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 show 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 has been 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 altering local climate, hydrology and biogeochemical cycles, resulting in novel urban ecosystems with no natural analogs[10]. If 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]. The widespread use of RAS has been proposed as a mechanism through which urban sustainability can be enhanced[14], but critics have questioned this techno-centric vision[15,16]. For instance, these technological advances could potentially cause conflict with the provision of high quality natural environments within cities[17], which can support important populations of many species[18], and are fundamental to the provision of ecosystem services that are beneficial for people[19].

Here we report the findings of an online horizon scan to evaluate and prioritise the opportunities and challenges for urban biodiversity and ecosystems, including their structure and function, associated with the emergence of RAS. Horizon scanning is an approach for exploring emerging trends and future developments, with the intention of fostering innovation and facilitating proactive responses by researchers, managers, policymakers and other stakeholders[20]. 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. Using a modified Delphi technique, which is a structured and iterative survey[20-22] (Figure 2), we systematically collate and synthesis knowledge from 170 expert participants based in 35 countries (Supplementary Figure 1). The exercise is therefore inclusive and incorporates a diversity of different perspectives[223].

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 the 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 were prioritised. Those that were, emphasised concerns surrounding waste from unrecovered RAS, and the quality and interpretation of RAS-collected data (Figure 4; Supplementary Table 1). These broad patterns masked considerable heterogeneity in scores between groups of participants according to their country of employment and area of expertise. However, we found no significant disagreement between participants working in different employment sectors (Supplementary Figures 2 and 3). This broad consensus suggests that the priorities of the research community and practitioners are closely aligned.

Country of employment

There were significant divergences between the views of participants from the Global North and South (Supplementary Figures 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 it assigned a score above zero by a single participant (Fisher’s Exact Test: χ^2=10.182, df=1, p=0.0007; Supplementary Figure 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 (Supplementary Figures 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: χ^2=8.987, df=1, 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: χ^2=3.605, df=1, p=0.04).

For the challenges, there was universal consensus among participants with non-environmental expertise that item 31 "*Unrecovered RAS and their components (e.g. batteries, heavy metals, plastics) will be a source of hazardous and non-degradable waste*" 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: χ^2=7.86, df=1, 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: χ^2=5.90, df=1, 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: χ^2=5.28, df=1, 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 could be 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[24,25]. Nevertheless, the participants felt that there will be wide-ranging impacts for urban land-use, with knock-on implications for habitat availability, quality and connectivity, and the stocks and flows of ecosystem services[26]. They highlighted that urban land-use and transport planning could be transformed if the uptake of autonomous vehicles is coupled with reduced personal vehicle ownership through vehicle sharing or public transport[27,28]. Participants argued that, if less land is required for transport infrastructure (e.g. roads, car parks, driveways), this could enable increases in the extent and quality of urban green space.

Conversely, autonomous vehicles could raise demand for transport infrastructure through a rebound effect[29], leading to urban sprawl and habitat fragmentation as people move further away from city centres due to commuting becoming more efficient. Participants also noted that autonomous transport systems will require new types of infrastructure (e.g. charging stations, maintenance and control facilities, vehicle depots) 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.

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[30]. As an example, sensors to monitor soil moisture, which would be integral in automated irrigation systems, are already being deployed for urban trees in the Netherlands[12]. Resilience to climate change could also be improved by smart buildings that are better able to regulate energy usage and reduce heat loss[31], through the use of technology like automatic reflectors. This could help reduce urban heat island effects and moderate harsh microclimates[32].

Landscape management is a major homogeniser of urban ecosystems[33], and 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. Likewise, RAS may be unable to respond adequately to species population variation and phenology, or when species that are protected or of conservation concern are encountered. Participants noted that automated management of hydrological systems could result in the homogenisation of water currents and timings of flow, disrupting the lifecycles of flow-sensitive species. Similarly, improved building maintenance could lead to the loss of nesting habitats and shelter, 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 less privileged residents in lower income areas typically having less access to green space and biodiversity[34-36], while experiencing greater exposure to environmental hazards such as air pollution[37,38] and extreme temperatures[39]. 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 citizens without access to technology become increasingly digitally marginalised[13,15] from interacting with, and accessing, the natural world.

