

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

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

142

143 We are currently witnessing the fourth industrial revolution¹. Technological innovations have
144 altered the way in which economies operate, and how people interact with built, social and
145 natural environments. One area of transformation has been the emergence of robotics and
146 autonomous systems (RAS), defined as technologies that can sense, analyse, interact with
147 and manipulate their physical environment². RAS include unmanned aerial vehicles
148 (drones), self-driving cars, robots able to repair infrastructure, and wireless sensor networks
149 used for monitoring. RAS therefore have a large range of potential applications, such as
150 autonomous transport, waste collection, infrastructure maintenance and repair, policing^{2,3},
151 and precision agriculture⁴ (Figure 1). RAS have already revolutionised how environmental
152 data are collected⁵, and species populations are monitored for conservation⁶ and/or control⁷.
153 Globally, the RAS market is projected to grow from \$6.2 billion in 2018 to \$17.7 billion in
154 2026⁸.

155 Concurrent with this technological revolution, urbanisation continues at an unprecedented
156 rate. By 2030, an additional 1.2 million km² of the planet's surface will be covered by towns
157 and cities, with ~90% of this development happening in Africa and Asia. Indeed, 7 billion
158 people will live in urban areas by 2050⁹. Urbanisation causes habitat loss, fragmentation and
159 degradation, as well as altering local climate, hydrology and biogeochemical cycles, resulting
160 in novel urban ecosystems with no natural analogs¹⁰. If poorly planned and executed, urban
161 expansion and densification can lead to substantial declines in many aspects of human well-
162 being¹¹.

163

164 Presently, we have little appreciation of the pathways through which the widespread uptake
165 and deployment of RAS could affect urban biodiversity and ecosystems^{12,13}. The widespread
166 use of RAS has been proposed as a mechanism through which urban sustainability can be
167 enhanced¹⁴, but critics have questioned this techno-centric vision^{15,16}. For instance, these
168 technological advances could potentially cause conflict with the provision of high quality
169 natural environments within cities¹⁷, which can support important populations of many
170 species¹⁸, and are fundamental to the provision of ecosystem services that are beneficial for
171 people¹⁹.

172

173 Here we report the findings of an online horizon scan to evaluate and prioritise the
174 opportunities and challenges for urban biodiversity and ecosystems, including their structure
175 and function, associated with the emergence of RAS. Horizon scanning is an approach for
176 exploring emerging trends and future developments, with the intention of fostering innovation
177 and facilitating proactive responses by researchers, managers, policymakers and other
178 stakeholders²⁰. To date, information on how RAS may impact urban biodiversity and
179 ecosystems remains scattered across multiple sources and disciplines, if it has been
180 recorded at all. Using a modified Delphi technique, which is a structured and iterative

181 survey²⁰⁻²² (Figure 2), we systematically collate and synthesis knowledge from 170 expert
182 participants based in 35 countries (Supplementary Figure 1). The exercise is therefore
183 inclusive and incorporates a diversity of different perspectives²²³.

184

185 **Results and Discussion**

186 Following two rounds of online questionnaires, the participants identified 32 opportunities
187 and 38 challenges for urban biodiversity and ecosystems associated with RAS (Figure 2).
188 These were prioritised in the round three, with participants scoring each opportunity and
189 challenge according to four criteria, using a 5-point Likert scale: (i) likelihood of occurrence;
190 (ii) potential impact (i.e. the magnitude of positive or negative effects); (iii) extensiveness (i.e.
191 how widespread the effects will be); and (iv) degree of novelty (i.e. how well known or
192 understood the issue is). Opportunities that highlighted how RAS could be used for
193 environmental monitoring scored particularly highly (Figure 3; Supplementary Table 1). In
194 contrast, fewer challenges were prioritised. Those that were, emphasised concerns
195 surrounding waste from unrecovered RAS, and the quality and interpretation of RAS-
196 collected data (Figure 4; Supplementary Table 1). These broad patterns masked
197 considerable heterogeneity in scores between groups of participants according to their
198 country of employment and area of expertise. However, we found no significant
199 disagreement between participants working in different employment sectors (Supplementary
200 Figures 2 and 3). This broad consensus suggests that the priorities of the research
201 community and practitioners are closely aligned.

202

203 **Country of employment**

204 There were significant divergences between the views of participants from the Global North
205 and South (Supplementary Figures 4 and 5). Over two thirds (69%; n=44/64) of Global North

206 participants indicated that the challenge “*Biodiversity will be reduced due to generic,*
207 *simplified and/or homogenised management by RAS*” (item 11 in Supplementary Table 1)
208 would be important, assigning scores greater than zero. Global South participants expressed
209 much lower concern for this challenge, with it assigned a score above zero by a single
210 participant (Fisher’s Exact Test: $\chi^2=10.182$, $df=1$, $p=0.0007$; Supplementary Figure 2). The
211 discussions in rounds four and five (Figure 2) revealed that participants thought RAS
212 management of urban habitats was not imminent in cities of the Global South, due to a lack
213 of financial, technical and political capacity.

214

215 All Global South participants (100%; $n=11$) in round three assigned scores greater than zero
216 to the opportunities “*Monitoring for rubbish and pollution levels by RAS in water sources will*
217 *improve aquatic biodiversity*” (item 35) and “*Smart buildings will be better able to regulate*
218 *energy usage and reduce heat loss (e.g. through automated reflectors), reducing urban*
219 *temperatures and providing less harsh microclimatic conditions for biodiversity under*
220 *ongoing climate change*” (item 10). Both items would tackle recognised issues in rapidly
221 expanding cities. Discussions indicated that Global South participants prioritised the
222 opportunities for RAS in mitigating pollution and urban heat island effects more than their
223 Global North counterparts, even though 80% ($n= 60/75$) of Global North participants also
224 assigned positive scores to these items.

