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

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

3

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130

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

145

146 We are currently witnessing the fourth industrial revolution¹. Technological innovations have
147 altered the way in which economies operate, and how people interact with built, social and
148 natural environments. One area of transformation is the emergence of robotics and
149 autonomous systems (RAS), defined as technologies that can sense, analyse, interact with
150 and manipulate their physical environment². RAS include unmanned aerial vehicles
151 (drones), self-driving cars, robots able to repair infrastructure, and wireless sensor networks
152 used for monitoring. RAS therefore have a large range of potential applications, such as
153 autonomous transport, waste collection, infrastructure maintenance and repair, policing^{2,3},
154 and precision agriculture⁴ (Figure 1). RAS have already revolutionised how environmental
155 data are collected⁵, and species populations are monitored for conservation⁶ and/or control⁷.
156 Globally, the RAS market is projected to grow from \$6.2 billion in 2018 to \$17.7 billion in
157 2026⁸.

158

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

167

168 Presently, we have little appreciation of the pathways through which the widespread uptake
169 and deployment of RAS could affect urban biodiversity and ecosystems^{12,13}. To date,
170 information on how RAS may impact urban biodiversity and ecosystems remains scattered
171 across multiple sources and disciplines, if it has been recorded at all. The widespread use of
172 RAS has been proposed as a mechanism to enhance urban sustainability¹⁴, but critics have
173 questioned this techno-centric vision^{15,16}. Moreover, while RAS are likely to have far-
174 reaching social, ecological, and technological ramifications, these are often discussed only in
175 terms of the extent to which their deployment will improve efficiency and data harvesting,
176 and the associated social implications¹⁷⁻¹⁹. Such a narrow focus will likely overlook
177 interactions across the social-ecological-technical systems that cities are increasingly
178 thought to represent²⁰. Without an understanding of the opportunities and challenges RAS
179 will bring, their uptake could cause conflict with the provision of high quality natural
180 environments within cities¹³, which can support important populations of many species²¹, and
181 are fundamental to the provision of ecosystem services that benefit people²².

182

183 Here we report the findings of an online horizon scan to evaluate and prioritise future
184 opportunities and challenges for urban biodiversity and ecosystems, including their structure,
185 function and service provision, associated with the emergence of RAS. Horizon scans are
186 not conducted to fill a knowledge gap in the conventional research sense, but are used to
187 explore arising trends and developments, with the intention of fostering innovation and
188 facilitating proactive responses by researchers, managers, policymakers and other
189 stakeholders²³. Using a modified Delphi technique, which is a structured and iterative
190 survey²³⁻²⁵ (Figure 2), we systematically collated and synthesised knowledge from 170
191 expert participants based in 35 countries (Extended Data Fig.). We designed the exercise to
192 involve a large range of participants and incorporate a diversity of perspectives²⁶.

193

194 **Results and Discussion**

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

206

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

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

215

216 **Country of employment**

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

221

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

232

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

243

244 **Area of expertise**

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

258

259 For the challenges, there was universal consensus among participants with non-
260 environmental expertise that “*Unrecovered RAS and their components (e.g. batteries, heavy*
261 *metals, plastics) will be a source of hazardous and non-degradable waste*” (item 31) will
262 pose a major problem. All (n=29) scored the item above zero, compared to 73% (n=40/55)
263 for participants with environmental expertise (Fisher’s Exact Test: odds ratio=0, 95% CI 0–
264 0.43, p=0.002). A greater proportion of non-environmental participants (76% n=22/29) also
265 scored challenge “*Pollution will increase if RAS are unable to identify or clean-up accidents*
266 *(e.g. spillages) that occur during automated maintenance/construction of infrastructure*” (item
267 32) above zero compared to those with environmental expertise (45% n=22/29) (Fisher’s
268 Exact Test: odds ratio=0.26 (95% CI 0.08–0.79), p=0.01). Again, a similar pattern was
269 observed for item 38 “*RAS will alter the hydrological microclimate (e.g. temperature, light),*
270 *altering aquatic communities and encouraging algal growth*”. A significantly greater
271 proportion of non-environmental compared to environmental participants (60% n=12/20 and
272 26% n=11/42 respectively) allocated scores above zero (Fisher’s Exact Test: odds
273 ratio=0.24 (95% CI 0.07–0.84), p=0.013).