Experiencing with nature can bring a range of human health and well-being benefits[40]. 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 through, for example, 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[41] and mental health[42]. Changes in noise levels could also improve experiences of biophonic sounds such as bird song[43]. It is already known that driving through green, rather than built, environments can provide some human health benefits[44]. 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[45]. Participants also felt that autonomous vehicles could improve access to green spaces for disadvantaged groups, children, elderly and disabled, thus reducing environmental inequalities. Finally, citizen science is now a component of urban biodiversity research and conservation[46] that can foster connectedness to nature[47]. Participants suggested RAS could provide a suite of different ways to engage and educate the public about biodiversity and ecosystems.

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 the time they are exposed to green spaces while travelling. In addition, walking and cycling could decline as new modes of transport become more attractive. RAS that mimic or replace ecosystem service provision (e.g. Singapore's cyborg supertrees[48], robotic pollinators[49]) may reduce people's appreciation of ecological functions[50], potentially undermining public support for, and values associated with, green infrastructure and biodiversity conservation[51].

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[52]. 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[53]. 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) will enable the monitoring of hard to detect species[54,55]. RAS also offer potential in the future to detect plant diseases within urban vegetation and, subsequently, control them[56].

Nevertheless, our participants highlighted that the technology and baseline taxonomy necessary for the identification of the vast majority of species autonomously is, as yet, unavailable. If RAS cannot reliably monitor cryptic or unappealing taxa, the existing trend for conservation actions to prioritise easy to identify and charismatic species in well-studied regions could intensify[57]. Participants emphasised that easily collected RAS data, such as tree canopy cover, could be used as surrogates for biodiversity 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[58]. Participants were worried that the sheer quantity, variety and complexity of big data gathered by RAS monitoring could make it difficult for decision-makers to coordinate citywide responses[59].

Topic five: Managing invasive and pest species

The abundance and diversity of invasive and pest species are often higher in cities[60]. One priority concern identified by the participants is that RAS could offer new introduction pathways, dispersal opportunities or different niches that could help invasive species to establish. Although RAS may provide novel approaches to managing invasive and pest species, participants were worried about how this would be implemented and the potential for error, whereby misidentification leads to non-target species being controlled accidently. 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[61], but 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 a larger rival. One possible mitigation might be that unmanned aerial vehicle activity is concentrated along corridors. 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[62] may disturb nesting and non-flying animals.

Topic seven: Managing pollution and waste

Air[63,64], noise[65] and light[66,67] 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[27], leading to lower emissions and improved air quality. 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[68]. RAS that monitor air quality, detect breaches of environmental law and clean-up pollutants are already under development[69,70]. Waste management is a major problem for urban sustainability, and participants noted that RAS[71] could provide a solution. Despite this potential, participants felt that unrecovered RAS could themselves contribute to the problem of electronic waste, which is a growing hazard for human, wildlife and ecosystem health[72].

Topic eight: Water and flooding

Freshwater, estuarine, wetland and coastal habitats are valuable components of urban ecosystems worldwide[73], and maintenance of water, sanitation and wastewater infrastructure is a major sustainability issue[74]. Participants thought that automated monitoring and management of water infrastructure could lead to a reduction in pollution incidents, improve water quality and reduce flooding[75,76]. 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[77]. Participants were concerned, however, that the opposite scenario could also 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[78].

Conclusions

We are currently in the midst of the fourth industrial revolution. Identifying, understanding and responding to the novel impacts, both positive and negative, of new technologies is essential for ensuring urban sustainability and maximising ecosystem service delivery. Here we prioritise the most important opportunities and challenges for urban biodiversity and ecosystems associated with RAS. Such explicit consideration of how urban biodiversity and ecosystems maybe 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 appreciate 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, environmental scientists should advocate for critical impact evaluations to be conducted before phased implementation. Long-term monitoring, comparative studies and controlled experiments could then further our understanding of how biodiversity and ecosystems will be effected. This is essential as the pace of technological change is much faster than that of environmental regulation, which is likely to be outdated by the time it is implemented. Although the future impacts of innovative RAS developments are hard to predict, examining them early is essential if we are to avoid detrimental and unintended consequences on urban biodiversity and ecosystems, but fully realise the benefits.

