoustic communication could benefit. Similarly, automated and 440 responsive lighting systems will reduce light impacts on nocturnal species, including 441 migrating birds<sup>102</sup>. RAS that monitor air quality, detect breaches of environmental law and clean-up pollutants are already under development<sup>103,104</sup>. Waste management is a major 442

problem for urban sustainability, and participants noted that RAS<sup>105</sup> could provide a solution
through automated detection and retrieval. Despite this potential, participants felt that
unrecovered RAS could themselves contribute to the generation of electronic waste, which is
a growing hazard for human, wildlife and ecosystem health<sup>106</sup>.

447

#### 448 **Topic eight: Water and flooding**

449 Freshwater, estuarine, wetland and coastal habitats are valuable components of urban 450 ecosystems worldwide<sup>107</sup>. Maintenance of water, sanitation and wastewater infrastructure is a major sustainability issue<sup>108</sup>. It is increasingly acknowledged that RAS could play a pivotal 451 role in how these systems are monitored and managed<sup>109</sup>, including improving drinking 452 water<sup>110</sup>, addressing water quality issues associated with sewerage systems<sup>111</sup> and 453 454 monitoring and managing diverse aspects of stormwater predictions and flows<sup>112</sup>. 455 Participants therefore concluded that automated monitoring and management of water 456 infrastructure could lead to a reduction in pollution incidents, improve water quality and reduce flooding<sup>113,114</sup>. Further, they felt that if stormwater flooding is diminished, there may 457 458 be scope for restoring heavily engineered river channels to a more natural condition, thereby enhancing biodiversity, ecosystem function and service provision<sup>115</sup>. Participants identified, 459 460 however, that the opposite scenario could materialise, whereby RAS-maintained stormwater 461 infrastructure increases reliance on hard engineered solutions, decreasing uptake of nature-462 based solutions (e.g. trees, wetlands, rain gardens, swales, retention basins) that provide habitat and other ecosystem services<sup>116</sup>. 463

464

# 465 **Conclusions**

- 466 The fourth industrial revolution is transforming the way economies and society operate.
- 467 Identifying, understanding and responding to the novel impacts, both positive and negative,

468 of new technologies is essential to ensure that natural environments are managed 469 sustainably, and the provision of ecosystem services maximised. Here we identified and 470 prioritised the most important opportunities and challenges for urban biodiversity and 471 ecosystems associated with RAS. Such explicit consideration of how urban biodiversity and 472 ecosystems may be affected by the development of technological solutions in our towns and 473 cities is critical if we are to prevent environmental issues being sidelined. However, we have 474 to acknowledge that some trade-offs to the detriment of the environment are likely to be 475 inevitable. Additionally, it is highly probable that multiple RAS will be deployed 476 simultaneously, making it extremely difficult to anticipate interactive effects. To mitigate and 477 minimise any potential harmful effects of RAS, we recommend that environmental scientists 478 advocate for critical impact evaluations before phased implementation. Long-term 479 monitoring, comparative studies and controlled experiments could then further our 480 understanding of how biodiversity and ecosystems will be affected. This is essential as the pace of technological change is rapid, challenging the capacity of environmental regulation 481 482 to respond quickly enough and appropriately. Although the future impacts of novel RAS are 483 hard to predict, early examination is essential to avoid detrimental and unintended 484 consequences on urban biodiversity and ecosystems, but fully realise the benefits.

## 485 Methods

### 486 Horizon scan participants

487 We adopted a mixed approach to recruiting experts to participant in the horizon scan to 488 minimise the likelihood of bias associated with relying on a single method. For instance, 489 snowball sampling (i.e. invitees suggesting additional experts who might be interested in 490 taking part) alone might over-represent individuals who are similar to one another, although it can be effective at successfully recruiting individuals from hard-to-reach groups<sup>117</sup>. We 491 492 therefore contacted individuals directly via email inviting them to join the horizon scan, as 493 well as using social media and snowball sampling. The 480 experts working across the 494 research, private, public and NGO sectors globally contacted directly were identified through 495 professional networks, mailing lists (e.g. groups with a focus on urban ecosystems; the 496 research, development and manufacture of RAS; urban infrastructure), authors lists of 497 recently published papers, and via the editorial boards of subject-specific journals. Of the 498 170 participants who took part in Round One, 143 (84%) were individuals who has been 499 invited directly, with the remainder obtained through snowball sampling and social media.

500

501 We asked participants to indicate their area of expertise from five categories: (i) 502 environmental (including ecology, conservation and all environmental sciences); (ii) 503 infrastructure (including engineering and maintenance); (iii) sustainable cities (covering any 504 aspect of urban sustainability, including the implementation of 'smart' cities); (iv) RAS 505 (including research, manufacture and application); or (v) urban planning (including 506 architecture and landscape architecture). Participants whose area of expertise did not fall 507 within these categories were excluded from the process. We collected information on 508 participants' country of employment. Subsequently, these were allocated into one of two 509 global regions, the Global North or Global South (low and middle income countries in South America, Asia, Oceania, Africa, South America and the Caribbean<sup>118</sup>). Participants specified 510

their employment sector according to four categories: (i) research; (ii) government; (iii)
private business; or (iv) NGO/not-for-profit.

513

Participants were asked to provide informed consent prior to taking part in the horizon scan activities. We made them aware that their involvement was entirely voluntary, that they could stop at any point and withdraw from the process without explanation, and that their answers would be anonymous and unidentifiable. Ethical approval was granted by the University of Leeds Research Ethics Committee (reference LTSEE-077). We piloted and pre-tested each round in the horizon scan process, which helped to refine the wording of questions and definitions of terminology.

521

## 522 Horizon scan using the Delphi technique

523 The horizon scan applied a modified Delphi technique, which is applied widely in the 524 conservation and environmental sciences literature<sup>24</sup>. The Delphi technique is a structured 525 and iterative survey of a group of participants. It has a number of advantages over standard 526 approaches to gathering opinions from groups of people. For example, it minimises social 527 pressures such as groupthink, halo effects and the influence of dominant individuals<sup>24</sup>. The 528 first round can be largely unstructured, to capture a broad range and depth of contributions. 529 In our horizon scan, we asked each participant to identify between two and five ways in 530 which the emergence of RAS could affect urban biodiversity and/or ecosystem 531 structure/function via a questionnaire. They could either be opportunities (i.e. RAS would 532 have a positive impact on biodiversity and ecosystem structure/function) or challenges (i.e. 533 RAS would have a negative impact) (Figure 2). Round One resulted in the submission of 604 534 pertinent statements. We removed statements not relevant to urban biodiversity or urban 535 ecosystems. Likewise, we excluded statements relating to artificial intelligence or 536 virtual/augmented reality, as these technologies fall outside the remit of RAS. MAG

subsequently collated and categorised the statements into major topics through content
analysis. A total of sixty opportunities and challenges were identified.

539

540 In Round Two, we presented participants with the 60 opportunities and challenges,

541 categorised by topic, for review. We asked them to clarify, expand, alter or make additions

542 wherever they felt necessary (Figure 2). This round resulted in a further 468 statements and,

543 consequently, a further 10 opportunities and challenges emerged.

544

545 In Round Three, we used a questionnaire to ask participants to prioritise the 70 opportunities 546 and challenges in order of importance (Figure 2). We asked participants to score four criteria<sup>25,119</sup> using a 5-point Likert scale ranging from -2 (very low) to +2 (very high): (i) 547 548 likelihood of occurrence; (ii) potential impact (i.e. the magnitude of positive or negative 549 effects); (iii) extensiveness (i.e. how widespread the effects will be); and (iv) degree of 550 novelty (i.e. how well known or understood the issue is). A 'do not know' option was also 551 available. We randomly ordered the opportunities and challenges between participants to minimise the influence of scoring fatigue<sup>120</sup>. For each participant, we generated a total score 552 553 (ranging from -8 to +8) for every opportunity and challenge by summing across all four 554 criteria. Opportunities and challenges were ranked according to the proportion of 555 respondents assigning them a summed score greater than zero. If a participant answered 556 'do not know' for one or more of the criteria for a particular opportunity or challenge, we 557 excluded all their scores for that opportunity or challenge. We generated score visualisations in the 'Likert' package<sup>121</sup> of R version 3.4.1<sup>122</sup>. Two-tailed Fisher's exact tests were used to 558 559 examine whether the percentage of participants scoring items above zero differed between 560 cohorts with different backgrounds (i.e. country of employment, employment sector and area 561 of expertise).