225

226 **Area of expertise**

227 There was considerable heterogeneity in how opportunities and challenges were prioritised
228 by participants with environmental and non-environmental expertise (Supplementary Figures
229 6 and 7). Significantly more participants with non-environmental expertise gave scores
230 above zero to opportunities that were about the use of RAS for the maintenance of green
231 infrastructure. The largest difference was for the opportunity “*An increase in RAS*”

232 *maintenance will allow more sites to become 'wild', as the landscape preferences of human*
233 *managers is removed"* (item 9), which 76% (n=22/29) of participants with non-environmental
234 expertise scored above zero compared to 38% (n=20/52) of those with environmental
235 expertise (Fisher's Exact Test: $\chi^2=8.987$, df=1, p=0.02). More participants with non-
236 environmental expertise (82%, n=23/28) scored the opportunity "*RAS to enable self-*
237 *repairing built infrastructure will reduce the impact of construction activities on ecosystems"*
238 (item 57) greater than zero compared to those with environmental expertise (58%; n=26/45)
239 (Fisher's Exact Test: $\chi^2=3.605$, df=1, p=0.04).

240

241 For the challenges, there was universal consensus among participants with non-
242 environmental expertise that item 31 "*Unrecovered RAS and their components (e.g.*
243 *batteries, heavy metals, plastics) will be a source of hazardous and non-degradable waste"*
244 will pose a major problem. All (n=29) scored the item above zero, compared to 73%
245 (n=40/55) for participants with environmental expertise (Fisher's Exact Test: $\chi^2=7.86$, df=1,
246 p=0.002). A greater proportion of non-environmental participants (76% n=22/29) also scored
247 challenge "*Pollution will increase if RAS are unable to identify or clean-up accidents (e.g.*
248 *spillages) that occur during automated maintenance/construction of infrastructure"* (item 32)
249 above zero compared to those with environmental expertise (45% n=22/29) (Fisher's Exact
250 Test: $\chi^2=5.90$, df=1, p=0.01). Again, a similar pattern was observed for item 38 "*RAS will*
251 *alter the hydrological microclimate (e.g. temperature, light), altering aquatic communities and*
252 *encouraging algal growth"*. A significantly greater proportion of non-environmental compared
253 to environmental participants (60% n=12/20 and 26% n=11/42 respectively) allocated scores
254 above zero (Fisher's Exact Test: $\chi^2=5.28$, df=1, p=0.013).

255

256 The mismatch in opinions of environmental and non-environmental participants in round
257 three indicate that the full benefits for urban biodiversity and ecosystem of RAS may not be

258 realised. Experts responsible for the development and implementation of RAS could
259 prioritise opportunities and challenges that do not align well with environmental concerns,
260 unless an interdisciplinary outlook is adopted. This highlights the critical importance of
261 reaching a consensus in rounds four and five of the horizon scan with a diverse set of
262 experts (Figure 2). A final set of 13 opportunities and 15 challenges were selected by the
263 participants, which could be grouped into eight topics (Table 1).

264

265 **Topic one: Urban land-use and habitat availability**

266 The emergence of autonomous vehicles in cities seems inevitable, but the scale and speed
267 of their uptake is unknown and could be hindered by financial, technological and
268 infrastructural barriers, public acceptability, or privacy and security concerns^{24,25}.

269 Nevertheless, the participants felt that there will be wide-ranging impacts for urban land-use,
270 with knock-on implications for habitat availability, quality and connectivity, and the stocks
271 and flows of ecosystem services²⁶. They highlighted that urban land-use and transport
272 planning could be transformed if the uptake of autonomous vehicles is coupled with reduced
273 personal vehicle ownership through vehicle sharing or public transport^{27,28}. Participants
274 argued that, if less land is required for transport infrastructure (e.g. roads, car parks,
275 driveways), this could enable increases in the extent and quality of urban green space.

276

277 Conversely, autonomous vehicles could raise demand for transport infrastructure through a
278 rebound effect²⁹, leading to urban sprawl and habitat fragmentation as people move further
279 away from city centres due to commuting becoming more efficient. Participants also noted
280 that autonomous transport systems will require new types of infrastructure (e.g. charging
281 stations, maintenance and control facilities, vehicle depots) that could result in additional
282 loss/fragmentation of green spaces. Furthermore, road systems may require even larger

283 amounts of paved surface to facilitate the movement of autonomous vehicles, potentially to
284 the detriment of roadside trees and vegetated margins.

285

286 **Topic two: Built and green infrastructure maintenance and management**

287 A specific RAS application within urban green infrastructure (the network of green/blue
288 spaces and other environmental features within an urban area) that was strongly supported
289 by our participants was the use of automated irrigation of vegetation to mitigate heat stress,
290 thereby optimising water use and the role trees can play in cooling cities³⁰. As an example,
291 sensors to monitor soil moisture, which would be integral in automated irrigation systems,
292 are already being deployed for urban trees in the Netherlands¹². Resilience to climate
293 change could also be improved by smart buildings that are better able to regulate energy
294 usage and reduce heat loss³¹, through the use of technology like automatic reflectors. This
295 could help reduce urban heat island effects and moderate harsh microclimates³².