Methods

Horizon scan participants

We invited 480 experts working across the research, private, public and NGO sectors globally to take part in the horizon scan. Further participants were sought through snowball sampling (i.e. invitees suggesting additional experts who might be interested in taking part), mailing lists (e.g. groups with a focus on urban ecosystems; the research, development and manufacture of RAS; urban infrastructure) and social media. We asked participants to indicate their area of expertise from five categories: (i) environmental (including ecology, conservation and all environmental sciences and professions); (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[79]). Participants specified their employment sector according to four categories: (i) research; (ii) government; (iii) private business; or (iv) NGO/not-for-profit.

We asked participants 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). Anonymised data are available, via MD, on the University of Leeds institutional data repository (http://archive.researchdata.leeds.ac.uk). We piloted and pre-tested each round in the horizon scan process, which helped to refine the wording of questions and definitions of terminology used.

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[21]. 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[21]. 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 get participants to prioritise the 70 opportunities and challenges in order of importance (Figure 2). We asked participants to score four criteria[22,80] 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[81]. 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 (see Supplementary Table 2 for resulting sample sizes). We generated score visualisations in the 'Likert' package[82] of R version 3.4.1[83]. 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. Across all the 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 final consensus workshop. The facilitated discussions resulted in a final consensus set of 13 opportunities and 15 challenges (Table 1).

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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).

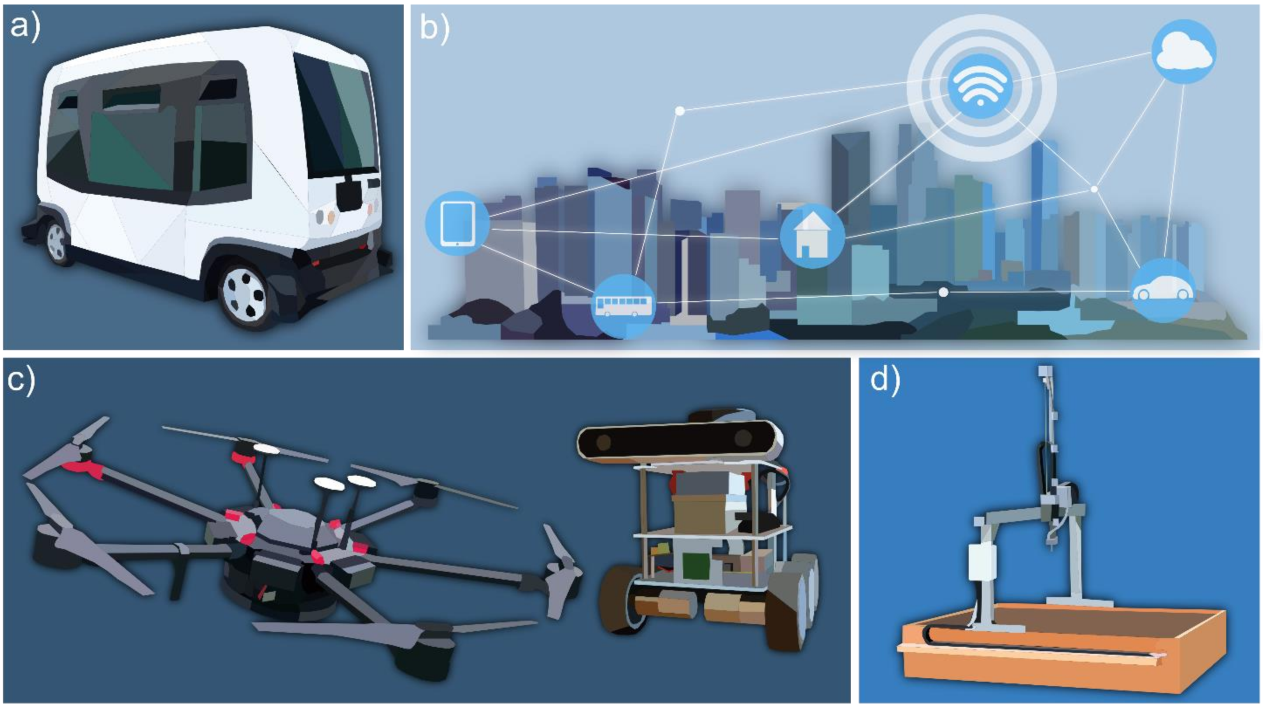

Figure 1. Examples of the potential for robotics and automated systems to transform cities. (a) 25% of transport in Dubai is planned to function autonomously by 2030[84]; (b) city-wide sensor networks, such as those used in Singapore, inform public safety, water management, and responsive public transport initiatives[85]; (c) 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/).