562

563 Final consensus on the most important opportunities and challenges was reached using 564 online group discussions (Round Four), followed by an online consensus workshop (Round 565 Five) (Figure 2; Supplementary Table 1). For Round Four, we allocated participants into one 566 of ten groups, with each group comprising of experts with diverse backgrounds. We asked 567 the groups to discuss the ranked 32 opportunities and 38 challenges, and agree on their ten 568 most important opportunities and ten most important challenges. It did not matter if these 569 differed from the Round Three rankings. Additionally, we asked groups to discuss whether 570 any of the opportunities or challenges were similar enough to be merged, and the 571 appropriateness, relevance and content of the topics. Across all groups, 14 opportunities 572 and 16 challenges were identified as most important. Participants, including at least one 573 representative from each of the ten discussion groups, took part in the consensus 574 workshop. The facilitated discussions resulted in agreement on the topics, and a final 575 consensus set of 13 opportunities and 15 challenges (Table 1).

576

# 577 Data Availability

578 Anonymised data are available from the University of Leeds institutional data repository at 579 <u>https://doi.org/10.5518/912</u>.

580

# 581 Acknowledgements

- 582 We are grateful to all our participants for taking part and to J. Bentley for preparing the
- 583 figures. The work was funded by the UK government's Engineering and Physical Sciences
- 584 Research Council (grant EP/N010523/1: "Balancing the impact of City Infrastructure
- 585 Engineering on Natural systems using Robots"). ZGD was funded by the European
- 586 Research Council (ERC) under the European Union's Horizon 2020 research and innovation
- 587 programme (Consolidator Grant No. 726104).

# 589 Author Contributions

- 590 MD conceived the study. MD, MAG, ZGD, SG, JCF, MJF developed and tested
- 591 questionnaire and webinar materials. AA, TA, PMLA, FA, CA, AJB, ABarkwith, ABerland,
- 592 CJB, CCR-B, LBB, DC, RC, TC, SConnop, SCrossland, MCD, DAD, CD, CTD, ECE, FJE,
- 593 PG, NMG, BG, AKH, JDH, CH, MH, DFH, TI, I-CI, DK, TK, IK, SJL, SBL, IM-F, PManning,
- 594 PMassini, SM, DDM, AO, GPL, LP-U, KP, GP, TJP, KEP, RAR, UR, SGP, HR, JPS, SdeS,
- 595 SS, CES, AS, TS, RPFS, CDS, MCS, TVdeV, SJV, PHW, C-LW, MW, NSGW, JY, KY, KPY
- 596 contributed data. MAG collated and analysed these data. MAG, MD, ZGD led writing the
- 597 paper. AA, TA, PMLA, FA, CA, AJB, ABarkwith, ABerland, CJB, CCR-B, LBB, DC, RC, TC,
- 598 SConnop, SCrossland, MCD, DAD, CD, CTD, ECE, FJE, NMG, BG, AKH, JDH, CH, MH,
- 599 DFH, TI, I-CI, DK, TK, IK, SJL, SBL, IM-F, PManning, PMassini, SM, DDM, AO, GPL, LP-U,
- 600 KP, GP, TJP, KEP, RAR, UR, SGP, HR, JPS, SdeS, SS, CES, AS, RPFS, CDS, MCS,
- TVdeV, SJV, PHW, C-LW, MW, NSGW, JY, KY, KPY contributed and agreed to the final

602 version.

603

# 604 **Competing Interests**

605 The authors declare no competing interests

606

#### 608 Table 1. The most important 13 opportunities and 15 challenges associated with robotics and automated systems for urban biodiversity

609 and ecosystems. The opportunities and challenges were prioritised as part of an online horizon scan involving 170 expert participants from 35

610 countries (Figure 2). The full set of 32 opportunities and 38 challenges identified by participants in Round Three is given in Supplementary Table 1.

611 Item numbers given in parenthesis is for cross referencing between figures and tables.

	Торіс	Opportunities	Challenges
	1. Urban land- use and habitat availability	abitat personal car ownership will reduce the amount of space needed for transport infrastructure (e.g. roads, car parks, driveways), allowing an increase in the extent and quality of urban green space and associated ecosystem services (item 54).	The replacement of ecosystem services (e.g. air purification, pollination) by RAS (e.g. artificial 'trees', robotic pollinators) will lead to habitat and biodiversity loss (item 62).
			Trees and other habitat features will be reduced in extent or removed to facilitate easier RAS navigation, and/or damaged through direct collision (item 60).
			Autonomous transport systems will require new infrastructure (e.g. charging stations, maintenance and control facilities, vehicle depots), leading to the loss/fragmentation of greenspaces (item 59).
	2. Maintenance and management of built and green infrastructure	Smart buildings will be better able to regulate energy usage and reduce heat loss (e.g. through automated reflectors), reducing urban temperatures and providing less harsh microclimatic conditions for biodiversity under ongoing climate change (item 10).	Biodiversity will be reduced due to generic, simplified and/or homogenised management by RAS. This includes over-intensive green space management, improved building maintenance and homogenisation of water currents and timings of flow (items 11, 14 and 37 merged).
		Irrigation of street trees and other vegetation by RAS will lead to greater resilience to climate change/urban heat stress (item 8).	
2			
3			
	3. Human- nature	RAS will decrease pollution, making cities more attractive for recreation and enhancing opportunities for experiencing	RAS will reduce human-nature interactions by, for example, reducing the need to leave the house as services are automated and decreasing awareness of the surrounding environment while

interactions	nature (item 42).	travelling (item 46).
	RAS will provide novel ways for people to learn about, and experience biodiversity and lead to a greater level of participation in citizen science and volunteer conservation activities (items 41, 43 and 44 merged).	RAS that mimic ecosystem service provision (e.g. artificial trees, robot pollinators) will reduce awareness of ecological functions and undermine public support for/valuation of GI and biodiversity conservation (item 52).
		RAS will exacerbate the exclusion of certain people from nature (item 48).
4. Biodiversity and environmental data and monitoring	Drones and other RAS (plus integrated technology such as thermal imaging/AI recording) will allow enhanced and more cost-effective detection, monitoring, mapping and analysis of habitats and species, particularly in areas that are not publicly or easily accessible (item 3).	The use of RAS without ecological knowledge of consequences will lead to misinterpretation of data and mismanagement of complex ecosystems that require understanding of thresholds, mechanistic explanations, species network interactions, etc. For instance, pest control programmes threaten unpopular species (e.g. wasps, termites) that fulfil important ecological functions (items 5 and 67 merged).
	Real-time monitoring of abiotic environmental variables by RAS will allow rapid assessment of environmental conditions, enabling more flexible response mechanisms, and informing the location and design of green infrastructure (item 4).	Data collected via RAS will be unreliable for hard to identify species groups (e.g. invertebrates) or less tangible ecosystem elements (e.g. landscape, aesthetic benefits), leading to under-valuing of 'invisible' species and elements (item 6).
5. Managing invasive and pest species		When managing/controlling pest or invasive species, RAS identification errors will harm non-target species (item 66).
pest species		RAS will provide new introduction pathways, facilitate dispersal, and provide new habitats for pest and invasive species (item 68).
6. RAS interactions with animals		Drone activity at new heights and new locations will threaten flying animals through a risk of direct collision and/or alteration of behaviour (item 19).
		Terrestrial robots will cause novel disturbances to animals, such as

		avoidance behaviour, altered foraging patterns, nest abandonment, etc (item 20).
7. Pollution and waste	RAS will improve detection, monitoring and clean-up of pollutants, benefitting ecosystem health (item 24).	Unrecovered RAS and their components (e.g. batteries, heavy metals, plastics) will be a source of hazardous and non-degradable
	RAS will reduce waste production through better monitoring and management of sewage, litter, recyclables and outputs from the food system (items 25 and 71 merged).	waste (item 31).
	RAS will increase detection of breaches of environmental law (e.g. fly-tipping, illegal site operation, illegal discharges, consent breaches, etc.) (item 26).	
	Automated and responsive building, street and vehicle lighting systems will reduce light pollution impacts on plants and nocturnal and/or migratory species (item 23).	
	Automated transport systems (including roadworks) will decrease vehicle emissions (by reducing the number of vehicles and improving traffic flow), leading to improved air quality and ecosystem health (item 21).	
8. Managing water and flooding	Monitoring and maintenance of water infrastructure by RAS will lead to fewer pollution incidents, improved water quality, and reduced flooding (item 34).	Maintenance of stormwater by RAS will increase reliance on 'hard' engineering solutions, decreasing uptake of nature-based stormwater solutions that provide habitat (item 39).