296

297 Landscape management is a major homogeniser of urban ecosystems³³, and participants
298 highlighted that autonomous care of green infrastructure could lead to the simplification of
299 ecosystems, with negative consequences for biodiversity¹³. This would be the likely outcome
300 if RAS make the removal of 'weeds', leaf litter and herbicide application significantly cheaper
301 and quicker. Likewise, RAS may be unable to respond adequately to species population
302 variation and phenology, or when species that are protected or of conservation concern are
303 encountered. Participants noted that automated management of hydrological systems could
304 result in the homogenisation of water currents and timings of flow, disrupting the lifecycles of
305 flow-sensitive species. Similarly, improved building maintenance could lead to the loss of
306 nesting habitats and shelter, especially for cavity and ground-nesting species.

307

308 **Topic three: Human-nature interactions**

309 RAS will inevitably alter the ways in which people experience, and gain benefits from, urban
310 biodiversity and ecosystems. However, it is less clear what changes will occur, or how
311 benefits will be distributed across sectors of society. Environmental injustice is a feature of
312 most cities worldwide, with less privileged residents in lower income areas typically having
313 less access to green space and biodiversity³⁴⁻³⁶, while experiencing greater exposure to
314 environmental hazards such as air pollution^{37,38} and extreme temperatures³⁹. RAS have the
315 potential to mitigate, but also compound such inequalities, and the issues we highlight here
316 will manifest differently according to political and social context. RAS could even lead to
317 novel forms of injustice by exacerbating a digital divide or producing additional economic
318 barriers, whereby citizens without access to technology become increasingly digitally
319 marginalised^{13,15} from interacting with, and accessing, the natural world.

320

321 Experiencing with nature can bring a range of human health and well-being benefits⁴⁰.
322 Participants suggested that RAS will fundamentally alter human-nature interactions, but this
323 could manifest itself in contrasting ways. On the positive side, RAS have the potential to
324 reduce noise and air pollution through, for example, decreased vehicle emissions from
325 improved traffic flow and/or reduced construction. In turn, this could make cities more
326 attractive for recreation, encouraging walking and cycling in green spaces, with positive
327 outcomes for physical⁴¹ and mental health⁴². Changes in noise levels could also improve
328 experiences of biophonic sounds such as bird song⁴³. It is already known that driving
329 through green, rather than built, environments can provide some human health benefits⁴⁴.
330 These could be further enhanced if autonomous transport systems were designed to
331 increase people's awareness of surrounding green space features, or if navigation
332 algorithms preferentially choose greener routes⁴⁵. Participants also felt that autonomous
333 vehicles could improve access to green spaces for disadvantaged groups, children, elderly
334 and disabled, thus reducing environmental inequalities. Finally, citizen science is now a

335 component of urban biodiversity research and conservation⁴⁶ that can foster connectedness
336 to nature⁴⁷. Participants suggested RAS could provide a suite of different ways to engage
337 and educate the public about biodiversity and ecosystems.

338

339 Alternatively, participants envisaged scenarios whereby RAS reduce human-nature
340 interactions. One possibility is that autonomous deliveries to households may minimise the
341 need for people to leave their homes, decreasing the time they are exposed to green spaces
342 while travelling. In addition, walking and cycling could decline as new modes of transport
343 become more attractive. RAS that mimic or replace ecosystem service provision (e.g.
344 Singapore's cyborg supertrees⁴⁸, robotic pollinators⁴⁹) may reduce people's appreciation of
345 ecological functions⁵⁰, potentially undermining public support for, and values associated with,
346 green infrastructure and biodiversity conservation⁵¹.

347

348 **Topic four: Biodiversity and environmental data and monitoring**

349 RAS are already widely used for the automated collection of biodiversity and environmental
350 monitoring data in towns and cities⁵². This has the potential to greatly enhance urban
351 planning and management decision-making¹². Continuing to expand such applications would
352 be a logical step and one that participants identified as an important opportunity⁵³. RAS will
353 allow faster and cheaper data collection over large spatial and temporal scales, particularly
354 across inaccessible or privately owned land. Ecoacoustic surveying and automated sampling
355 of environmental DNA (eDNA) will enable the monitoring of hard to detect species^{54,55}. RAS
356 also offer potential in the future to detect plant diseases within urban vegetation and,
357 subsequently, control them⁵⁶.

358

359 Nevertheless, our participants highlighted that the technology and baseline taxonomy
360 necessary for the identification of the vast majority of species autonomously is, as yet,
361 unavailable. If RAS cannot reliably monitor cryptic or unappealing taxa, the existing trend for
362 conservation actions to prioritise easy to identify and charismatic species in well-studied
363 regions could intensify⁵⁷. Participants emphasised that easily collected RAS data, such as
364 tree canopy cover, could be used as surrogates for biodiversity without proper evidence
365 informing their efficacy. This would mirror current practices, rather than offering any
366 fundamental improvements in monitoring. Moreover, there is a risk that subjective or
367 intangible ecosystem elements (e.g. landscape, aesthetic, spiritual benefits) that cannot be
368 captured or quantified autonomously may be overlooked in decision-making⁵⁸. Participants
369 were worried that the sheer quantity, variety and complexity of big data gathered by RAS
370 monitoring could make it difficult for decision-makers to coordinate citywide responses⁵⁹.