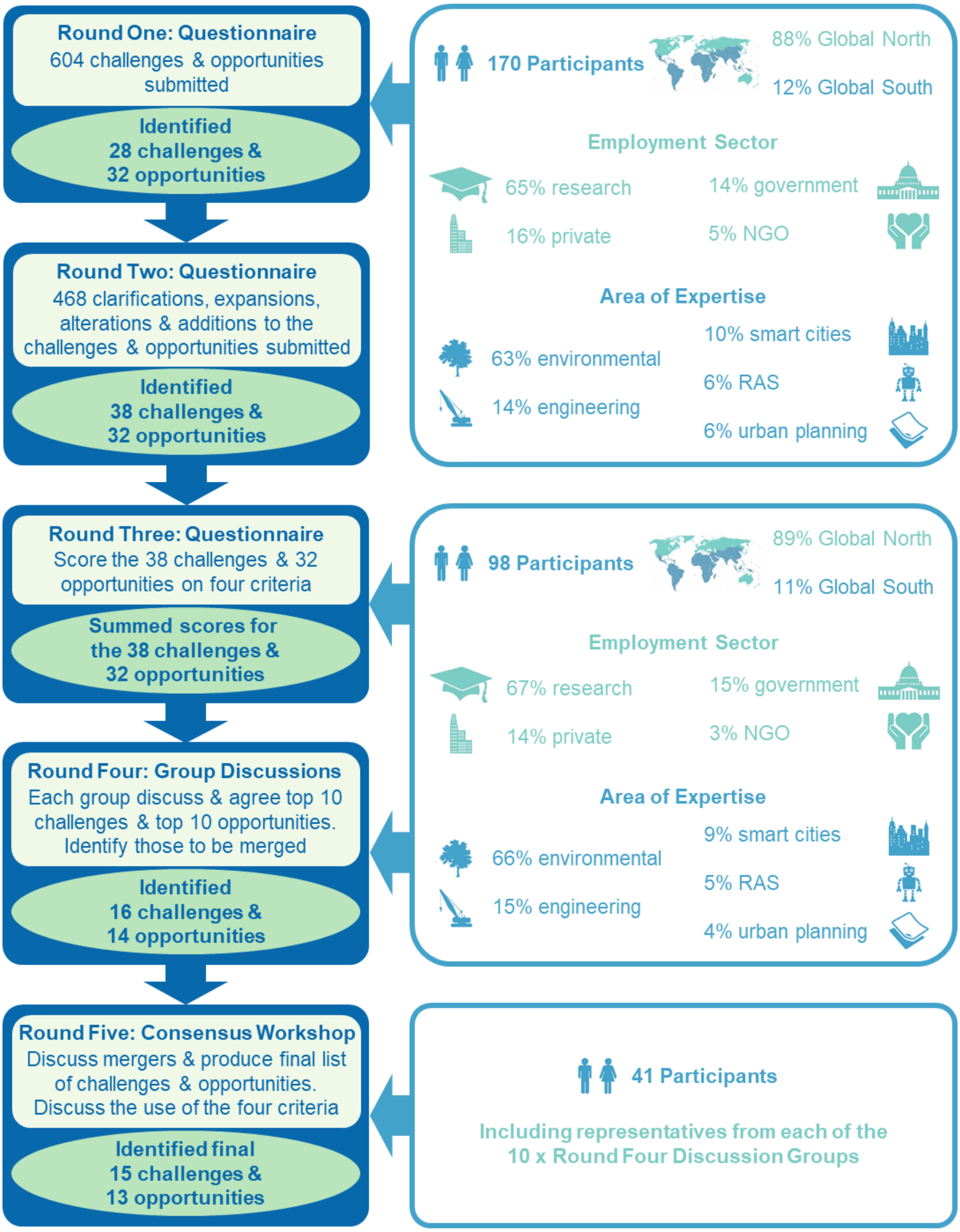

Figure 2. Horizon scan process used to identify and prioritise opportunities and challenges associated with robotics and automated systems for urban biodiversity and ecosystems. The horizon scan comprised an online survey, following a modified Delphi technique, which was conducted over five rounds.