618 619	Figure 1. Examples of the potential for robotics and automated systems to transform cities.
620	(a) 25% of transport in Dubai is planned to function autonomously by 2030 <sup>124</sup> ; (b) city-wide sensor
621	networks, such as those used in Singapore, inform public safety, water management, and
622	responsive public transport initiatives <sup>125</sup> ; (c) through the use of unmanned aerial and ground-based
623	vehicles, Leeds, UK, is expecting to implement fully autonomous maintenance of built
624	infrastructure by 2035 <sup>2</sup> ; and (d) precision agricultural technology for small-scale urban agriculture
625	(https://farm.bot/).
626	
627	
628	

629	
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631	Figure 2. Horizon scan process used to identify and prioritise opportunities and
632	challenges associated with robotics and automated systems for urban biodiversity
633	and ecosystems. The horizon scan comprised an online survey, following a modified Delphi
634	technique, which was conducted over five rounds.
635	
636	
637	
638	
639	Figure 3. Opportunities associated with robotics and automated systems for urban
640	biodiversity and ecosystems, ranked according to Round Three participant scores.
641	The distribution of summed participant scores (range: -8 to +8) across four criteria
642	(likelihood, impact, extent, novelty) for each of the 32 opportunities. Items are ordered
643	according to the percentage of participants who gave summed scores greater than zero.
644	Percentage values indicate the proportion of participants giving negative, neutral and
645	positive scores (left hand side, central and right hand side of the shaded bars respectively).
646	The full wording agreed by the participants for each opportunity is in Supplementary Table 1:
647	'mm' is an abbreviation for 'monitoring and management'; item number given in parenthesis
648	is for cross-referencing between figures and tables.

651	Figure 4. Challenges associated with robotics and automated systems for urban
652	biodiversity and ecosystems, ranked according to Round Three participant scores.
653	The distribution of summed participant scores (range: -8 to +8) across four criteria
654	(likelihood, impact, extent, novelty) for each of the 38 challenges. Items are ordered
655	according to the percentage of participants who gave summed scores greater than zero.
656	Percentage values indicate the proportion of participants giving negative, neutral and
657	positive scores (left hand side, central and right hand side of the shaded bars respectively).
658	The full wording agreed by the participants for each challenge is in Supplementary Table 1:
659	'mm' is an abbreviation for 'monitoring and management'; item number given in parenthesis
660	is for cross-referencing between figures and tables.

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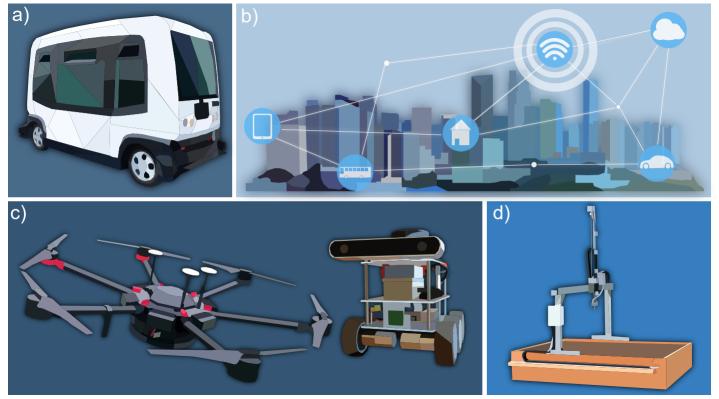
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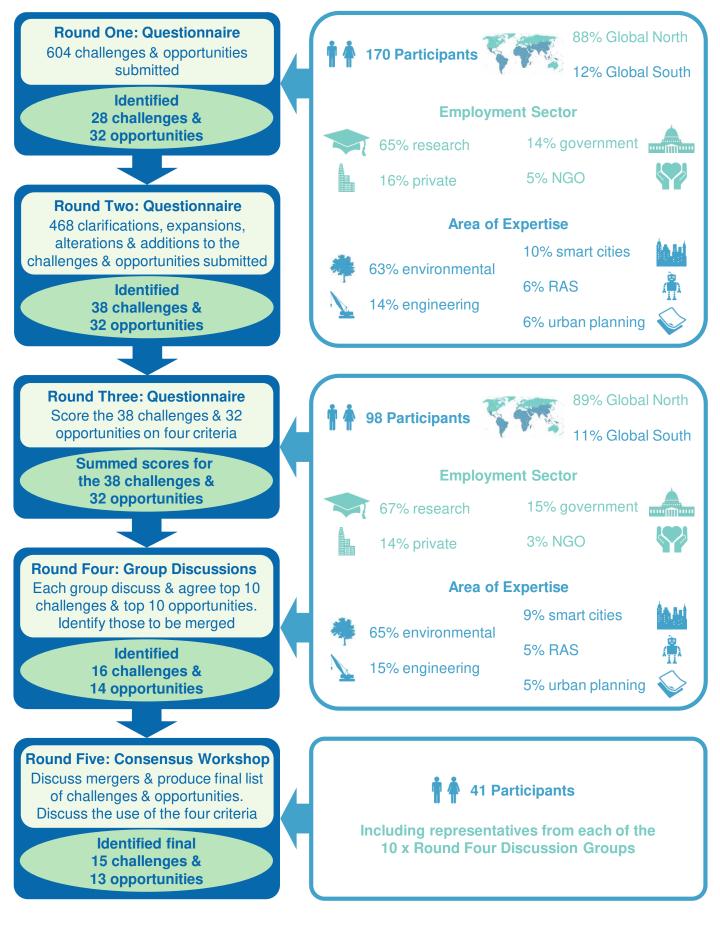
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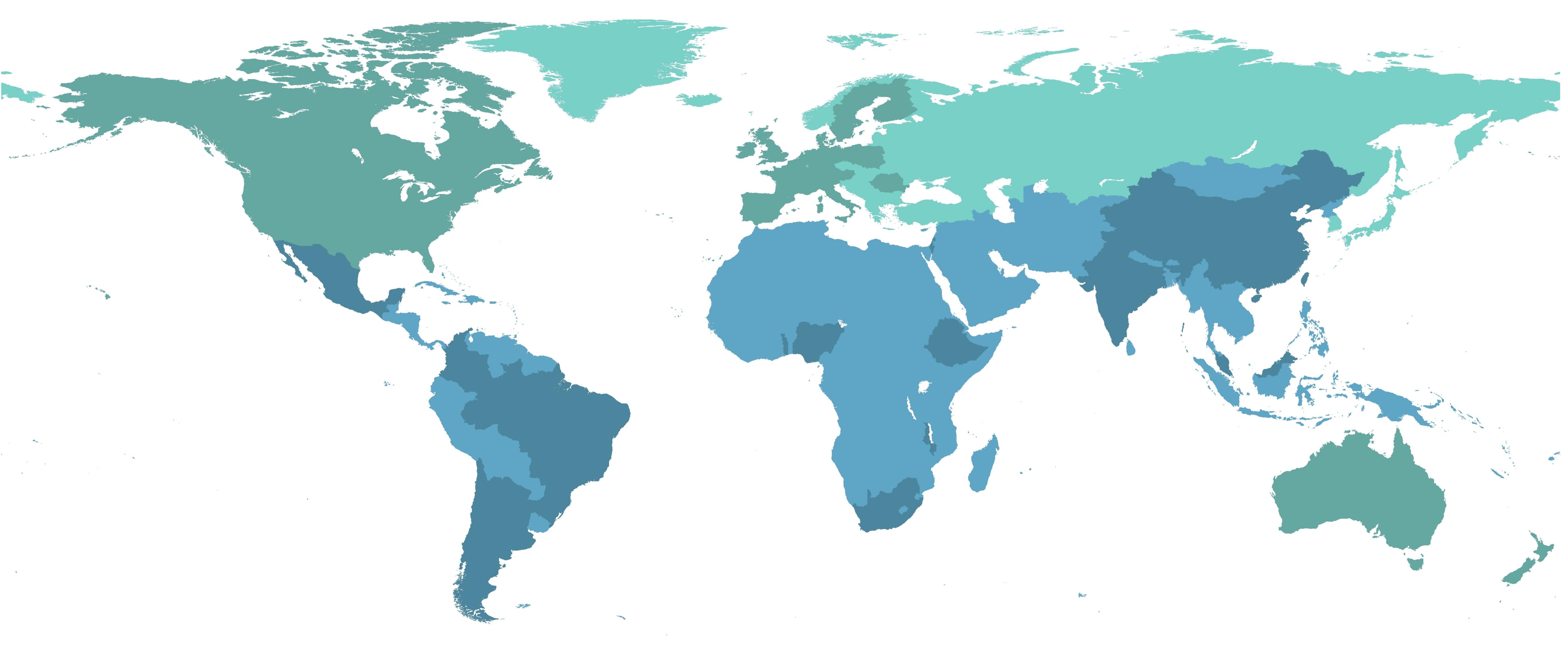
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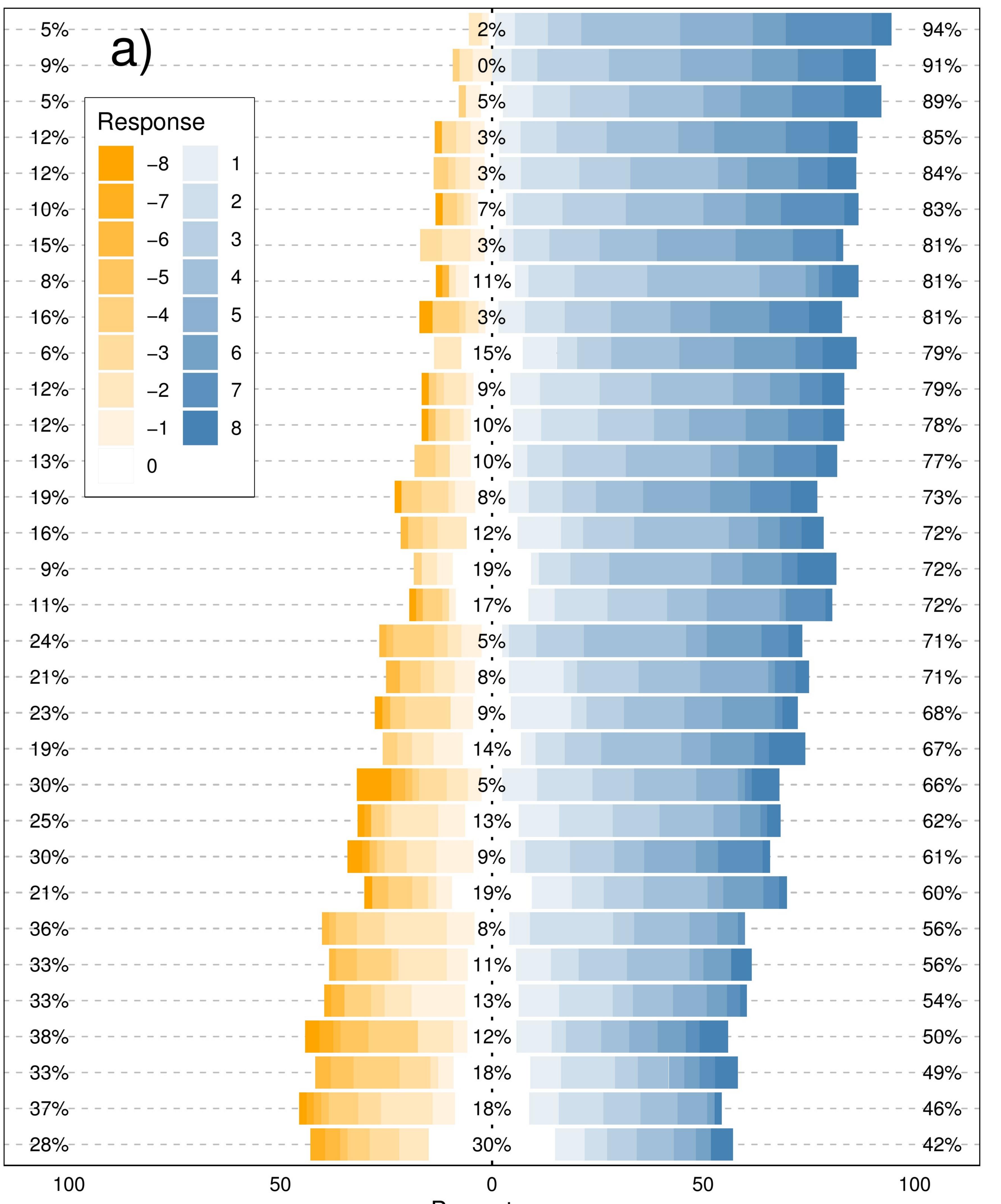