274

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

283

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

285 The emergence of autonomous vehicles in cities seems inevitable, but the scale and speed
286 of their uptake is unknown and could be hindered by financial, technological and
287 infrastructural barriers, public acceptability, or privacy and security concerns^{29,30}.
288 Nevertheless, participants anticipated wide-ranging impacts for urban land-use and
289 management, with implications for habitat extent, availability, quality and connectivity, and
290 the stocks and flows of ecosystem services³¹, not least because alterations to the amount
291 and quality of green space affects both species³² and people's well-being³³. Participants
292 highlighted that urban land-use and transport planning could be transformed^{34,35} if the uptake
293 of autonomous vehicles is coupled with reduced personal vehicle ownership through vehicle
294 sharing or public transport³⁶⁻³⁸. Participants argued that, if less land is required for transport
295 infrastructure (e.g. roads, car parks, driveways)³⁹, this could enable increases in the extent
296 and quality of urban green space. Supporting this view, research suggests that the need for
297 parking could be reduced by 80-90%⁴⁰.

298

299 Conversely, participants highlighted that autonomous vehicles could raise demand for
300 private vehicle transport infrastructure, leading to urban sprawl and habitat
301 loss/fragmentation as people move further away from centres of employment because
302 commuting becomes more efficient^{41,42}. Urban sprawl has a major impact on biodiversity⁴³.
303 Participants also noted that autonomous transport systems will require new types of
304 infrastructure (e.g. charging stations, maintenance and control facilities, vehicle depots)⁴⁴
305 that could result in additional loss/fragmentation of green spaces. Furthermore, road
306 systems may require even larger amounts of paved surface to facilitate the movement of
307 autonomous vehicles, potentially to the detriment of roadside trees and vegetated margins³⁹.

308

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

310 A specific RAS application within urban green infrastructure (the network of green/blue
311 spaces and other environmental features within an urban area) that was strongly supported
312 by our participants was the use of automated irrigation of vegetation to mitigate heat stress,
313 thereby optimising water use and the role trees can play in cooling cities. For example,
314 sensors to monitor soil moisture, an integral component in automated irrigation systems, are
315 deployed for urban trees in the Netherlands¹², and similar applications are available for
316 urban gardening⁴⁵. This is likely to be particularly important in arid cities as irrigation can be
317 informed by weather data and measures of evapotranspiration⁴⁶. Resilience to climate
318 change could also be improved by smart buildings that are better able to regulate energy
319 usage and reduce heat loss⁴⁷, through the use of technology like light sensing blinds and
320 reflectors⁴⁸. This could help reduce urban heat island effects and moderate harsh
321 microclimates⁴⁹.

322

323 Landscape management is a major driver of urban ecosystems⁵⁰, which can be especially
324 complex, due to the range of habitat types and the variety of stakeholder requirements⁵¹.
325 Participants highlighted that autonomous care of green infrastructure could lead to the
326 simplification of ecosystems, with negative consequences for biodiversity¹³. This would be
327 the likely outcome if RAS make the removal of 'weeds', leaf litter and herbicide application
328 significantly cheaper and quicker, such as through the widespread uptake of robotic lawn
329 mowers or tree-climbing robots for pruning⁵². Urban ecosystems can be heterogeneous in
330 habitat type and structure⁵¹ and phenology⁵³. RAS, therefore, may be unable to respond
331 adequately to species population variation and phenology, or when species that are
332 protected or of conservation concern are encountered. For hydrological systems in
333 particular, participants noted that automated management could result in the
334 homogenisation of water currents and timings of flow, which are known to disrupt the
335 lifecycles of flow-sensitive species⁵⁴. Similarly, improved building maintenance could lead to

336 the loss of nesting habitats and shelter (e.g. for house sparrows *Passer domesticus*⁵⁵),
337 especially for cavity and ground-nesting species.

338

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

340 RAS will inevitably alter the ways in which people experience, and gain benefits from, urban
341 biodiversity and ecosystems. However, it is less clear what changes will occur, or how
342 benefits will be distributed across sectors of society. Environmental injustice is a feature of
343 most cities worldwide, with residents in lower income areas typically having less access to
344 green space and biodiversity⁵⁶⁻⁵⁸, while experiencing greater exposure to environmental
345 hazards such as air pollution^{59,60} and extreme temperatures⁶¹. RAS have the potential to
346 mitigate, but also compound such inequalities, and the issues we highlight here will manifest
347 differently according to political and social context. RAS could even lead to novel forms of
348 injustice by exacerbating a digital divide or producing additional economic barriers, whereby
349 those without access to technology become increasingly digitally marginalised^{13,15} from
350 interacting with, and accessing, the natural world.