371

372 **Topic five: Managing invasive and pest species**

373 The abundance and diversity of invasive and pest species are often higher in cities⁶⁰. One
374 priority concern identified by the participants is that RAS could offer new introduction
375 pathways, dispersal opportunities or different niches that could help invasive species to
376 establish. Although RAS may provide novel approaches to managing invasive and pest
377 species, participants were worried about how this would be implemented and the potential
378 for error, whereby misidentification leads to non-target species being controlled accidentally.
379 Likewise, RAS-mediated pest control could threaten unpopular taxa, such as wasps or
380 termites, if the interventions are not informed by knowledge of the important ecosystem
381 functions such species underpin.

382

383 **Topic six: RAS interactions with animals**

384 The negative impact of unmanned aerial vehicles on wildlife is well-documented⁶¹, but
385 participants highlighted that RAS activity at new heights and locations within cities will
386 generate novel threats, particularly for raptors that may perceive drones as prey or a larger
387 rival. One possible mitigation might be that unmanned aerial vehicle activity is concentrated
388 along corridors. However, participants noted that this could further fragment habitat by
389 creating a 3-dimensional barrier to animal movement, which might disproportionately affect
390 migratory species. Similarly, ground-based or tree-climbing robots⁶² may disturb nesting and
391 non-flying animals.

392

393 **Topic seven: Managing pollution and waste**

394 Air^{63,64}, noise⁶⁵ and light^{66,67} pollution can substantially alter urban ecosystem function.
395 Participants believed that RAS would generate a range of important opportunities for
396 reducing and mitigating such pollution. For instance, automated transport systems and road
397 repairs could reduce vehicle numbers and improve traffic flow²⁷, leading to lower emissions
398 and improved air quality. If increased autonomous vehicle use reduced noise from traffic,
399 species that rely on acoustic communication could benefit. Similarly, automated and
400 responsive lighting systems will reduce light impacts on nocturnal species, including
401 migrating birds⁶⁸. RAS that monitor air quality, detect breaches of environmental law and
402 clean-up pollutants are already under development^{69,70}. Waste management is a major
403 problem for urban sustainability, and participants noted that RAS⁷¹ could provide a solution.
404 Despite this potential, participants felt that unrecovered RAS could themselves contribute to
405 the problem of electronic waste, which is a growing hazard for human, wildlife and
406 ecosystem health⁷².

407

408 **Topic eight: Water and flooding**

409 Freshwater, estuarine, wetland and coastal habitats are valuable components of urban
410 ecosystems worldwide⁷³, and maintenance of water, sanitation and wastewater infrastructure
411 is a major sustainability issue⁷⁴. Participants thought that automated monitoring and
412 management of water infrastructure could lead to a reduction in pollution incidents, improve
413 water quality and reduce flooding^{75,76}. If stormwater flooding is diminished, there may be
414 scope for restoring heavily engineered river channels to a more natural condition, thereby
415 enhancing biodiversity, ecosystem function and service provision⁷⁷. Participants were
416 concerned, however, that the opposite scenario could also materialise, whereby RAS-
417 maintained stormwater infrastructure increases reliance on hard engineered solutions,
418 decreasing uptake of nature-based solutions (e.g. trees, wetlands, rain gardens, swales,
419 retention basins) that provide habitat and other ecosystem services⁷⁸.

420

421 **Conclusions**

422 We are currently in the midst of the fourth industrial revolution. Identifying, understanding
423 and responding to the novel impacts, both positive and negative, of new technologies is
424 essential for ensuring urban sustainability and maximising ecosystem service delivery. Here
425 we prioritise the most important opportunities and challenges for urban biodiversity and
426 ecosystems associated with RAS. Such explicit consideration of how urban biodiversity and
427 ecosystems maybe affected by the development of technological solutions in our towns and
428 cities is critical if we are to prevent environmental issues being sidelined. However, we have
429 to appreciate that some trade-offs to the detriment of the environment are likely to be
430 inevitable. Additionally, it is highly probable that multiple RAS will be deployed
431 simultaneously, making it extremely difficult to anticipate interactive effects. To mitigate and
432 minimise any potential harmful effects of RAS, environmental scientists should advocate for
433 critical impact evaluations to be conducted before phased implementation. Long-term
434 monitoring, comparative studies and controlled experiments could then further our

435 understanding of how biodiversity and ecosystems will be effected. This is essential as the
436 pace of technological change is much faster than that of environmental regulation, which is
437 likely to be outdated by the time it is implemented. Although the future impacts of innovative
438 RAS developments are hard to predict, examining them early is essential if we are to avoid
439 detrimental and unintended consequences on urban biodiversity and ecosystems, but fully
440 realise the benefits.

441 **Methods**

442 **Horizon scan participants**

443 We invited 480 experts working across the research, private, public and NGO sectors
444 globally to take part in the horizon scan. Further participants were sought through snowball
445 sampling (i.e. invitees suggesting additional experts who might be interested in taking part),
446 mailing lists (e.g. groups with a focus on urban ecosystems; the research, development and
447 manufacture of RAS; urban infrastructure) and social media. We asked participants to
448 indicate their area of expertise from five categories: (i) environmental (including ecology,
449 conservation and all environmental sciences and professions); (ii) infrastructure (including
450 engineering and maintenance); (iii) sustainable cities (covering any aspect of urban
451 sustainability, including the implementation of 'smart' cities); (iv) RAS (including research,
452 manufacture and application); or (v) urban planning (including architecture and landscape
453 architecture). Participants whose area of expertise did not fall within these categories were
454 excluded from the process. We collected information on participants' country of employment.
455 Subsequently, these were allocated into one of two global regions, the Global North or
456 Global South (low and middle income countries in South America, Asia, Oceania, Africa,
457 South America and the Caribbean⁷⁹). Participants specified their employment sector
458 according to four categories: (i) research; (ii) government; (iii) private business; or (iv)
459 NGO/not-for-profit.