Habitat & species monitoring (3)	4%						- 3%		92%
Abiotic variable monitoring (4)	7%	Res	spons	se			- <mark>2</mark> %		91%
Pollutant mm (24)	7%		-8		1		5%		88%
Smart buildings (10)	- 10%		-7		2		6%		84%
Waste production mm (25)	8%		-6		3		8%		83%
GI management (7)	- 13%		-5		4		4%		83%
Water pollution monitoring (35)	6%		-4		5		12%		82%
Roadworks & transport system management (21)	- 13%		-3		6		6%		82%
Pest & invasive species mm (64)	-12%						6%		81%
Environmental law compliance monitoring (26)	- 10%		-2		7		9%		81%
Lighting systems (23)	- 10%		-1		8		10%		80%
Water infrastructure mm (34)	7%		0				13%		80%
River intervention mm (36)	8%						13%		79%
Food waste mm (71)	- 13%						9%		78%
Transport system & car ownership decreses (54)	- 18%						7%		75%
Street vegetation irrigation (8)	-21%						6%		73%
Animal deterrence (17)	- 14%						14%		72%
Education & citizen science (43)	- 17%						11%		72%
Traffic system noise pollution declines (22)	- 19%						9%		71%
Pollution decreases enhance recreation (42)	- 12%						17%		70%
Vehicle animal collision detection (16)	-24%					-	6%		70%
Self-repairing built infrastructure (57)	- 15%						18%		67%
Traffic system pollutant run–off reductions (33)	- 27%						11%		62%
Wheel-less transport infrastructure (55)	- 29%						9%		62%
Built structure declines (56)	-24%						15%		62%
Food for urban exploiter species reduces (65)	- 30%						9%		61%
New employment opportunities in GI mm (45)	-31%				-		10%		59%
Urban agriculture increases (70)	- 32%						13%		55%
Wilder landscapes (9)	- 32%						16%		52%
Ecosystem service mimicry (58)	- 37%						12%		51%
Leisure time increases (44)	- 35%						17%		48%
Human-nature interaction increases (41)	- 28%						25%		47%
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Unrecovered technological waste (31)	-1-3% -	[					5%		82%
Management without ecological knowledge (67)	-1-1-%	Res	spon	se			10%		79%
Data unreliability (6)	-18% -		-8		1		7%		76%
Data misintperetation (5)	14% -		-7		2		12%		74%
Threats to flying species (19)	-23% -		-6		3		6%		71%
Human-nature interaction declines (46)	-16% -		-5		4		15%		70%
Pest & invasive species management errors (66)	-20% -		-4		5		13%		68%
Novel disturbances (20)	-28% -		-3		6		<u>5</u> %		67%
Transport system & persistent vehicle use (61)	-25% -		-2		7		11%		64%
Vehicle animal collisions rise (18)	-24% -		_1 0		8		13%		63%
Water flow homogenisation due to management (37)	-21% -		0				17%		62%
Biodiversity homogenisation due to management (11)	-30% -					-	9%		61%
Ecosystem service mimicry & biodiversity loss (62)	-27% -					-	12%		60%
Pest & invasive species introductions (68)	-25% -						15%		60%
Leisure time increases (53)	-25% -						15%		60%
Noise frequency changes (28)	-26% -					-	15%		59%
Habitat feature reductions & removals (60)	-31% -						10%		59%
Ecosystem service mimicry & awareness reductions (52)	-22% -					-	19%		59%
Transport system land use increases (59)	-36% -				·		6%		58%
Buildings maintenance improvements (14)	-30% -						12%		58%
Food for urban exploiter species reduces (69)	-29% -						14%		57%
Construction pollution increases (32)	-28% -						15%		56%
Light pollution increases (29)	-32% -						14%		54%
GI decreases (15)	-30% -						17%		53%
Human-nature interaction decreases (49)	-32% -				• • •		15%		53%
Urban agriculture increases (72)	-32% -				• •		15%		52%
Species adaptation capacity reduces (63)	-32% -				• •		15%		52%
People excluded from nature increases (48)	-35% -				· -		15%	-	50%
Electromagnetic radiation increases (30)	-31% -				•		21%	-	49%
Irrigation system failures (12)	-32% -						19%	-	49%
Site mismanagement (40)	-34% -				-		17%	-	49%
Transport system & car ownership increases (27)	-38% -						15%		47%
Irrigation & water security threats (13)	41% -						13%		47%
Transport system & pollution increases (47)	-44% -						16%		40%
Hard engineering stormwater solution reliance rises (39)	-35% -						25%		40%
Hydrological microclimate changes (38)	-39% -						24%		37%
Human GI management declines (50)	-52% -						12%		36%
GI management flexibility declines (51)	-60% -						14%		26%
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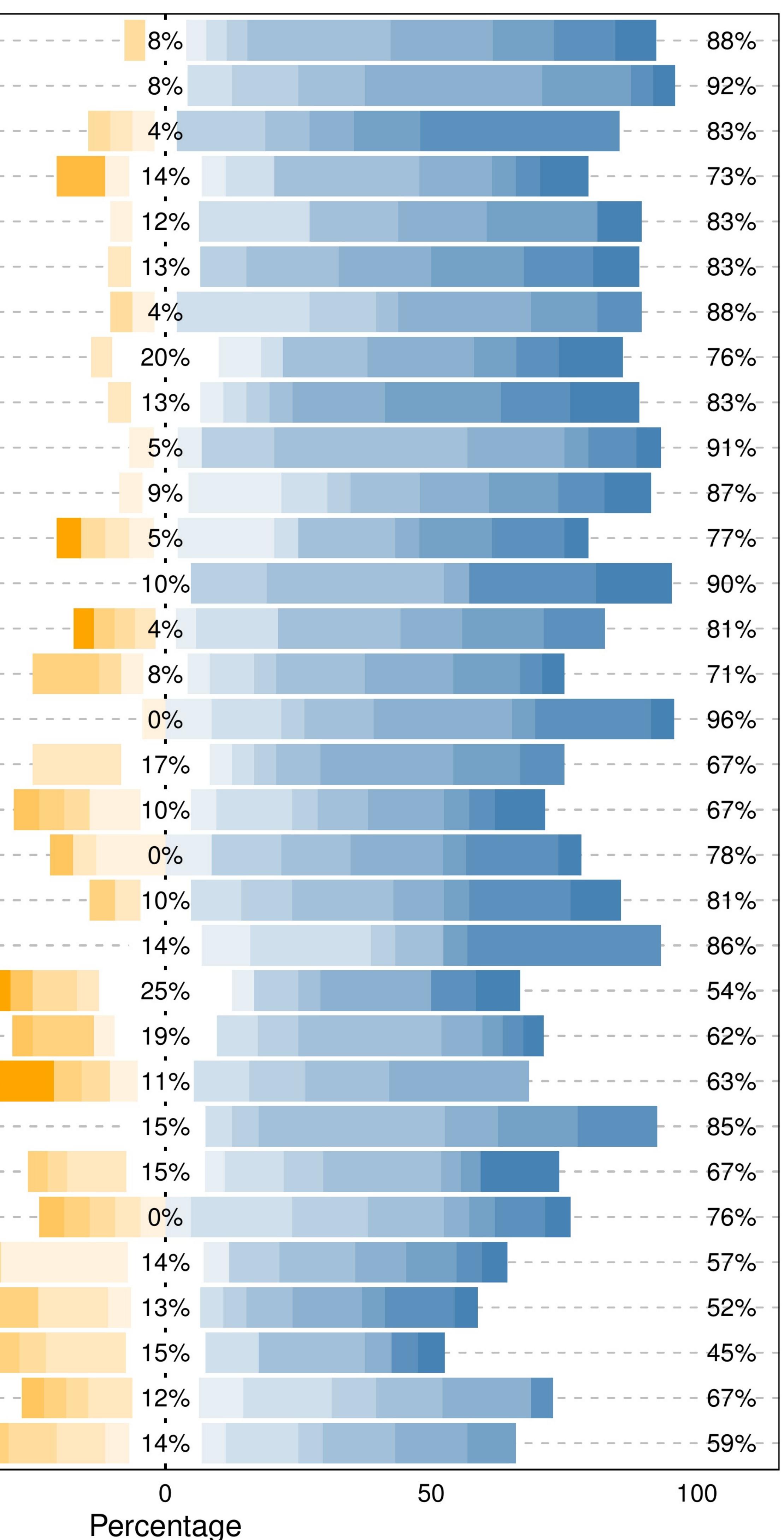