351

352 Experiencing nature can bring a range of human health and well-being benefits⁶².
353 Participants suggested that RAS will fundamentally alter human-nature interactions, but this
354 could manifest itself in contrasting ways. On the positive side, RAS have the potential to
355 reduce noise and air pollution⁶³⁻⁶⁵ through, for example, automated infrastructure repairs
356 leading to decreased vehicle emissions from improved traffic flow and/or reduced
357 construction. In turn, this could make cities more attractive for recreation, encouraging
358 walking and cycling in green spaces, with positive outcomes for physical⁶⁶ and mental
359 health⁶⁷. Changes in noise levels could also improve experiences of biophonic sounds such
360 as bird song⁶⁸. Driving through green, rather than built, environments can provide human
361 health benefits⁶⁹. These could be further enhanced if autonomous transport systems were

362 designed to increase people's awareness of surrounding green space features, or if
363 navigation algorithms preferentially choose greener routes⁷⁰. Autonomous vehicles could
364 alter how disadvantaged groups such as children, elderly and disabled travel⁷¹. Participants
365 felt that this might mean improved access to green spaces, thus reducing environmental
366 inequalities. Finally, community (or citizen) science is now a component of urban biodiversity
367 research and conservation⁷² that can foster connectedness to nature⁷³. Participants
368 suggested RAS could provide a suite of different ways to engage and educate the public
369 about biodiversity and ecosystems such as through easier access to and input into real-time
370 data on species⁷⁴.

371

372 Alternatively, participants envisaged scenarios whereby RAS reduce human-nature
373 interactions. One possibility is that autonomous deliveries to households may minimise the
374 need for people to leave their homes, decreasing their exposure to green spaces while
375 travelling. In addition, walking and cycling could decline as new modes of transport
376 predominate⁷⁵. RAS that mimic or replace ecosystem service provision (e.g. Singapore's
377 cyborg supertrees⁷⁶, robotic pollinators⁷⁷) may reduce people's appreciation of ecological
378 functions⁷⁸, potentially undermining public support for, and values associated with, green
379 infrastructure and biodiversity conservation⁷⁹. This is in line with what is thought to be
380 occurring as people's experience of nature is increasingly dominated by digital media⁸⁰.

381

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

383 RAS are already widely used for the automated collection of biodiversity and environmental
384 monitoring data in towns and cities⁸¹. This has the potential to greatly enhance urban
385 planning and management decision-making¹². Continuing to expand such applications would
386 be a logical step and one that participants identified as an important opportunity⁸². RAS will
387 allow faster and cheaper data collection over large spatial and temporal scales, particularly

388 across inaccessible or privately owned land. Ecoacoustic surveying and automated sampling
389 of environmental DNA (eDNA) is already enabling the monitoring of hard to detect
390 species^{83,84}. RAS also offer potential to detect plant diseases in urban vegetation and,
391 subsequently inform control measures^{85,86}.

392

393 Nevertheless, our participants highlighted that the technology and baseline taxonomy
394 necessary for the identification of the vast majority of species autonomously is currently
395 unavailable. If RAS cannot reliably monitor cryptic, little-known or unappealing taxa, the
396 existing trend for conservation actions to prioritise easy to identify and charismatic species in
397 well-studied regions could intensify⁸⁷. Participants emphasised that easily collected RAS
398 data, such as tree canopy cover, could serve as surrogates for biodiversity and ecosystem
399 structure/function without proper evidence informing their efficacy. This would mirror current
400 practices, rather than offering any fundamental improvements in monitoring. Moreover, there
401 is a risk that subjective or intangible ecosystem elements (e.g. landscape, aesthetic, spiritual
402 benefits) that cannot be captured or quantified autonomously may be overlooked in decision-
403 making⁸⁸. Participants expressed concern that the quantity, variety and complexity of big
404 data gathered by RAS monitoring could present new barriers to decision-makers when
405 coordinating citywide responses⁸⁹.

406

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

408 The abundance and diversity of invasive and pest species are often high in cities⁹⁰. One
409 priority concern identified by the participants is that RAS could facilitate new introduction
410 pathways, dispersal opportunities or different niches that could help invasive species to
411 establish. Participants noted that RAS offer clear opportunities for earlier and more efficient
412 pest and invasive species detection, monitoring and management^{91,92}. However, participants
413 were concerned the implementation of such novel approaches, citing the potential for error,

414 whereby misidentification leads to accidentally controlling non-target species. Likewise,
415 RAS-mediated pest control could threaten unpopular taxa, such as wasps or termites, if the
416 interventions are not informed by knowledge of the important ecosystem functions such
417 species underpin.