460

461 We asked participants to provide informed consent prior to taking part in the horizon scan
462 activities. We made them aware that their involvement was entirely voluntary, that they could
463 stop at any point and withdraw from the process without explanation, and that their answers
464 would be anonymous and unidentifiable. Ethical approval was granted by the University of
465 Leeds Research Ethics Committee (reference LTSEE-077). Anonymised data are available,
466 via MD, on the University of Leeds institutional data repository

467 (<http://archive.researchdata.leeds.ac.uk>). We piloted and pre-tested each round in the
468 horizon scan process, which helped to refine the wording of questions and definitions of
469 terminology used.

470

471 **Horizon scan using the Delphi technique**

472 The horizon scan applied a modified Delphi technique, which is applied widely in the
473 conservation and environmental sciences literature²¹. The Delphi technique is a structured
474 and iterative survey of a group of participants. It has a number of advantages over standard
475 approaches to gathering opinions from groups of people. For example, it minimises social
476 pressures such as groupthink, halo effects and the influence of dominant individuals²¹. The
477 first round can be largely unstructured, to capture a broad range and depth of contributions.
478 In our horizon scan, we asked each participant to identify between two and five ways in
479 which the emergence of RAS could affect urban biodiversity and/or ecosystem
480 structure/function via a questionnaire. They could either be opportunities (i.e. RAS would
481 have a positive impact on biodiversity and ecosystem structure/function) or challenges (i.e.
482 RAS would have a negative impact) (Figure 2). Round one resulted in the submission of 604
483 pertinent statements. We removed statements not relevant to urban biodiversity or urban
484 ecosystems. Likewise, we excluded statements relating to artificial intelligence or
485 virtual/augmented reality, as these technologies fall outside the remit of RAS. MAG
486 subsequently collated and categorised the statements into major topics through content
487 analysis. A total of sixty opportunities and challenges were identified.

488

489 In round two, we presented participants with the 60 opportunities and challenges,
490 categorised by topic, for review. We asked them to clarify, expand, alter or make additions
491 wherever they felt necessary (Figure 2). This round resulted in a further 468 statements and,
492 consequently, a further 10 opportunities and challenges emerged.

493

494 In round three, we used a questionnaire to get participants to prioritise the 70 opportunities
495 and challenges in order of importance (Figure 2). We asked participants to score four
496 criteria^{22,80} using a 5-point Likert scale ranging from -2 (very low) to +2 (very high): (i)
497 likelihood of occurrence; (ii) potential impact (i.e. the magnitude of positive or negative
498 effects); (iii) extensiveness (i.e. how widespread the effects will be); and (iv) degree of
499 novelty (i.e. how well known or understood the issue is). A 'do not know' option was also
500 available. We randomly ordered the opportunities and challenges between participants to
501 minimise the influence of scoring fatigue⁸¹. For each participant, we generated a total score
502 (ranging from -8 to +8) for every opportunity and challenge by summing across all four
503 criteria. Opportunities and challenges were ranked according to the proportion of
504 respondents assigning them a summed score greater than zero. If a participant answered
505 'do not know' for one or more of the criteria for a particular opportunity or challenge, we
506 excluded all their scores for that opportunity or challenge (see Supplementary Table 2 for
507 resulting sample sizes). We generated score visualisations in the 'Likert' package⁸² of R
508 version 3.4.1⁸³. Two-tailed Fisher's exact tests were used to examine whether the
509 percentage of participants scoring items above zero differed between cohorts with different
510 backgrounds (i.e. country of employment, employment sector and area of expertise).

511

512 Final consensus on the most important opportunities and challenges was reached using
513 online group discussions (round four), followed by an online consensus workshop (round
514 five) (Figure 2; Supplementary Table 1). For round four, we allocated participants into one of
515 ten groups, with each group comprising of experts with diverse backgrounds. We asked the
516 groups to discuss the ranked 32 opportunities and 38 challenges, and agree on their ten
517 most important opportunities and ten most important challenges. It did not matter if these
518 differed from the round three rankings. Additionally, we asked groups to discuss whether any
519 of the opportunities or challenges were similar enough to be merged. Across all the groups,

520 14 opportunities and 16 challenges were identified as most important. Participants, including
521 at least one representative from each of the ten discussion groups, took part in the final
522 consensus workshop. The facilitated discussions resulted in a final consensus set of 13
523 opportunities and 15 challenges (Table 1).

524

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532

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

and ecosystems. The opportunities and challenges were prioritised as part of an online horizon scan involving 170 expert participants from 35 countries (Figure 2). The full set of 32 opportunities and 38 challenges identified by participants in round three is given in Supplementary Table 1.

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

Topic	Opportunities	Challenges
1. Urban land-use and habitat availability	Autonomous transport systems and associated decreased 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).	<p>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).</p> <p>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).</p> <p>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).</p>
2. Maintenance and management of built and green infrastructure	<p>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).</p> <p>Irrigation of street trees and other vegetation by RAS will lead to greater resilience to climate change/urban heat stress (item 8).</p>	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).

