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

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

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

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

Presently, we have little appreciation of the pathways through which the widespread uptake and deployment of RAS could affect urban biodiversity and ecosystems[12,13]. To date, information on how RAS may impact urban biodiversity and ecosystems remains scattered 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[14], but critics have questioned this techno-centric vision[15,16]. Moreover, while RAS are likely to have far-reaching social, ecological, and technological ramifications, these are often discussed only in terms of the extent to which their deployment will improve efficiency and data harvesting, and the associated social implications[17-19]. Such a narrow focus will likely overlook interactions across the social-ecological-technical systems that cities are increasingly thought to represent[20]. Without an understanding of the opportunities and challenges RAS will bring, their uptake could cause conflict with the provision of high quality natural environments within cities[13], which can support important populations of many species[21], and are fundamental to the provision of ecosystem services that benefit people[22].

Here we report the findings of an online horizon scan to evaluate and prioritise future opportunities and challenges for urban biodiversity and ecosystems, including their structure, function and service provision, associated with the emergence of RAS. Horizon scans are not conducted to fill a knowledge gap in the conventional research sense, but are used to explore arising trends and developments, with the intention of fostering innovation and facilitating proactive responses by researchers, managers, policymakers and other stakeholders[23]. Using a modified Delphi technique, which is a structured and iterative survey[23-25] (Figure 2), we systematically collated and synthesised knowledge from 170 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[26].

Results and Discussion

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

These patterns from the whole dataset masked heterogeneity between groups of 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.

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[27,28].

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

All Global South participants (100%; n=11) in Round Three assigned scores greater than zero to the opportunities "*Monitoring for rubbish and pollution levels by RAS in water sources will improve aquatic biodiversity*" (item 35) and "*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). Both items would tackle recognised issues in rapidly expanding cities. Discussions indicated that Global South participants prioritised the opportunities for RAS in mitigating pollution and urban heat island effects more than their Global North counterparts, even though 80% (n= 60/75) of Global North participants also assigned positive scores to these items.

Area of expertise

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

For the challenges, there was universal consensus among participants with non-environmental expertise that "*Unrecovered RAS and their components (e.g. batteries, heavy 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 0–0.43, 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 (e.g. spillages) that occur during automated maintenance/construction of infrastructure*" (item 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 observed for item 38 "*RAS will alter the hydrological microclimate (e.g. temperature, light), altering aquatic communities and encouraging algal growth*". A significantly greater proportion of non-environmental compared to environmental participants (60% n=12/20 and 26% n=11/42 respectively) allocated scores above zero (Fisher's Exact Test: odds ratio=0.24 (95% CI 0.07–0.84), p=0.013).

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

Topic one: Urban land-use and habitat availability

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

Conversely, participants highlighted that autonomous vehicles could raise demand for private vehicle transport infrastructure, leading to urban sprawl and habitat loss/fragmentation as people move further away from centres of employment because commuting becomes more efficient[41,42]. Urban sprawl has a major impact on biodiversity[43]. Participants also noted that autonomous transport systems will require new types of infrastructure (e.g. charging stations, maintenance and control facilities, vehicle depots)[44] that could result in additional loss/fragmentation of green spaces. Furthermore, road 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[39].

Topic two: Built and green infrastructure maintenance and management

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

Landscape management is a major driver of urban ecosystems[50], which can be especially complex, due to the range of habitat types and the variety of stakeholder requirements[51]. Participants highlighted that autonomous care of green infrastructure could lead to the simplification of ecosystems, with negative consequences for biodiversity[13]. This would be the likely outcome if RAS make the removal of ‘weeds’, leaf litter and herbicide application significantly cheaper and quicker, such as through the widespread uptake of robotic lawn mowers or tree-climbing robots for pruning[52]. Urban ecosystems can be heterogeneous in habitat type and structure[51] and phenology[53]. RAS, therefore, may be unable to respond adequately to species population variation and phenology, or when species that are protected or of conservation concern are encountered. For hydrological systems in particular, participants noted that automated management could result in the homogenisation of water currents and timings of flow, which are known to disrupt the lifecycles of flow-sensitive species[54]. Similarly, improved building maintenance could lead to the loss of nesting habitats and shelter (e.g. for house sparrows *Passer domesticus*[55]), especially for cavity and ground-nesting species.