418

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

420 The negative impact of unmanned aerial vehicles on wildlife is well-documented⁹³, but
421 evidence from some studies in non-urban settings suggest this impact may not be
422 universal^{94,95}. Nevertheless, participants highlighted that RAS activity at new heights and
423 locations within cities will generate novel threats, particularly for raptors that may perceive
424 drones as prey or competitors. Concentrating unmanned aerial vehicle activity along
425 corridors is a possible mitigation strategy. However, participants noted that this could further
426 fragment habitat by creating a 3-dimensional barrier to animal movement, which might
427 disproportionately affect migratory species. Similarly, ground-based or tree-climbing robots⁹⁶
428 may disturb nesting and non-flying animals.

429

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

431 Air^{97,98}, noise⁹⁹ and light^{100,101} pollution can substantially alter urban ecosystem function.
432 Participants believed that RAS would generate a range of important opportunities for
433 reducing and mitigating such pollution. For instance, automated transport systems and road
434 repairs could reduce vehicle numbers and improve traffic flow³⁶, leading to lower emissions
435 and improved air quality^{64,65}. If increased autonomous vehicle use reduced noise from traffic,
436 species that rely on acoustic communication could benefit. Similarly, automated and
437 responsive lighting systems will reduce light impacts on nocturnal species, including
438 migrating birds¹⁰². RAS that monitor air quality, detect breaches of environmental law and
439 clean-up pollutants are already under development^{103,104}. Waste management is a major

440 problem for urban sustainability, and participants noted that RAS¹⁰⁵ could provide a solution
441 through automated detection and retrieval. Despite this potential, participants felt that
442 unrecovered RAS could themselves contribute to the generation of electronic waste, which is
443 a growing hazard for human, wildlife and ecosystem health¹⁰⁶.

444

445 **Topic eight: Water and flooding**

446 Freshwater, estuarine, wetland and coastal habitats are valuable components of urban
447 ecosystems worldwide¹⁰⁷. Maintenance of water, sanitation and wastewater infrastructure is
448 a major sustainability issue¹⁰⁸. It is increasingly acknowledged that RAS could play a pivotal
449 role in how these systems are monitored and managed¹⁰⁹, including improving drinking
450 water¹¹⁰, addressing water quality issues associated with sewerage systems¹¹¹ and
451 monitoring and managing diverse aspects of stormwater predictions and flows¹¹².
452 Participants therefore concluded that automated monitoring and management of water
453 infrastructure could lead to a reduction in pollution incidents, improve water quality and
454 reduce flooding^{113,114}. Further, they felt that if stormwater flooding is diminished, there may
455 be scope for restoring heavily engineered river channels to a more natural condition, thereby
456 enhancing biodiversity, ecosystem function and service provision¹¹⁵. Participants identified,
457 however, that the opposite scenario could materialise, whereby RAS-maintained stormwater
458 infrastructure increases reliance on hard engineered solutions, decreasing uptake of nature-
459 based solutions (e.g. trees, wetlands, rain gardens, swales, retention basins) that provide
460 habitat and other ecosystem services¹¹⁶.

461

462 **Conclusions**

463 The fourth industrial revolution is transforming the way economies and society operate.

464 Identifying, understanding and responding to the novel impacts, both positive and negative,

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

482 **Methods**

483 **Horizon scan participants**

484 We adopted a mixed approach to recruiting experts to participant in the horizon scan to
485 minimise the likelihood of bias associated with relying on a single method. For instance,
486 snowball sampling (i.e. invitees suggesting additional experts who might be interested in
487 taking part) alone might over-represent individuals who are similar to one another, although
488 it can be effective at successfully recruiting individuals from hard-to-reach groups¹¹⁷. We
489 therefore contacted individuals directly via email inviting them to join the horizon scan, as
490 well as using social media and snowball sampling. The 480 experts working across the
491 research, private, public and NGO sectors globally contacted directly were identified through
492 professional networks, mailing lists (e.g. groups with a focus on urban ecosystems; the
493 research, development and manufacture of RAS; urban infrastructure), authors lists of
494 recently published papers, and via the editorial boards of subject-specific journals. Of the
495 170 participants who took part in Round One, 143 (84%) were individuals who has been
496 invited directly, with the remainder obtained through snowball sampling and social media.