3. Human-nature interactions	<p>RAS will decrease pollution, making cities more attractive for recreation and enhancing opportunities for experiencing nature (item 42).</p> <p>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).</p>	<p>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 travelling (item 46).</p> <p>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).</p> <p>RAS will exacerbate the exclusion of certain people from nature (item 48).</p>
4. Biodiversity and environmental data and monitoring	<p>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).</p> <p>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).</p>	<p>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).</p> <p>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-valuation of 'invisible' species and elements (item 6).</p>
5. Managing invasive and pest species		<p>When managing/controlling pest or invasive species, RAS identification errors will harm non-target species (item 66).</p> <p>RAS will provide new introduction pathways, facilitate dispersal, and provide new habitats for pest and invasive species (item 68).</p>

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).

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).

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).

Unrecovered RAS and their components (e.g. batteries, heavy metals, plastics) will be a source of hazardous and non-degradable waste (item 31).

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).

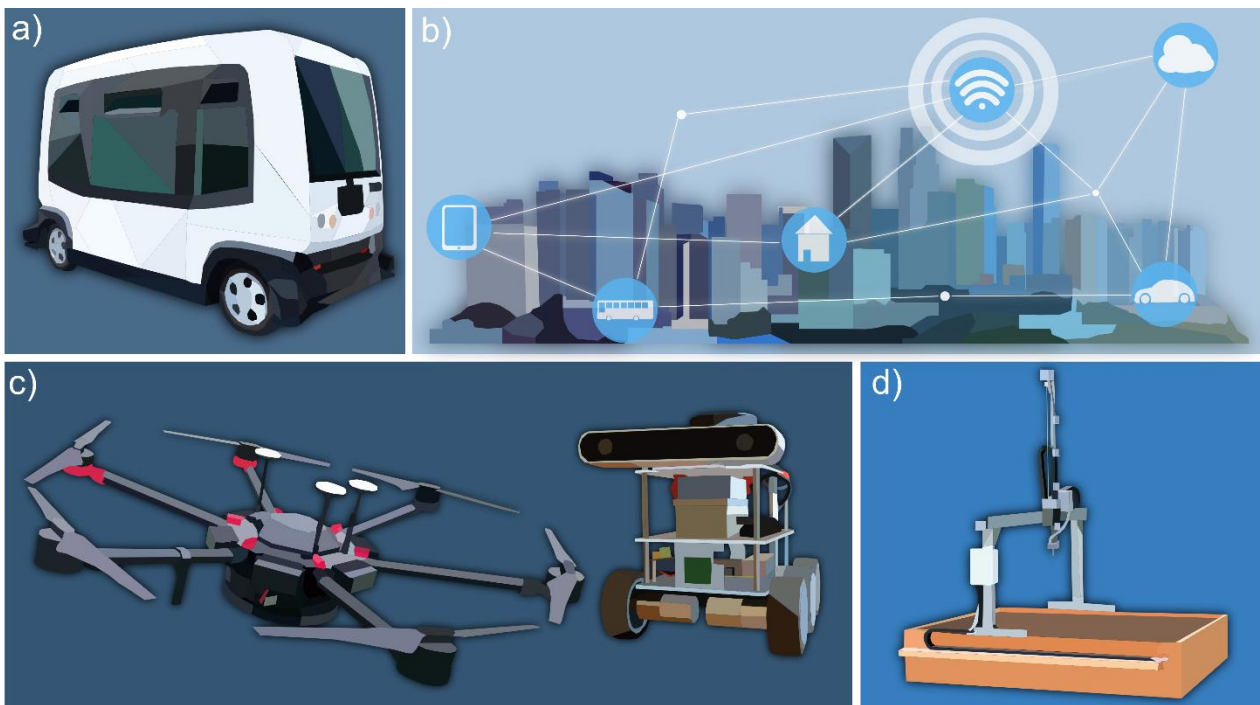


Figure 1. Examples of the potential for robotics and automated systems to transform cities.

(a) 25% of transport in Dubai is planned to function autonomously by 2030⁸⁴; (b) city-wide sensor networks, such as those used in Singapore, inform public safety, water management, and responsive public transport initiatives⁸⁵; (c) Leeds, UK, is expecting to implement fully autonomous maintenance of built infrastructure by 2035²; and (d) precision agricultural technology for small-scale urban agriculture (<https://farm.bot/>).