Topic three: Human-nature interactions

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

Experiencing nature can bring a range of human health and well-being benefits[62]. Participants suggested that RAS will fundamentally alter human-nature interactions, but this could manifest itself in contrasting ways. On the positive side, RAS have the potential to reduce noise and air pollution[63-65] through, for example, automated infrastructure repairs leading to decreased vehicle emissions from improved traffic flow and/or reduced construction. In turn, this could make cities more attractive for recreation, encouraging walking and cycling in green spaces, with positive outcomes for physical[66] and mental health[67]. Changes in noise levels could also improve experiences of biophonic sounds such as bird song[68]. Driving through green, rather than built, environments can provide human health benefits[69]. These could be further enhanced if autonomous transport systems were designed to increase people's awareness of surrounding green space features, or if navigation algorithms preferentially choose greener routes[70]. Autonomous vehicles could alter how disadvantaged groups such as children, elderly and disabled travel[71]. Participants felt that this might mean improved access to green spaces, thus reducing environmental inequalities. Finally, community (or citizen) science is now a component of urban biodiversity research and conservation[72] that can foster connectedness to nature[73]. Participants suggested RAS could provide a suite of different ways to engage and educate the public about biodiversity and ecosystems such as through easier access to and input into real-time data on species[74].

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

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[81]. This has the potential to greatly enhance urban planning and management decision-making[12]. Continuing to expand such applications would be a logical step and one that participants identified as an important opportunity[82]. RAS will allow faster and cheaper data collection over large spatial and temporal scales, particularly across inaccessible or privately owned land. Ecoacoustic surveying and automated sampling of environmental DNA (eDNA) is already enabling the monitoring of hard to detect species[83,84]. RAS also offer potential to detect plant diseases in urban vegetation and, subsequently inform control measures[85,86].

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

Topic five: Managing invasive and pest species

The abundance and diversity of invasive and pest species are often high in cities[90]. 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[91,92]. However, participants were concerned the implementation of such novel approaches, citing the potential for error, whereby misidentification leads to accidentally controlling non-target species. Likewise, RAS-mediated pest control could threaten unpopular taxa, such as wasps or termites, if the interventions are not informed by knowledge of the important ecosystem functions such species underpin.

Topic six: RAS interactions with animals

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

Topic seven: Managing pollution and waste

Air[97,98], noise[99] and light[100,101] pollution can substantially alter urban ecosystem function. Participants believed that RAS would generate a range of important opportunities for reducing and mitigating such pollution. For instance, automated transport systems and road repairs could reduce vehicle numbers and improve traffic flow[36], leading to lower emissions and improved air quality[64,65]. If increased autonomous vehicle use reduced noise from traffic, species that rely on acoustic communication could benefit. Similarly, automated and responsive lighting systems will reduce light impacts on nocturnal species, including migrating birds[102]. RAS that monitor air quality, detect breaches of environmental law and clean-up pollutants are already under development[103,104]. Waste management is a major problem for urban sustainability, and participants noted that RAS[105] 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[106].

Topic eight: Water and flooding

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

Conclusions

The fourth industrial revolution is transforming the way economies and society operate. Identifying, understanding and responding to the novel impacts, both positive and negative, of new technologies is essential to ensure that natural environments are managed sustainably, and the provision of ecosystem services maximised. Here we identified and prioritised the most important opportunities and challenges for urban biodiversity and ecosystems associated with RAS. Such explicit consideration of how urban biodiversity and ecosystems may be affected by the development of technological solutions in our towns and cities is critical if we are to prevent environmental issues being sidelined. However, we have to acknowledge that some trade-offs to the detriment of the environment are likely to be inevitable. Additionally, it is highly probable that multiple RAS will be deployed simultaneously, making it extremely difficult to anticipate interactive effects. To mitigate and minimise any potential harmful effects of RAS, we recommend that environmental scientists advocate for critical impact evaluations before phased implementation. Long-term monitoring, comparative studies and controlled experiments could then further our 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 to respond quickly enough and appropriately. Although the future impacts of novel RAS are hard to predict, early examination is essential to avoid detrimental and unintended consequences on urban biodiversity and ecosystems, but fully realise the benefits.