497

498 We asked participants to indicate their area of expertise from five categories: (i)
499 environmental (including ecology, conservation and all environmental sciences); (ii)
500 infrastructure (including engineering and maintenance); (iii) sustainable cities (covering any
501 aspect of urban sustainability, including the implementation of 'smart' cities); (iv) RAS
502 (including research, manufacture and application); or (v) urban planning (including
503 architecture and landscape architecture). Participants whose area of expertise did not fall
504 within these categories were excluded from the process. We collected information on
505 participants' country of employment. Subsequently, these were allocated into one of two
506 global regions, the Global North or Global South (low and middle income countries in South
507 America, Asia, Oceania, Africa, South America and the Caribbean¹¹⁸). Participants specified

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

510

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

518

519 **Horizon scan using the Delphi technique**

520 The horizon scan applied a modified Delphi technique, which is applied widely in the
521 conservation and environmental sciences literature²⁴. The Delphi technique is a structured
522 and iterative survey of a group of participants. It has a number of advantages over standard
523 approaches to gathering opinions from groups of people. For example, it minimises social
524 pressures such as groupthink, halo effects and the influence of dominant individuals²⁴. The
525 first round can be largely unstructured, to capture a broad range and depth of contributions.
526 In our horizon scan, we asked each participant to identify between two and five ways in
527 which the emergence of RAS could affect urban biodiversity and/or ecosystem
528 structure/function via a questionnaire. They could either be opportunities (i.e. RAS would
529 have a positive impact on biodiversity and ecosystem structure/function) or challenges (i.e.
530 RAS would have a negative impact) (Figure 2). Round One resulted in the submission of 604
531 pertinent statements. We removed statements not relevant to urban biodiversity or urban
532 ecosystems. Likewise, we excluded statements relating to artificial intelligence or
533 virtual/augmented reality, as these technologies fall outside the remit of RAS. MAG

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

536

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

541

542 In Round Three, we used a questionnaire to ask participants to prioritise the 70 opportunities
543 and challenges in order of importance (Figure 2). We asked participants to score four
544 criteria^{25,119} using a 5-point Likert scale ranging from -2 (very low) to +2 (very high): (i)
545 likelihood of occurrence; (ii) potential impact (i.e. the magnitude of positive or negative
546 effects); (iii) extensiveness (i.e. how widespread the effects will be); and (iv) degree of
547 novelty (i.e. how well known or understood the issue is). A 'do not know' option was also
548 available. We randomly ordered the opportunities and challenges between participants to
549 minimise the influence of scoring fatigue¹²⁰. For each participant, we generated a total score
550 (ranging from -8 to +8) for every opportunity and challenge by summing across all four
551 criteria. Opportunities and challenges were ranked according to the proportion of
552 respondents assigning them a summed score greater than zero. If a participant answered
553 'do not know' for one or more of the criteria for a particular opportunity or challenge, we
554 excluded all their scores for that opportunity or challenge. We generated score visualisations
555 in the 'Likert' package¹²¹ of R version 3.4.1¹²². Two-tailed Fisher's exact tests were used to
556 examine whether the percentage of participants scoring items above zero differed between
557 cohorts with different backgrounds (i.e. country of employment, employment sector and area
558 of expertise).

559

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

573

574 **Data Availability**

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

577

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585

586 **Author Contributions**

587 MD conceived the study. MD, MAG, ZGD, SG, JCF, MJF developed and tested
588 questionnaire and webinar materials. All authors contributed data. MAG collated and
589 analysed these data. MAG, MD, ZGD led writing the paper, with all authors contributing and
590 agreeing to the final version.

591

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-valuing 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).