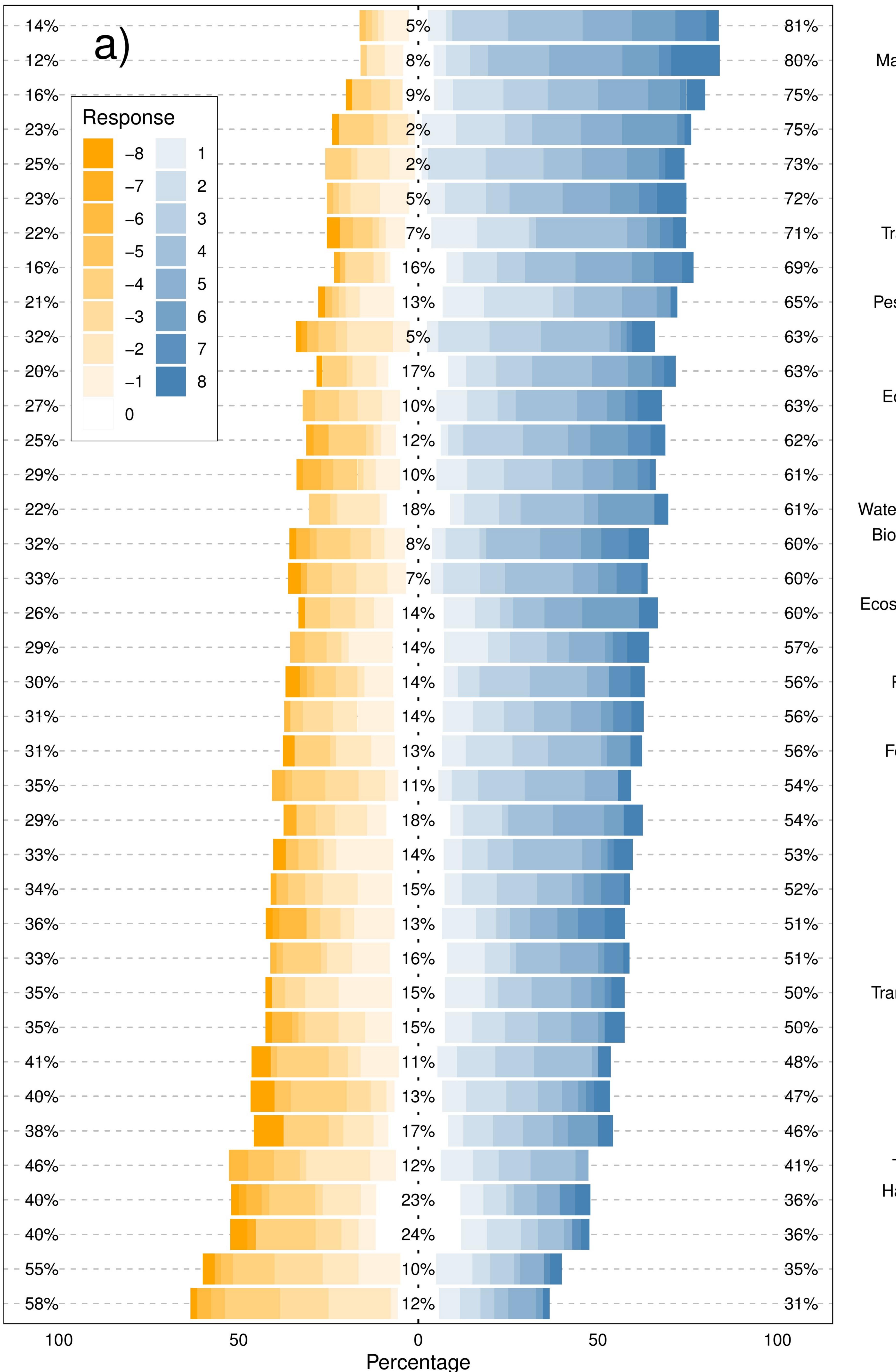


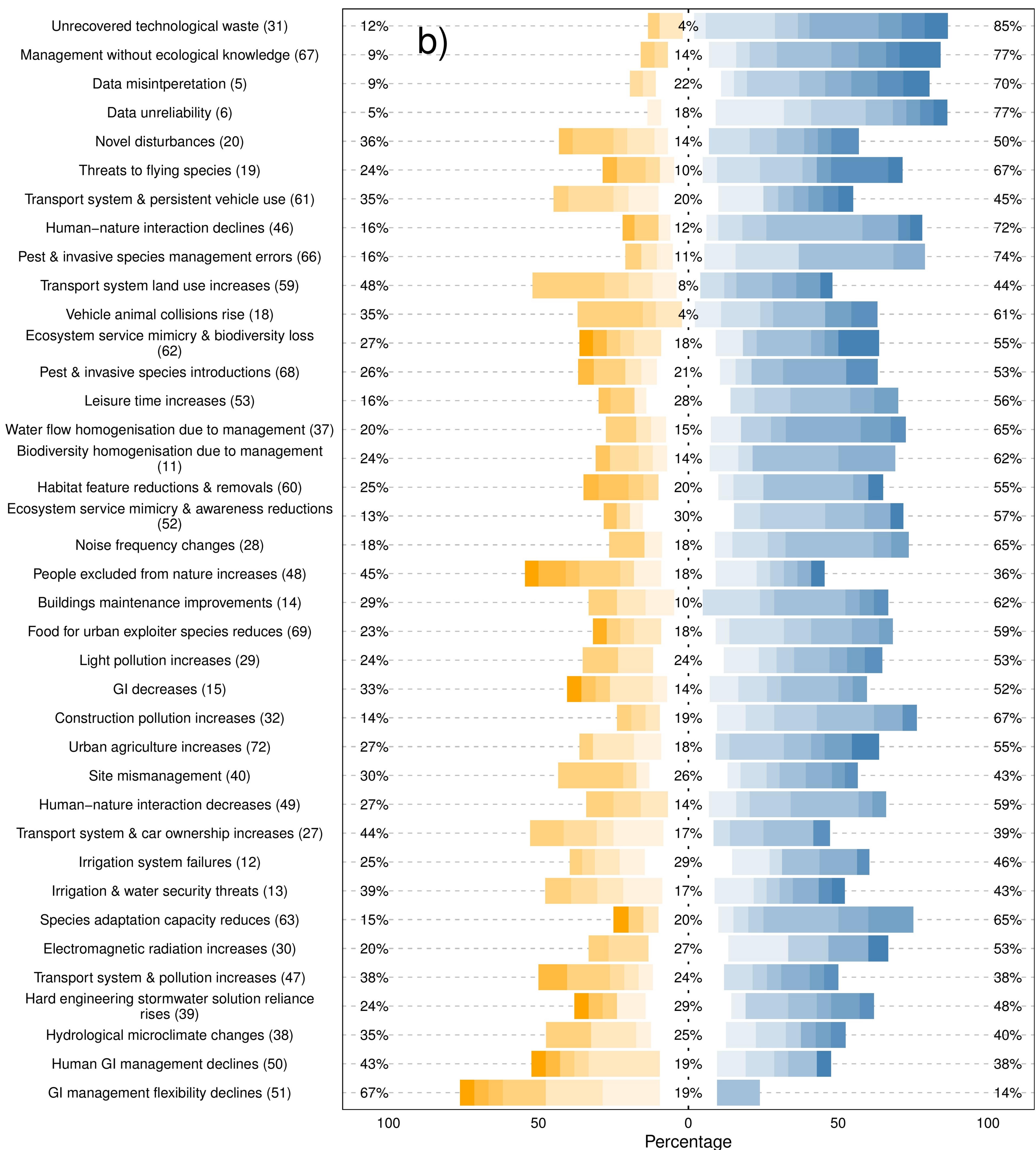
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