Methods

Horizon scan participants

We adopted a mixed approach to recruiting experts to participant in the horizon scan to minimise the likelihood of bias associated with relying on a single method. For instance, snowball sampling (i.e. invitees suggesting additional experts who might be interested in 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[117]. We therefore contacted individuals directly via email inviting them to join the horizon scan, as well as using social media and snowball sampling. The 480 experts working across the research, private, public and NGO sectors globally contacted directly were identified through professional networks, mailing lists (e.g. groups with a focus on urban ecosystems; the research, development and manufacture of RAS; urban infrastructure), authors lists of recently published papers, and via the editorial boards of subject-specific journals. Of the 170 participants who took part in Round One, 143 (84%) were individuals who has been invited directly, with the remainder obtained through snowball sampling and social media.

We asked participants to indicate their area of expertise from five categories: (i) environmental (including ecology, conservation and all environmental sciences); (ii) infrastructure (including engineering and maintenance); (iii) sustainable cities (covering any aspect of urban sustainability, including the implementation of 'smart' cities); (iv) RAS (including research, manufacture and application); or (v) urban planning (including architecture and landscape architecture). Participants whose area of expertise did not fall within these categories were excluded from the process. We collected information on participants' country of employment. Subsequently, these were allocated into one of two global regions, the Global North or Global South (low and middle income countries in South America, Asia, Oceania, Africa, South America and the Caribbean[118]). Participants specified their employment sector according to four categories: (i) research; (ii) government; (iii) private business; or (iv) NGO/not-for-profit.

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.

Horizon scan using the Delphi technique

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

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

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

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

Data Availability

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

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Author Contributions

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

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).	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). Irrigation of street trees and other vegetation by RAS will lead to greater resilience to climate change/urban heat stress (item 8).	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	RAS will decrease pollution, making cities more attractive for recreation and enhancing opportunities for experiencing nature (item 42).	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).
	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).
		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). 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).

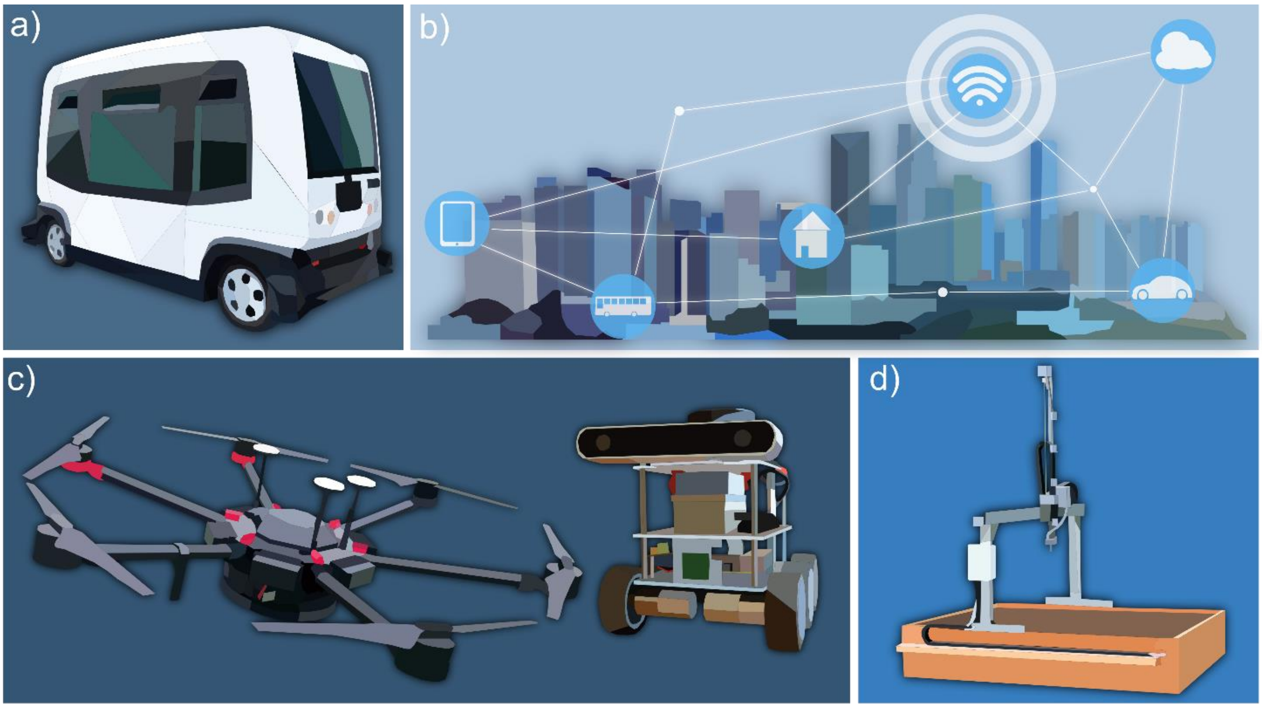

Figure 1. Examples of the potential for robotics and automated systems to transform cities. (a) 25% of transport in Dubai is planned to function autonomously by 2030[124]; (b) city-wide sensor networks, such as those used in Singapore, inform public safety, water management, and responsive public transport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