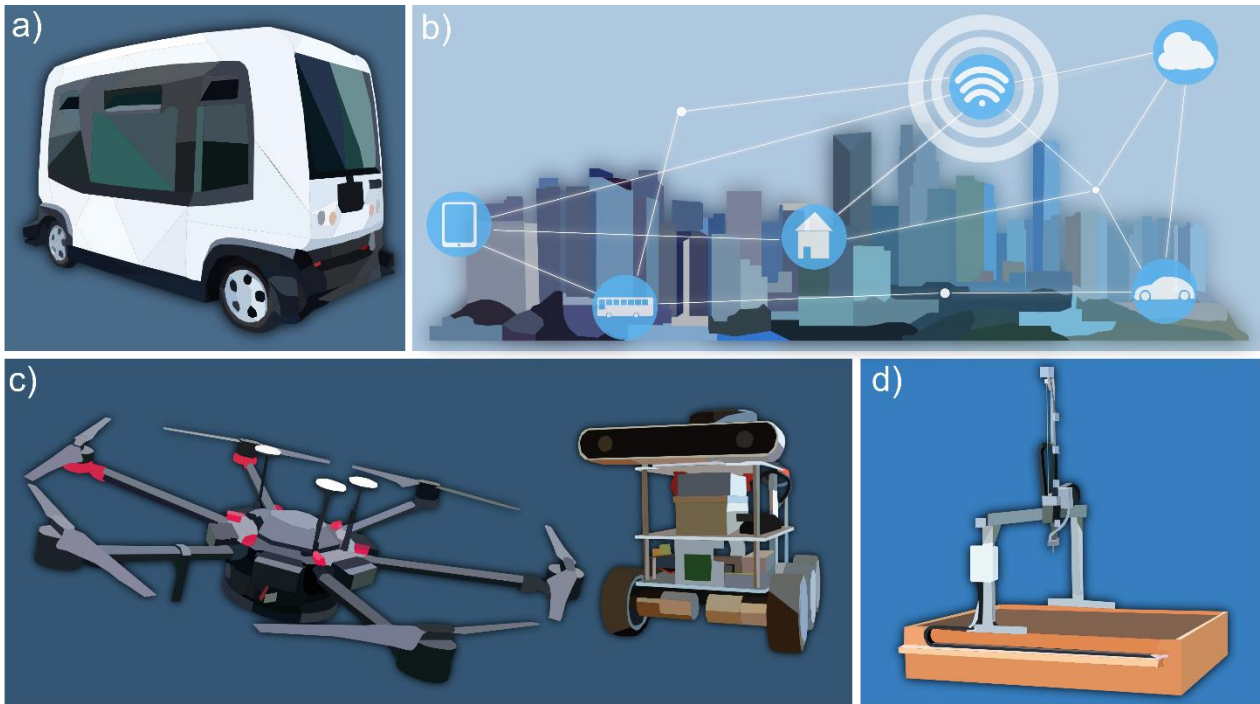


Figure 1. Examples of the potential for robotics and automated systems to transform cities.

(a) 25% of transport in Dubai is planned to function autonomously by 2030¹²⁴; (b) city-wide sensor networks, such as those used in Singapore, inform public safety, water management, and responsive public transport initiatives¹²⁵; (c) through the use of unmanned aerial and ground-based vehicles, 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/>).