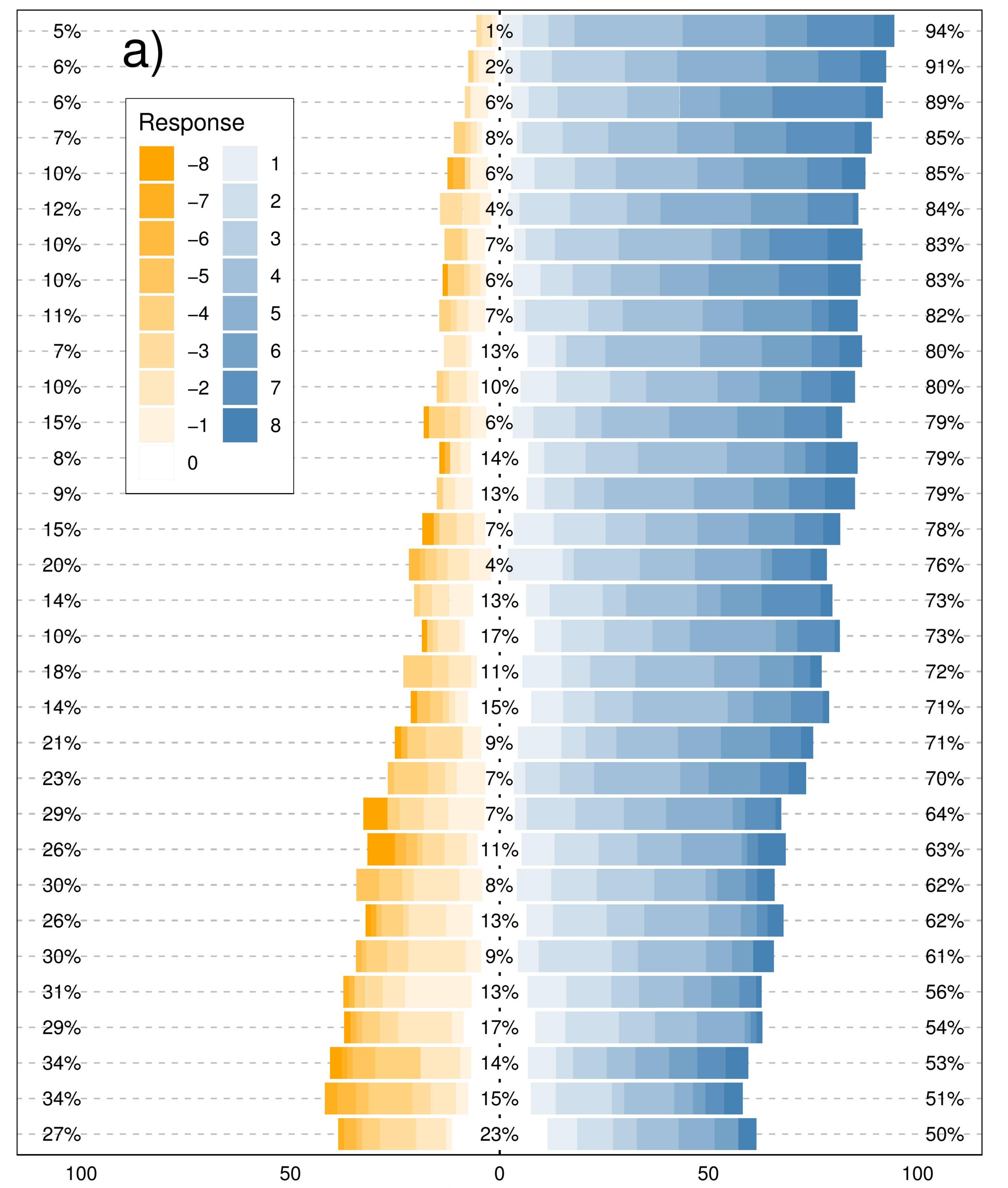
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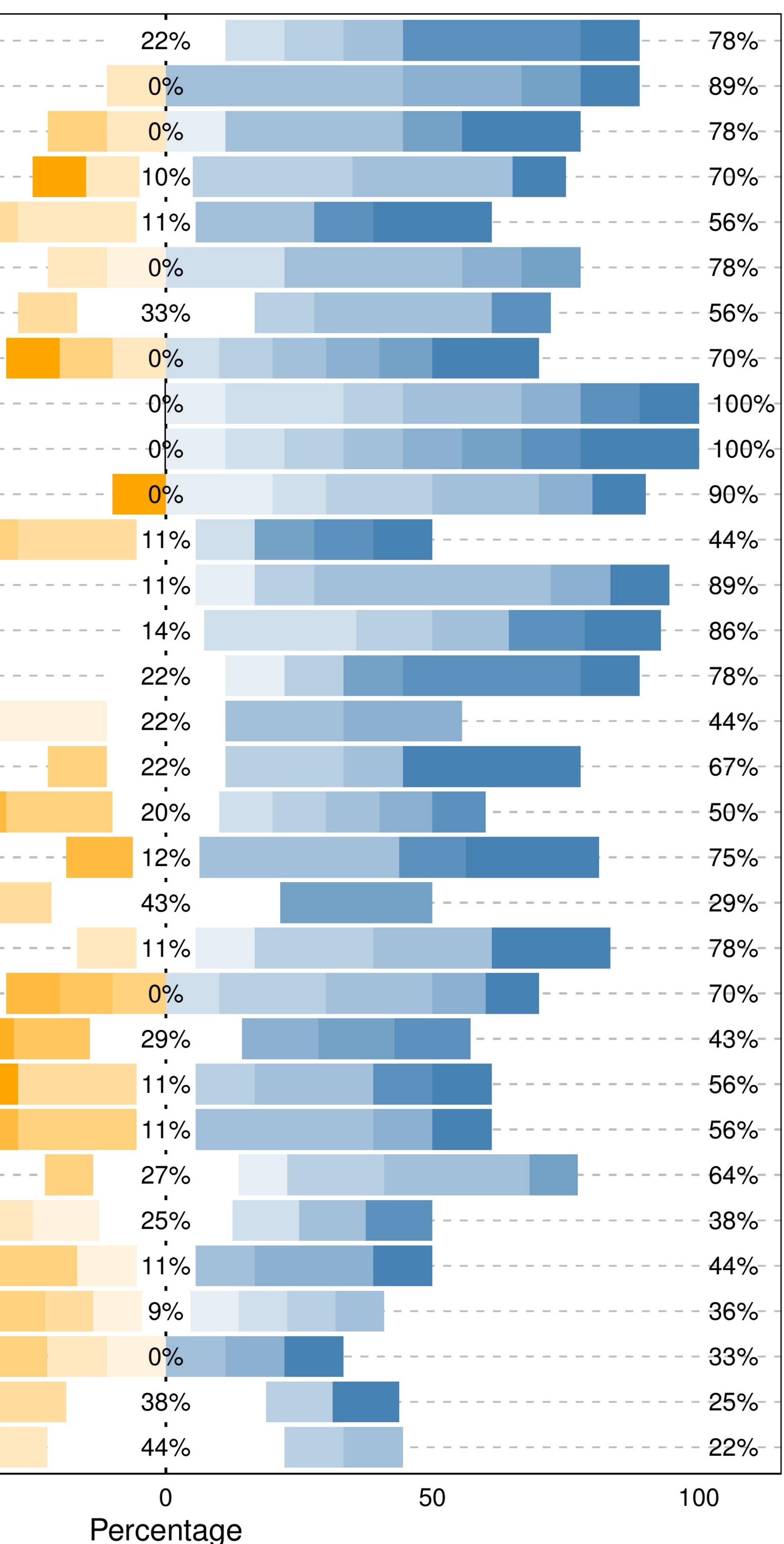