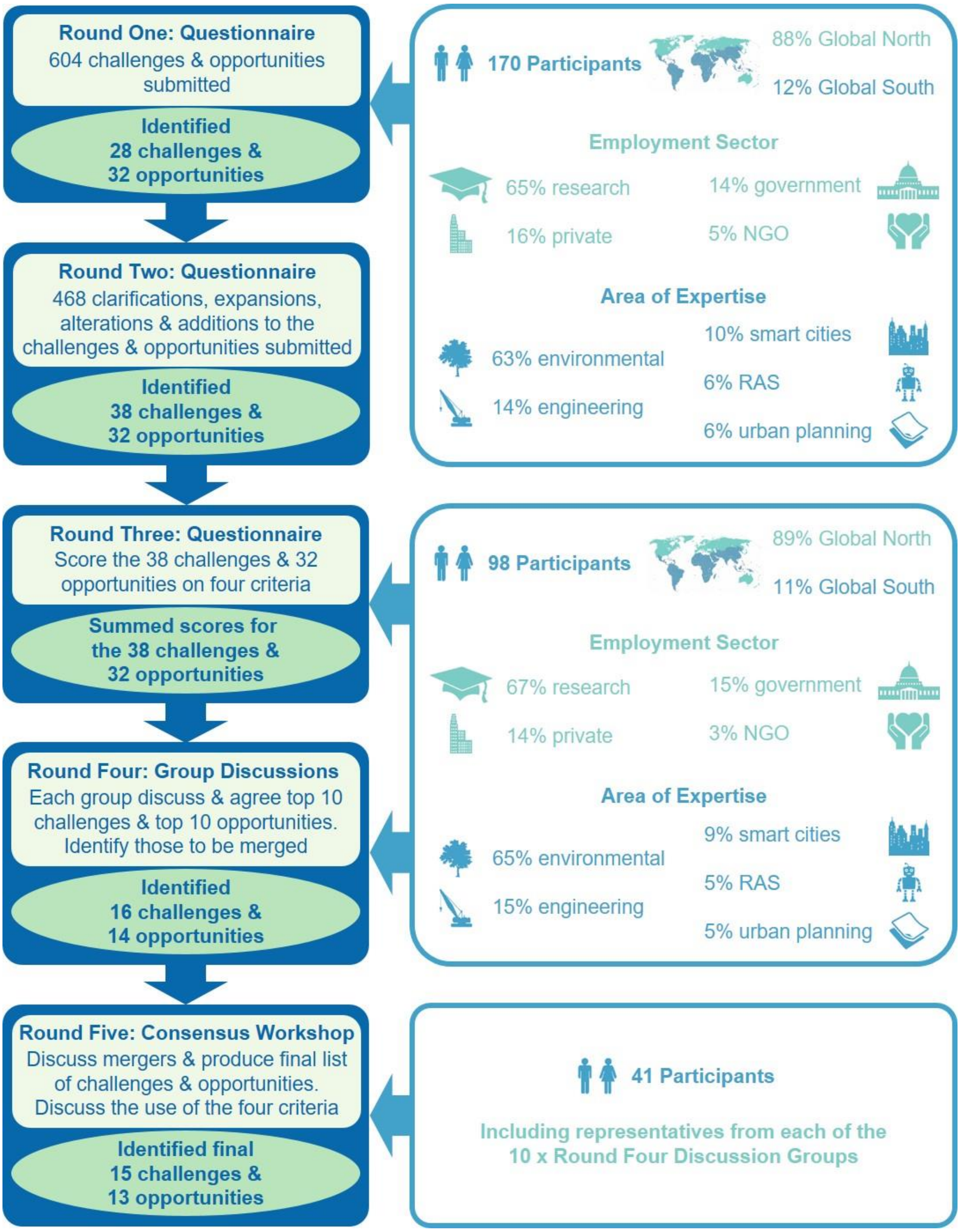

Figure 2. Horizon scan process used to identify and prioritise opportunities and challenges associated with robotics and automated systems for urban biodiversity and ecosystems. The horizon scan comprised an online survey, following a modified Delphi technique, which was conducted over five rounds.