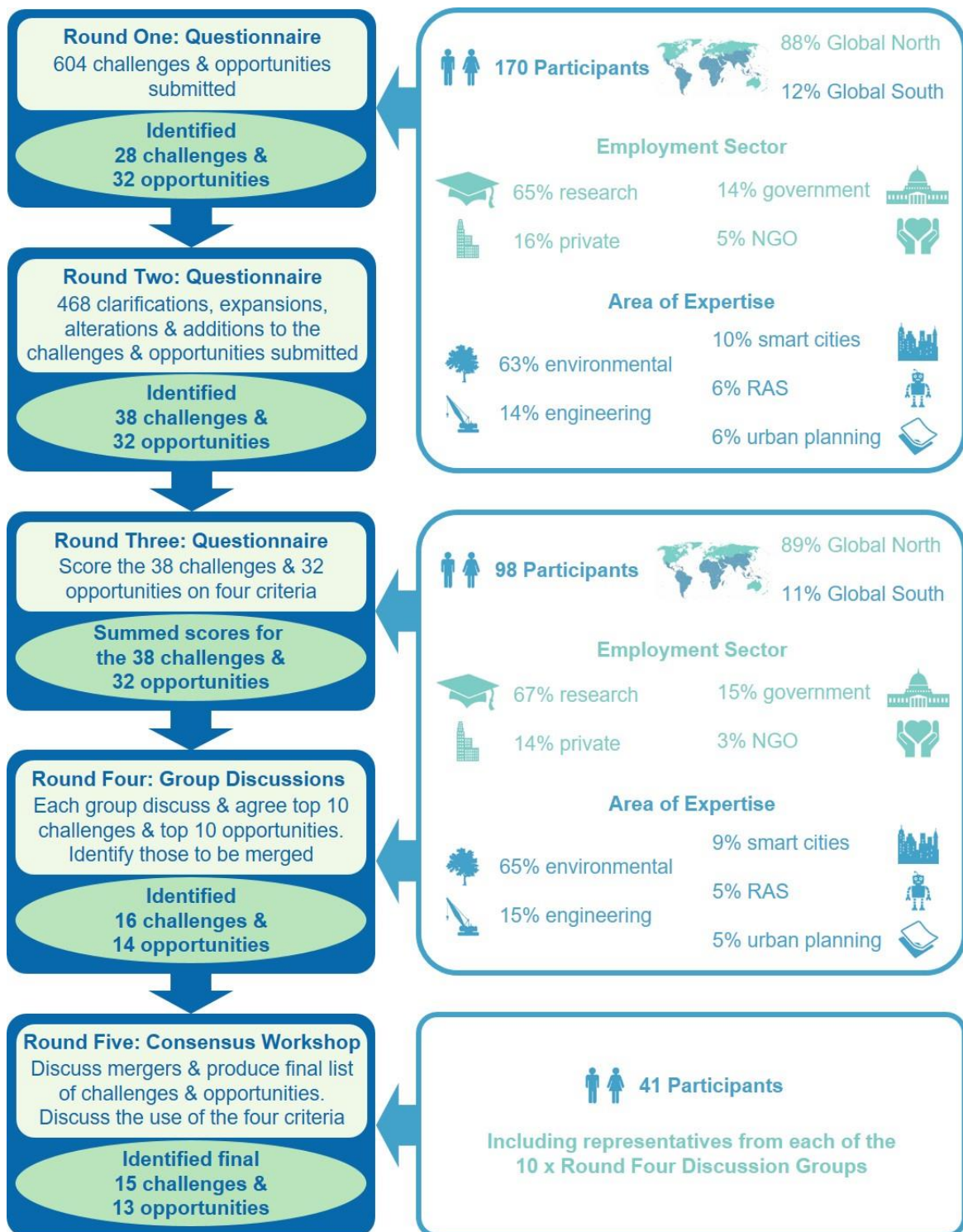


Figure 2. Horizon scan process used to identify and prioritise opportunities and challenges associated with robotics and automated systems for urban biodiversity and ecosystems. The horizon scan comprised an online survey, following a modified Delphi technique, which was conducted over five rounds.

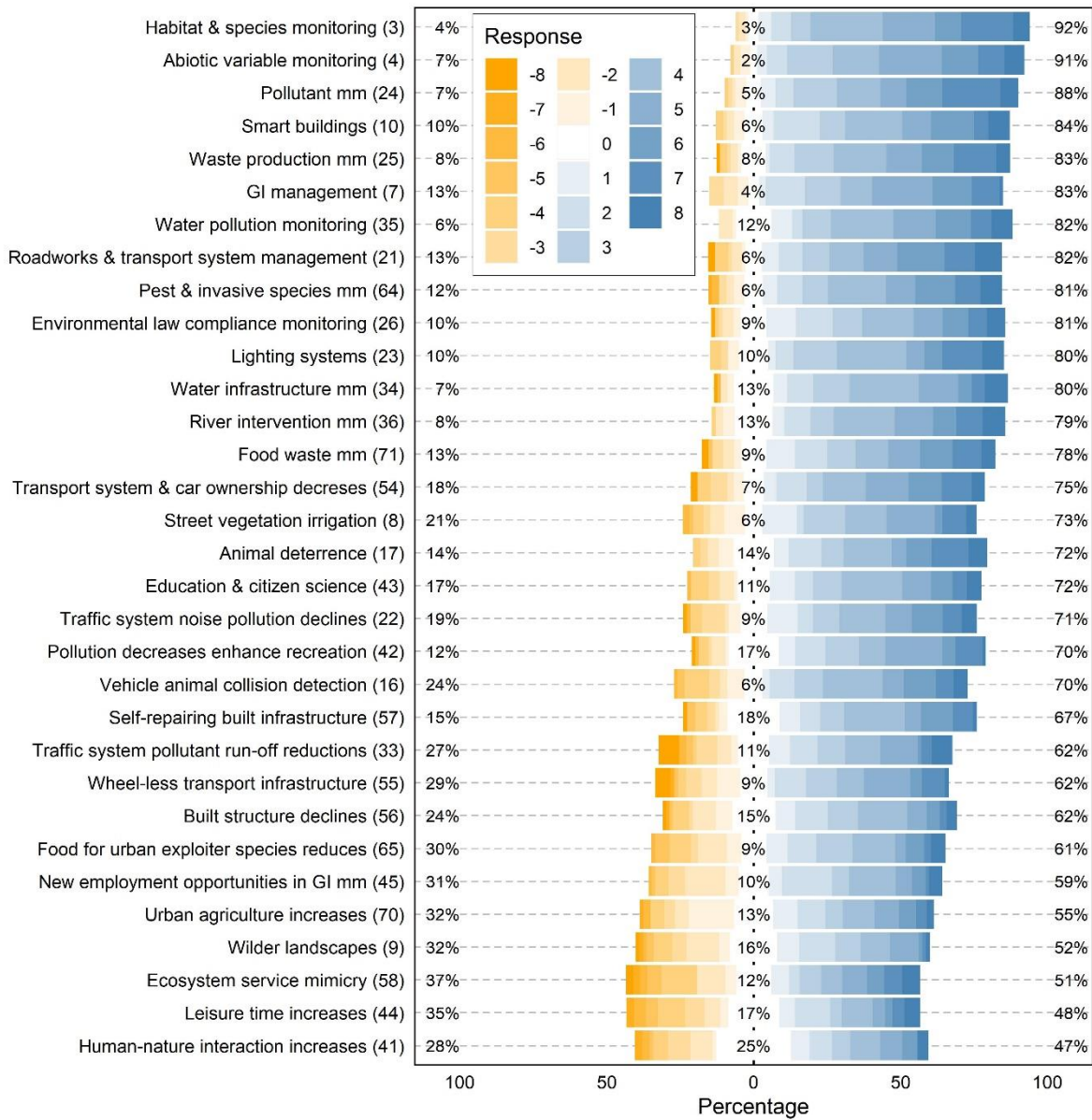


Figure 3. Opportunities associated with robotics and automated systems for urban biodiversity and ecosystems, ranked according to Round Three participant scores.