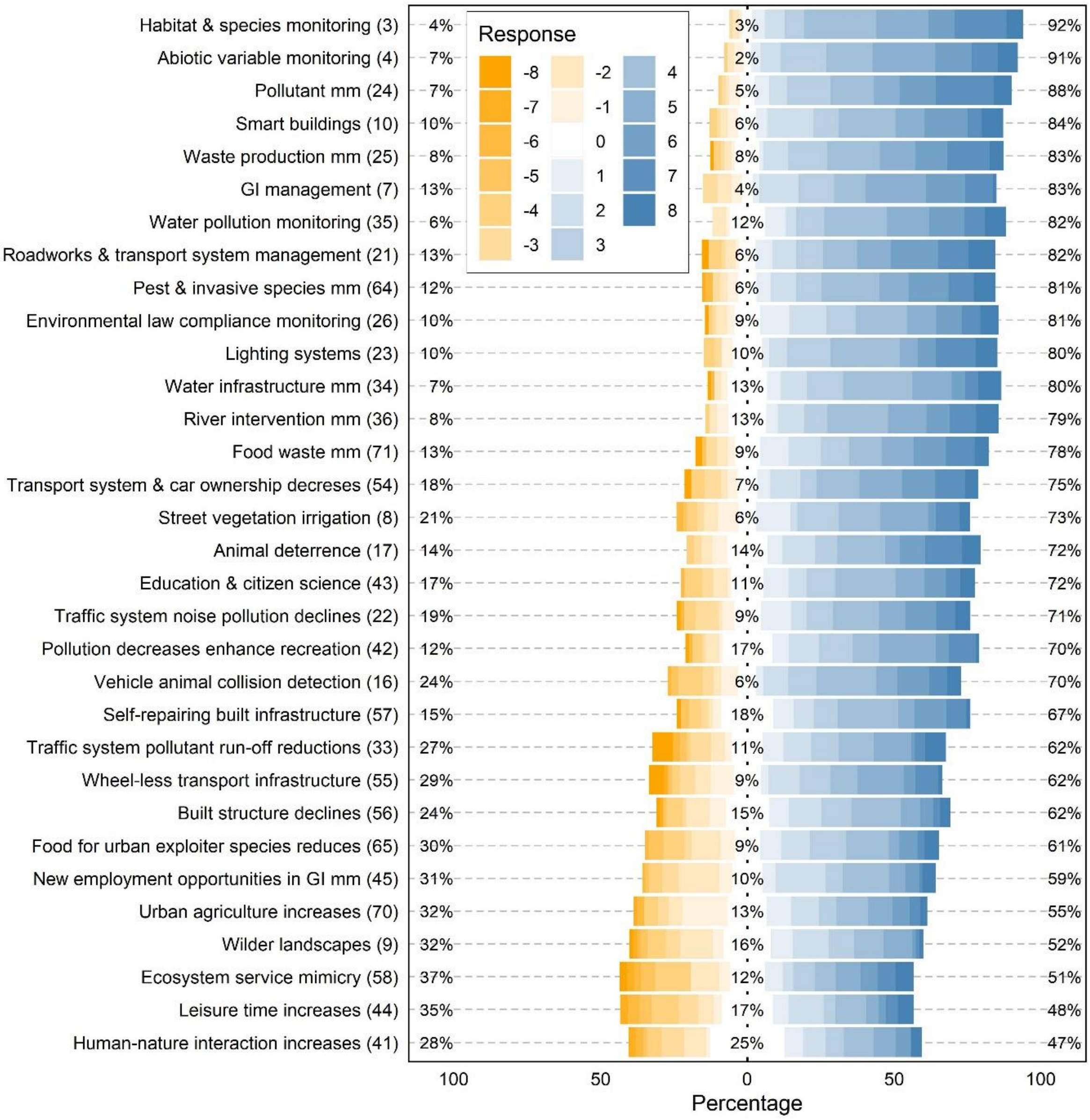

Figure 3. Opportunities associated with robotics and automated systems for urban biodiversity and ecosystems, ranked according to round three participant scores. The distribution of summed participant scores (range: -8 to +8) across four criteria (likelihood, impact, extent, novelty) for each of the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