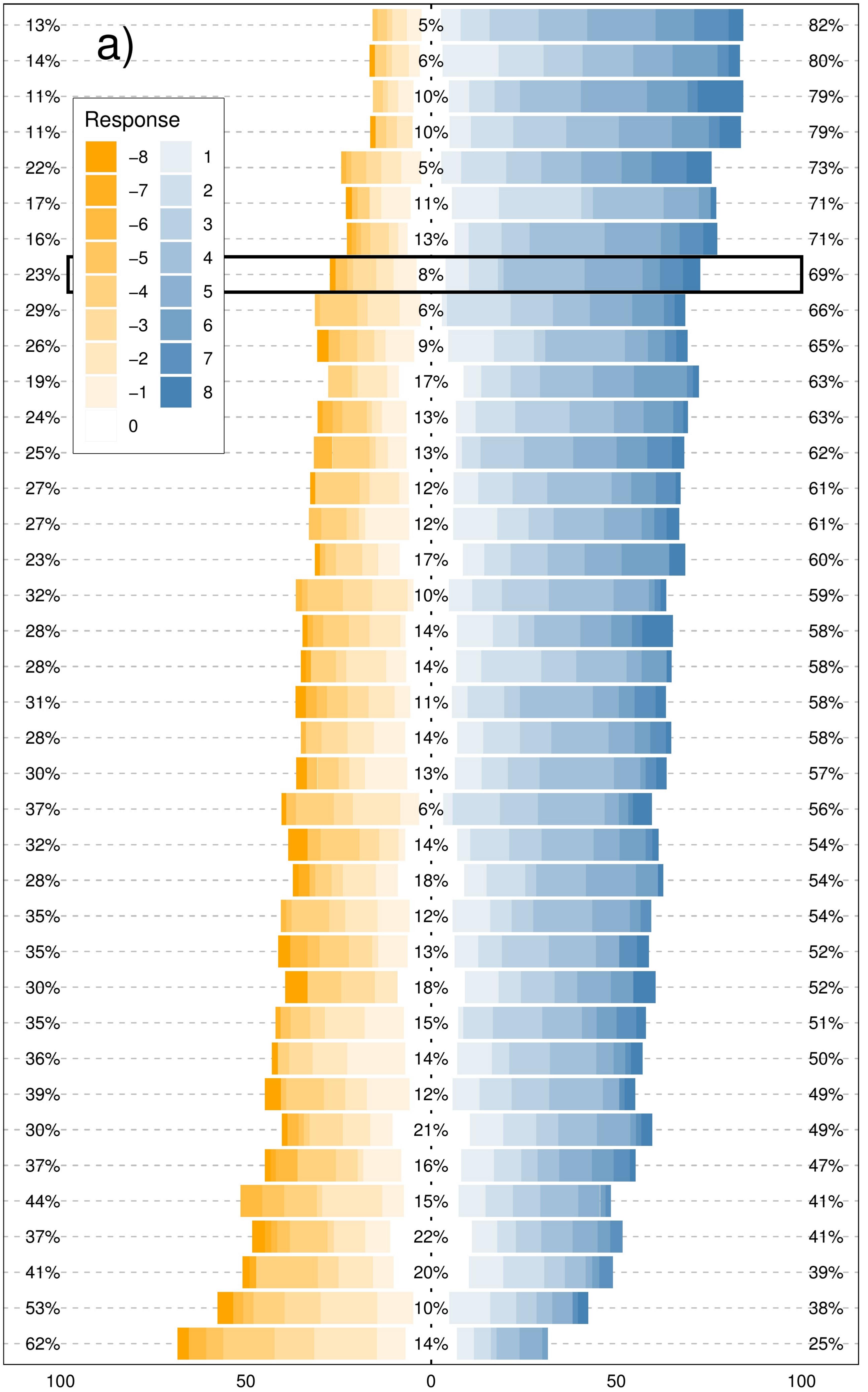


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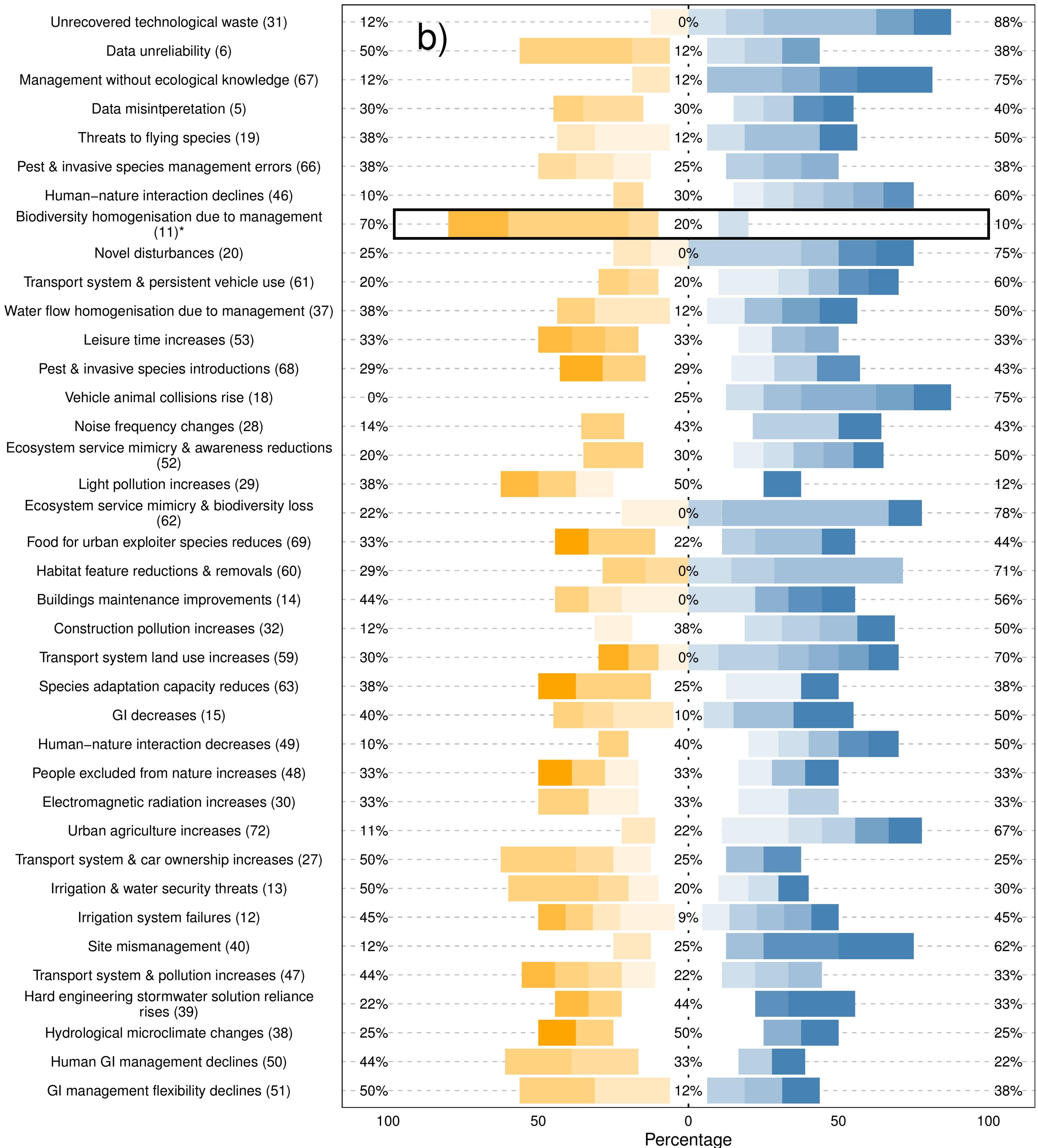
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