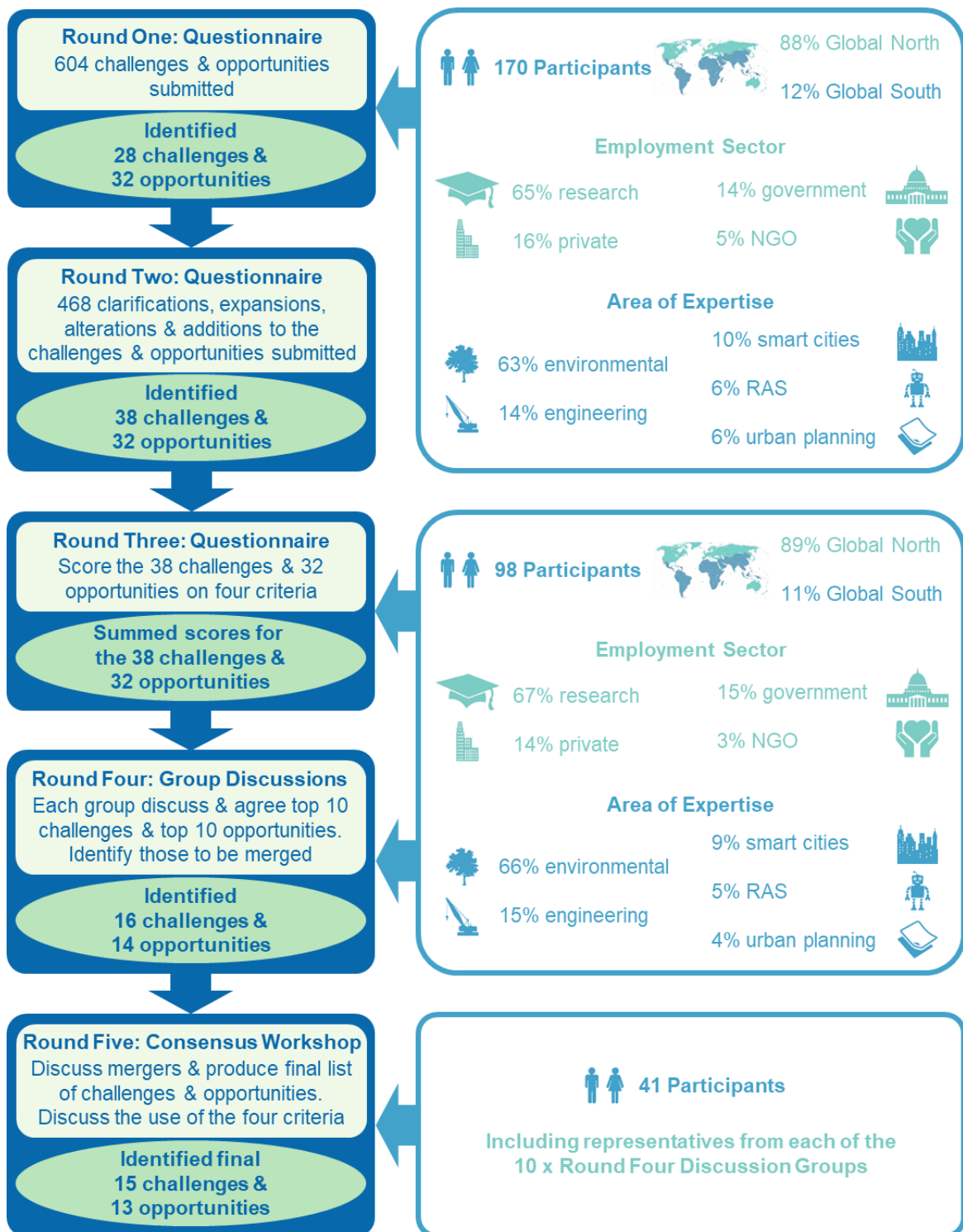


Figure 2. Horizon scan process used to identify and prioritise opportunities and challenges associated with robotics and automated systems for urban biodiversity and ecosystems. The horizon scan comprised an online survey, following a modified Delphi technique, which was conducted over five rounds.