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 the 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 is 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.

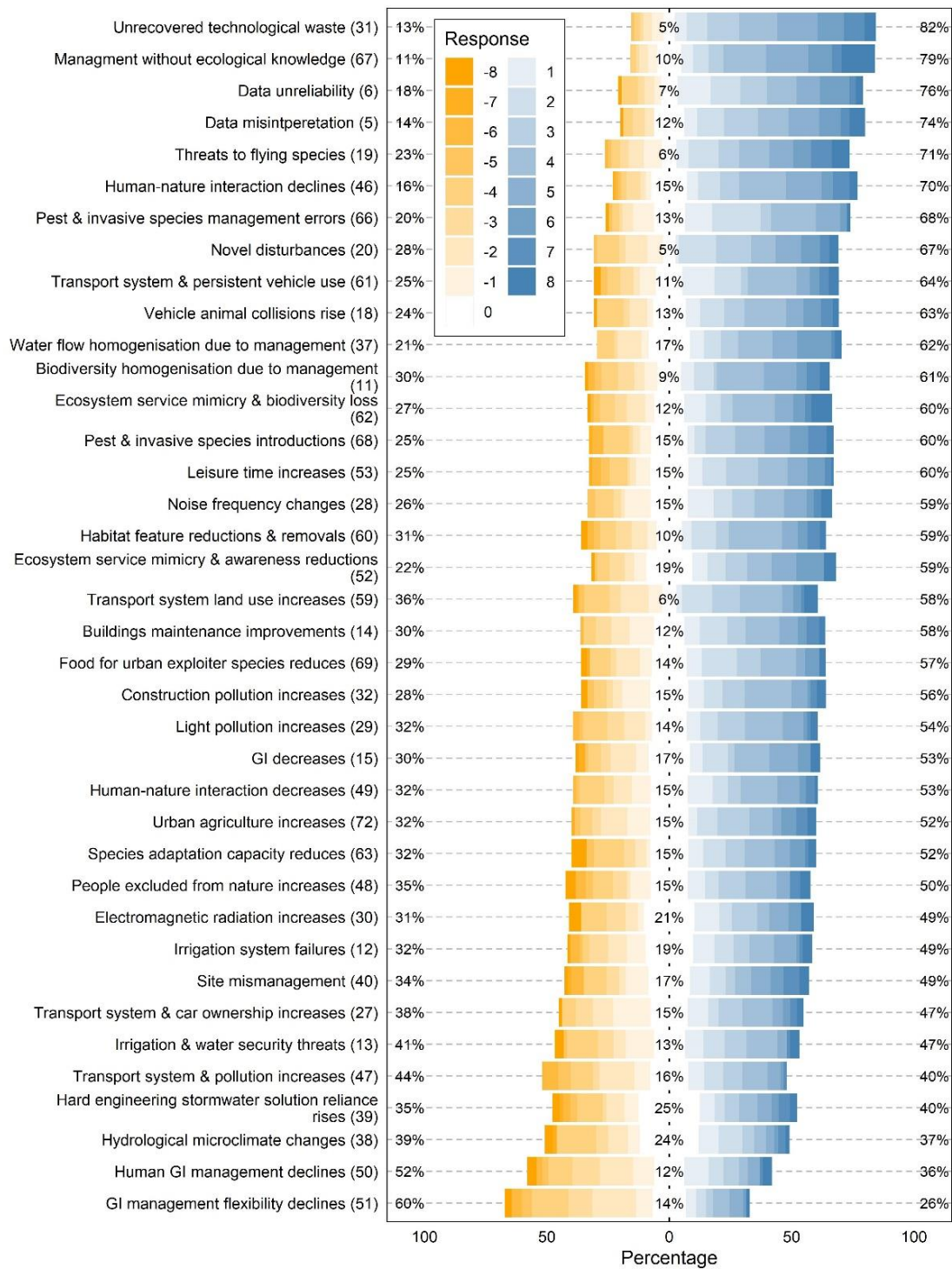


Figure 4. Challenges associated with robotics and automated systems for urban biodiversity and ecosystems, ranked according to Round Three participant scores.

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 the 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 is 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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