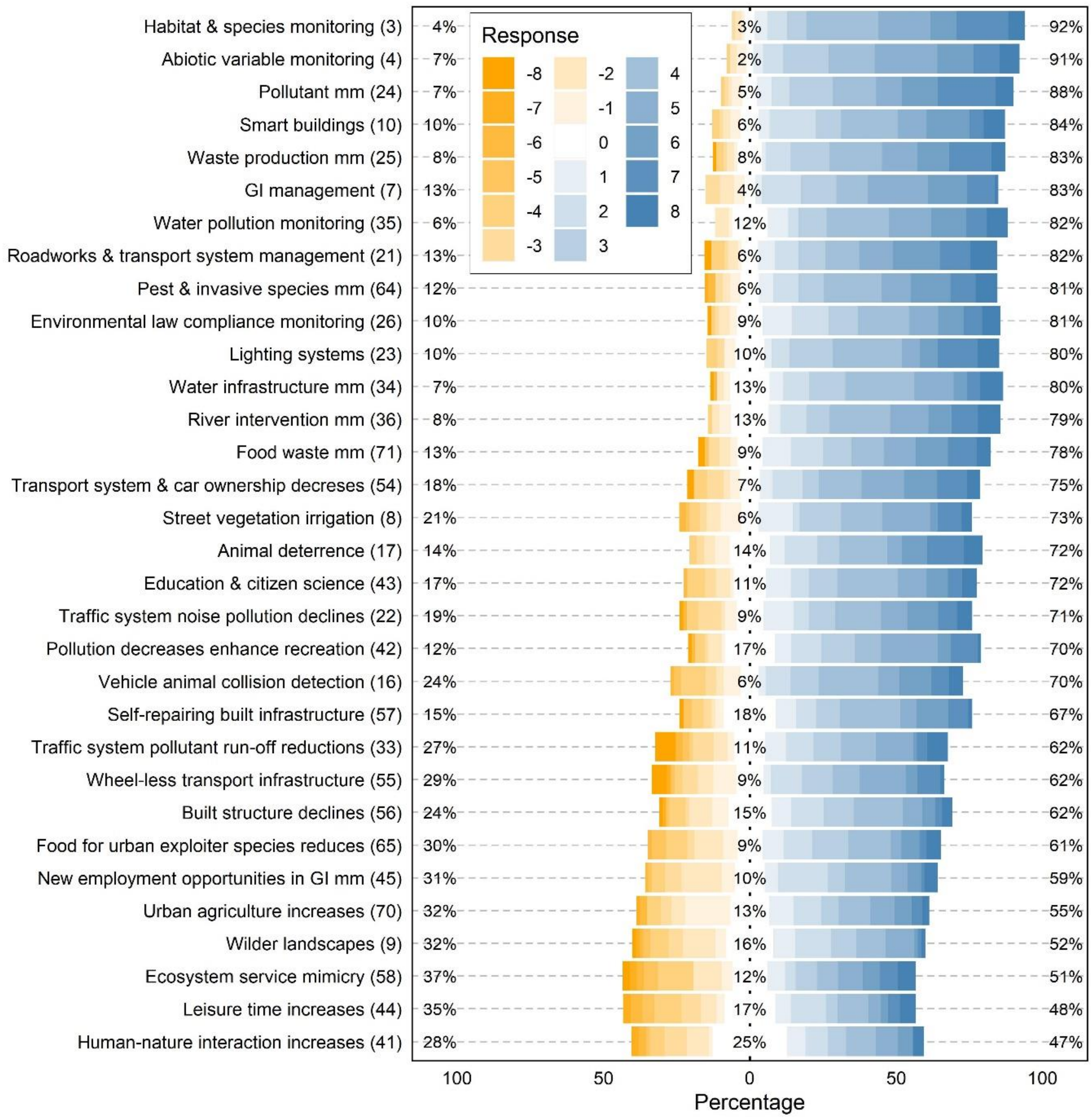

Figure 3. Opportunities associated with robotics and automated systems for urban biodiversity and ecosystems, ranked according to Round Three participant scores. The distribution of summed participant scores (range: -8 to +8) across four criteria (likelihood, impact, extent, novelty) for each of the 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.