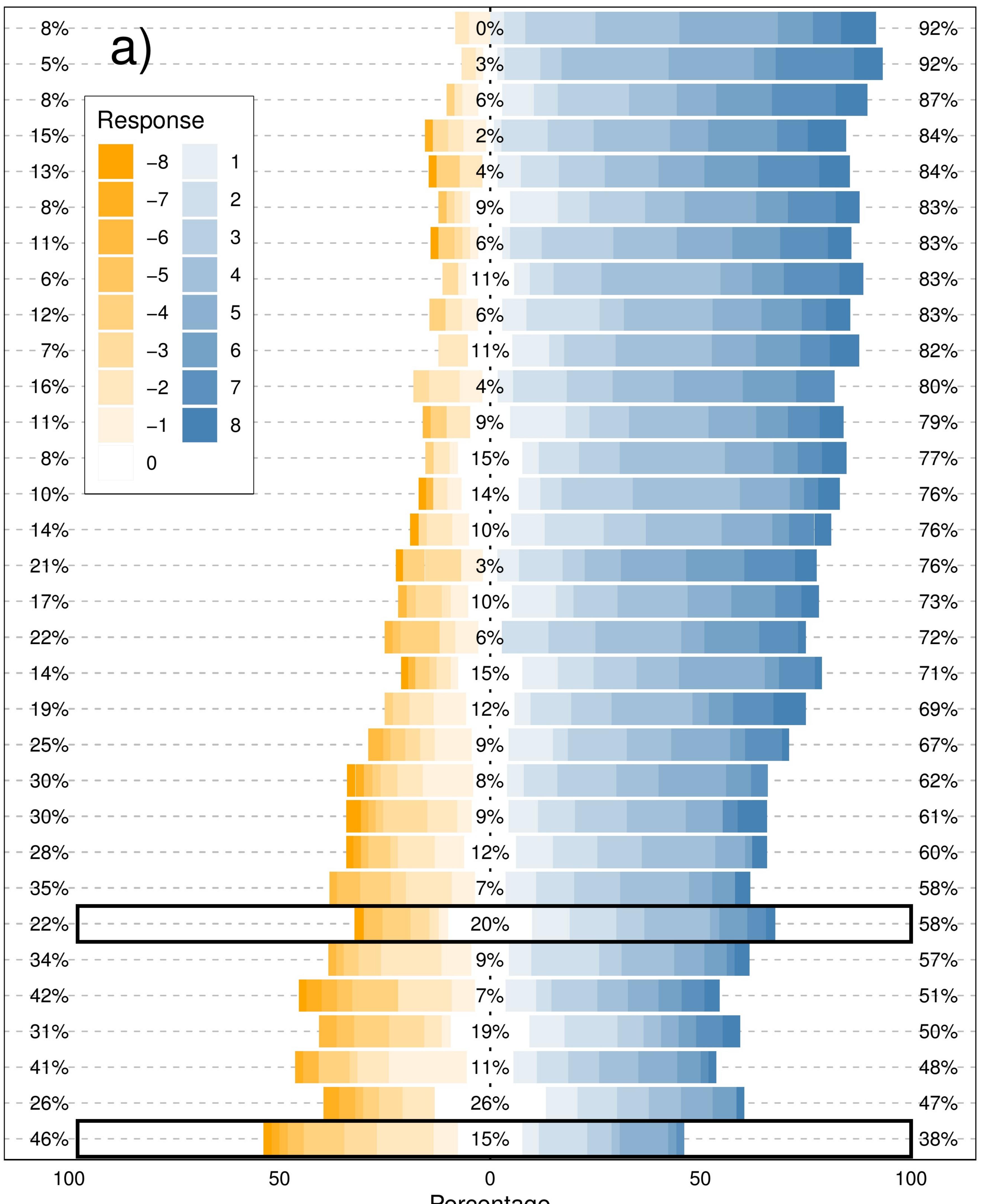
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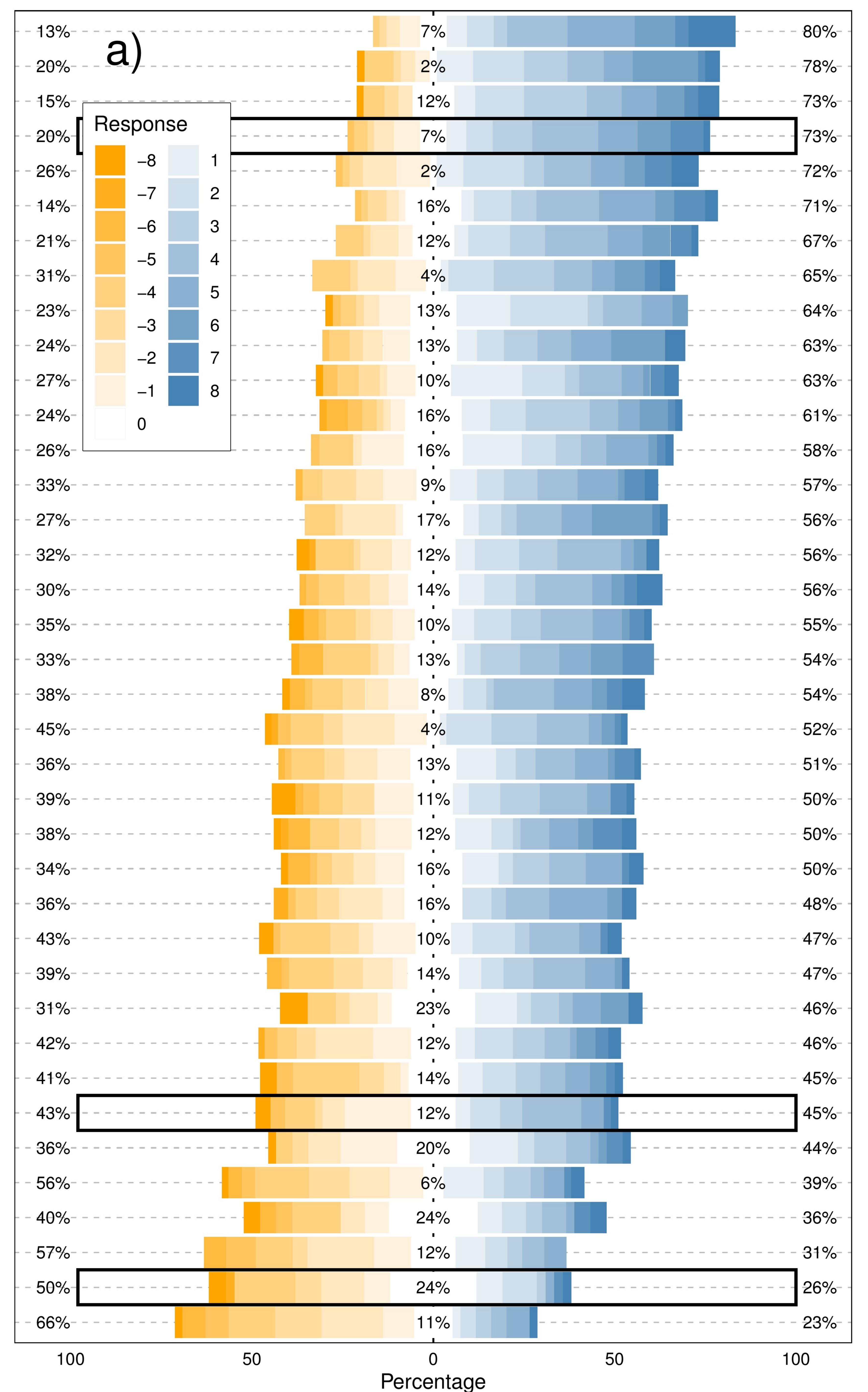


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