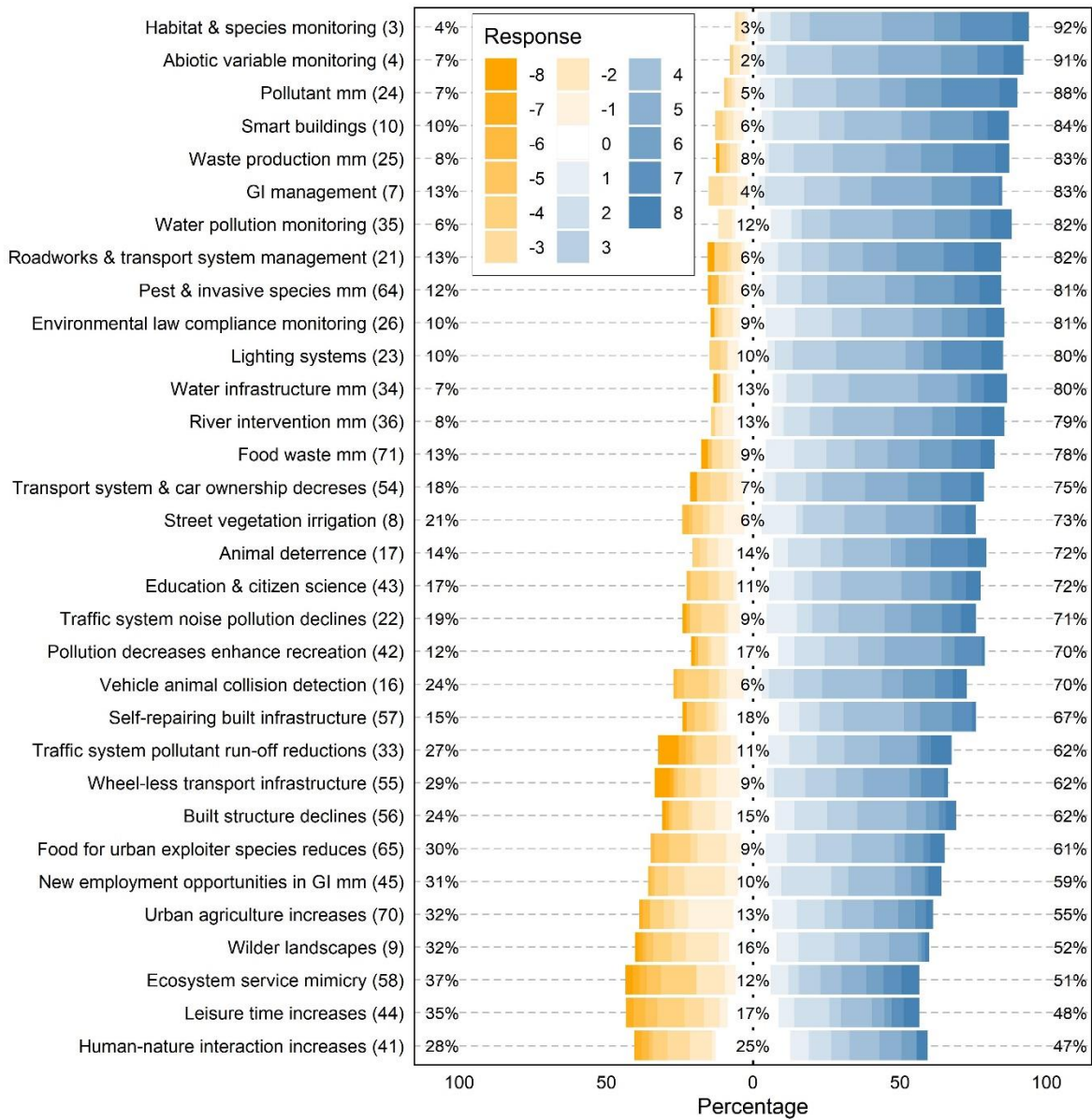


Figure 3. Opportunities associated with robotics and automated systems for urban biodiversity and ecosystems, ranked according to round three participant scores. The distribution of summed participant scores (range: -8 to +8) across four criteria (likelihood, impact, extent, novelty) for each of the 32 opportunities. Items are ordered according to percentage of participants 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.

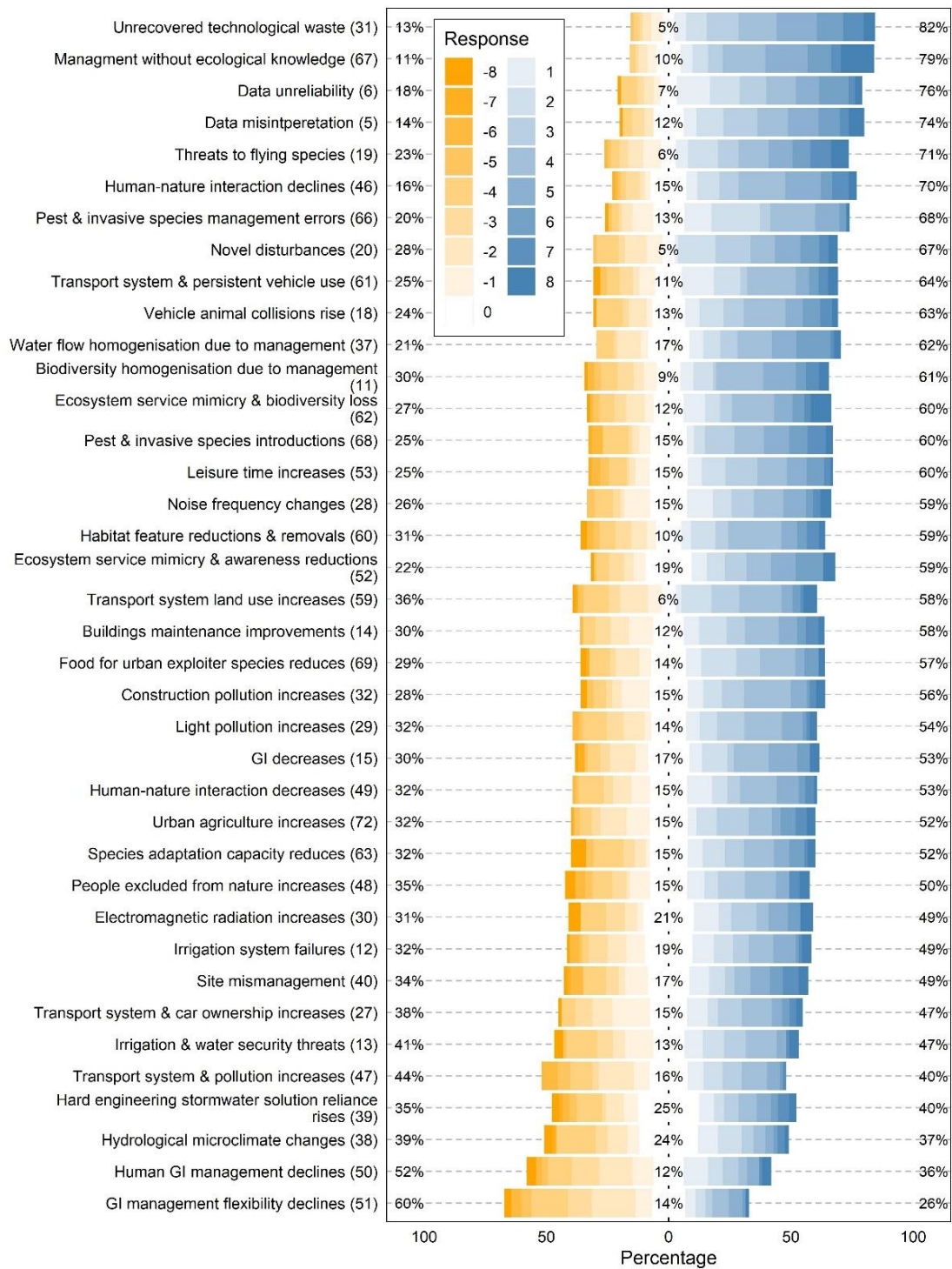


Figure 4. Challenges associated with robotics and automated systems for urban biodiversity and ecosystems, ranked according to round three participant scores. The distribution of summed participant scores (range: -8 to +8) across four criteria (likelihood, impact, extent, novelty) for each of the 38 challenges. Items are ordered according to percentage of participants 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.

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