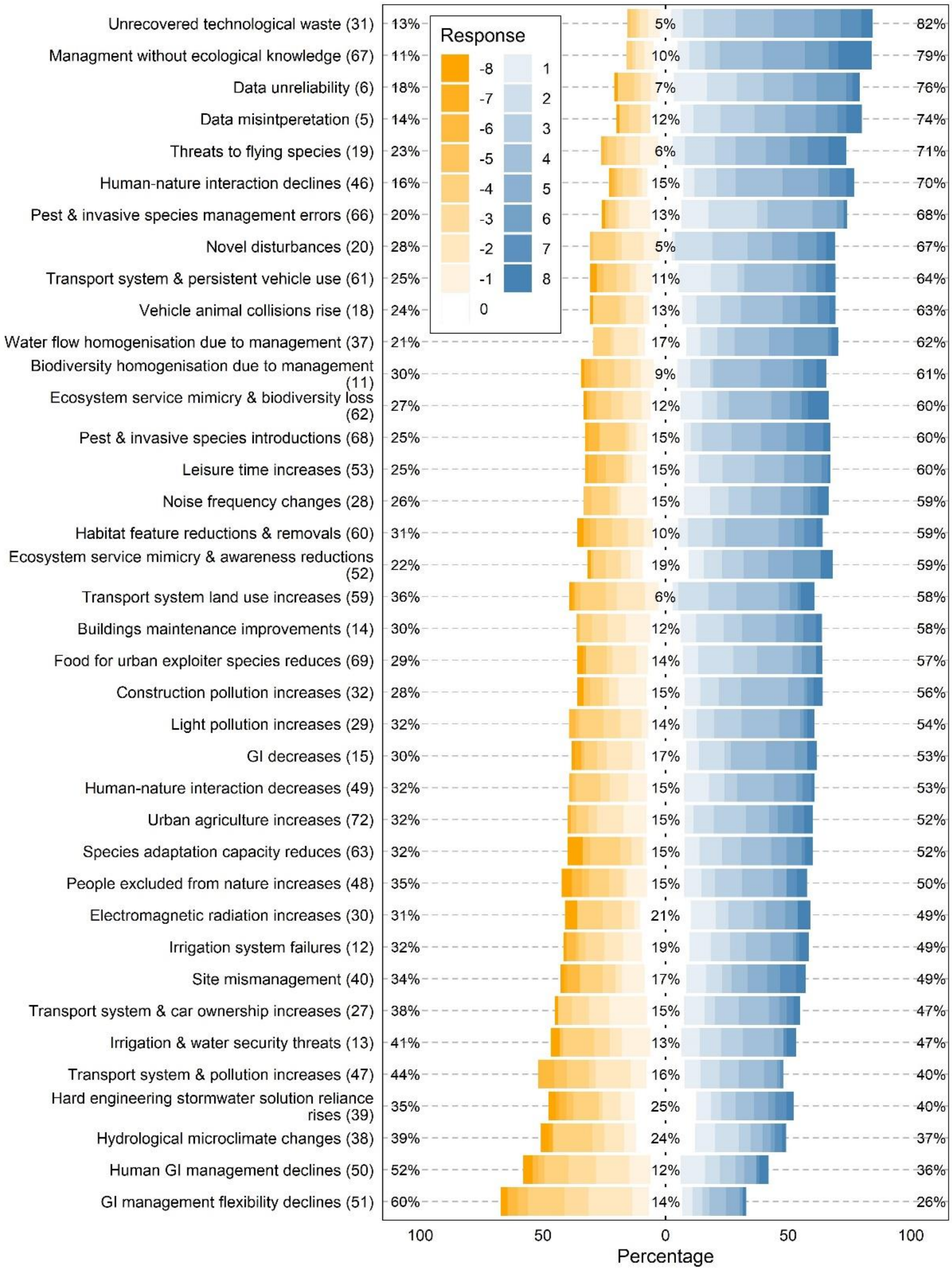

Figure 4. Challenges associated with robotics and automated systems for urban biodiversity and ecosystems, ranked according to Round Three participant scores. The distribution of summed participant scores (range: -8 to +8) across four criteria (likelihood, impact, extent, novelty) for each of the 38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