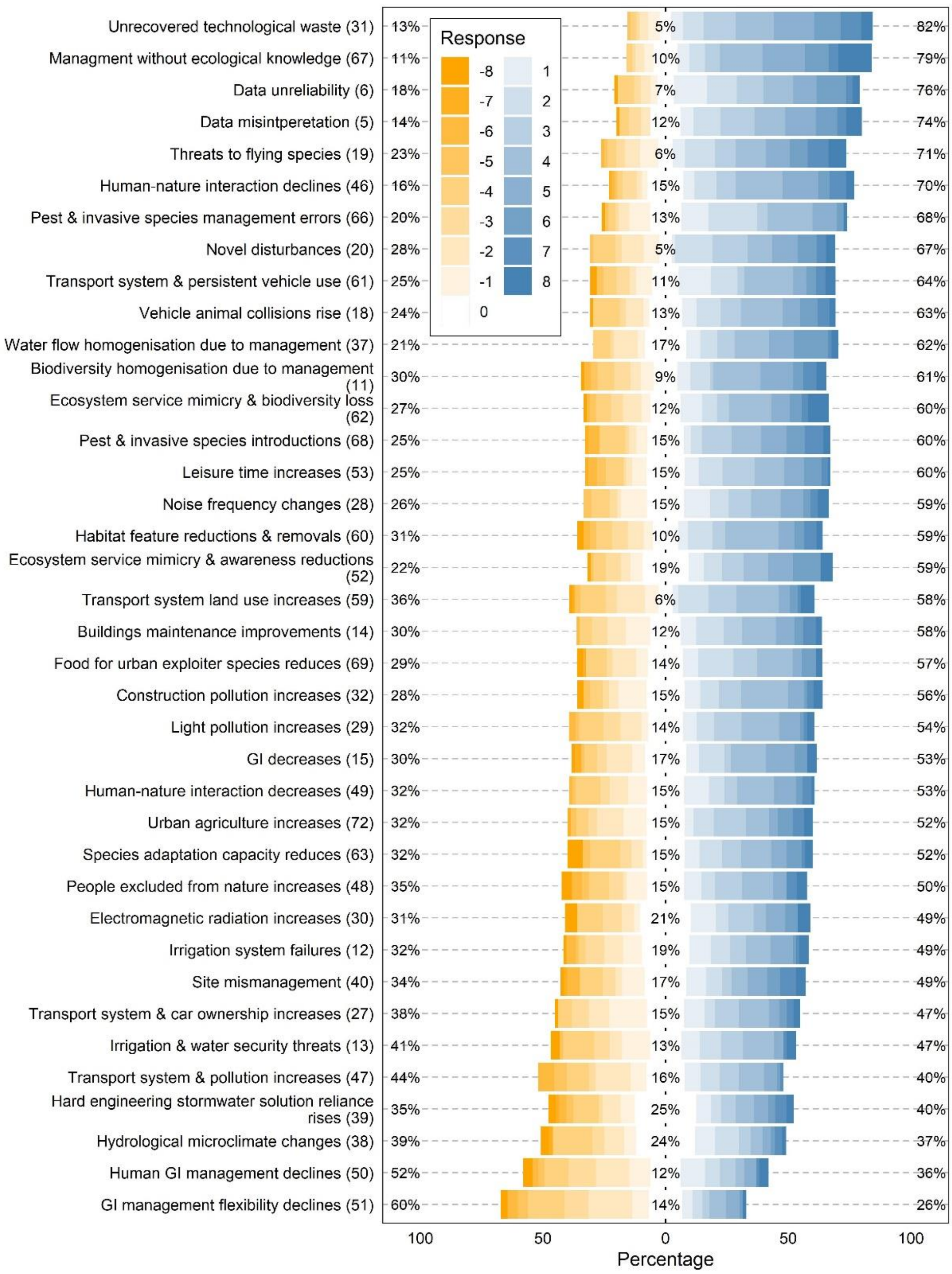

Figure 4. Challenges associated with robotics and automated systems for urban biodiversity and ecosystems, ranked according to round three participant scores. The distribution of summed participant scores (range: -8 to +8) across four criteria (likelihood, impact, extent, novelty) for each of the 38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