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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 major innovation is the emergence of robotics and autonomous systems (RAS), which have the potential to revolutionize 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 prioritized opportunities were primarily centred on the deployment of RAS for the monitoring and management of biodiversity and ecosystems. Fewer challenges were prioritized. Those that were emphasized 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 difficult to predict, examining potentially important developments early is essential if we are to avoid detrimental consequences but fully realize 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] (Fig. 1). RAS have already revolutionized how environmental data are collected[5] and how 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, urbanization 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

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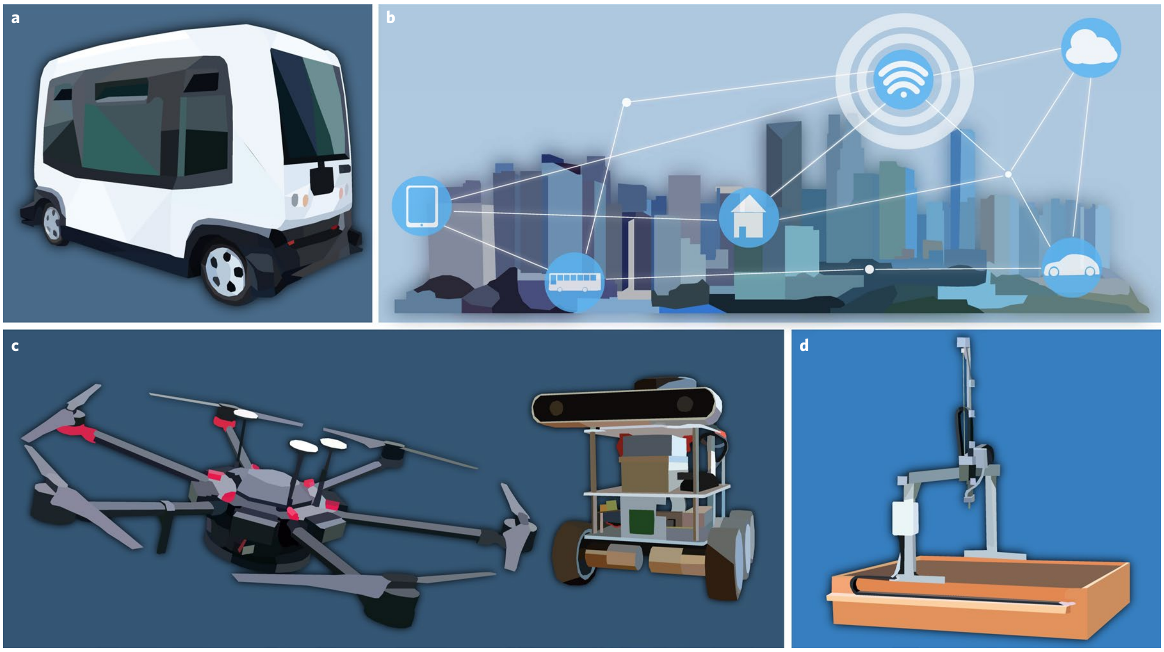

Fig. 1 | Examples of the potential for RAS to transform cities. a, 25% of transport in Dubai is planned to function autonomously by 2030[121]. **b**, City-wide sensor networks, such as those used in Singapore (https://www.smartnation.sg/), inform public safety, water management and responsive public transport initiatives. **c**, Through the use of unmanned aerial and ground-based vehicles, Leeds, United Kingdom, is expecting to implement fully autonomous maintenance of built infrastructure by 2035[2]. **d**, Precision agricultural technology for small-scale urban agriculture (https://farm.bot/).

Asia. Indeed, 7 billion people will live in urban areas by 2050[9]. Urbanization causes habitat loss, fragmentation and degradation, as well as altering local climate, hydrology and biogeochemical cycles, resulting in novel urban ecosystems with no natural analogues[10]. When poorly planned and executed, urban expansion and densification can lead to substantial declines in many aspects of human wellbeing[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 technocentric 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 probably 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] that 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 prioritize 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] (Fig. 2), we systematically collated and synthesized knowledge from 170 expert participants based in 35 countries (Extended Data Fig. 1). We designed the exercise to involve a large range of participants and to 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 (Fig. 2). These were prioritized in round three, with participants scoring each opportunity and challenge according to four criteria, using a five-point Likert scale: (1) likelihood of occurrence; (2) potential impact (that is, the magnitude of positive or negative effects); (3) extensiveness (that is, how widespread the effects will be); and (4) degree of novelty (that is, how well known or understood the issue is). Opportunities that highlighted how RAS could be used for environmental monitoring scored particularly highly (Fig. 3 and Supplementary Table 1). In contrast, fewer challenges received high scores. Those that did emphasized concerns surrounding waste from unrecovered RAS, and the quality and interpretation of RAS-collected data (Fig. 4 and Supplementary Table 1).

These patterns from the whole dataset masked heterogeneity between groups of participants, which could be due to at least three factors: (1) variation in background/expertise; (2) variation in which opportunities and challenges are considered important in particular contexts; and (3) 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

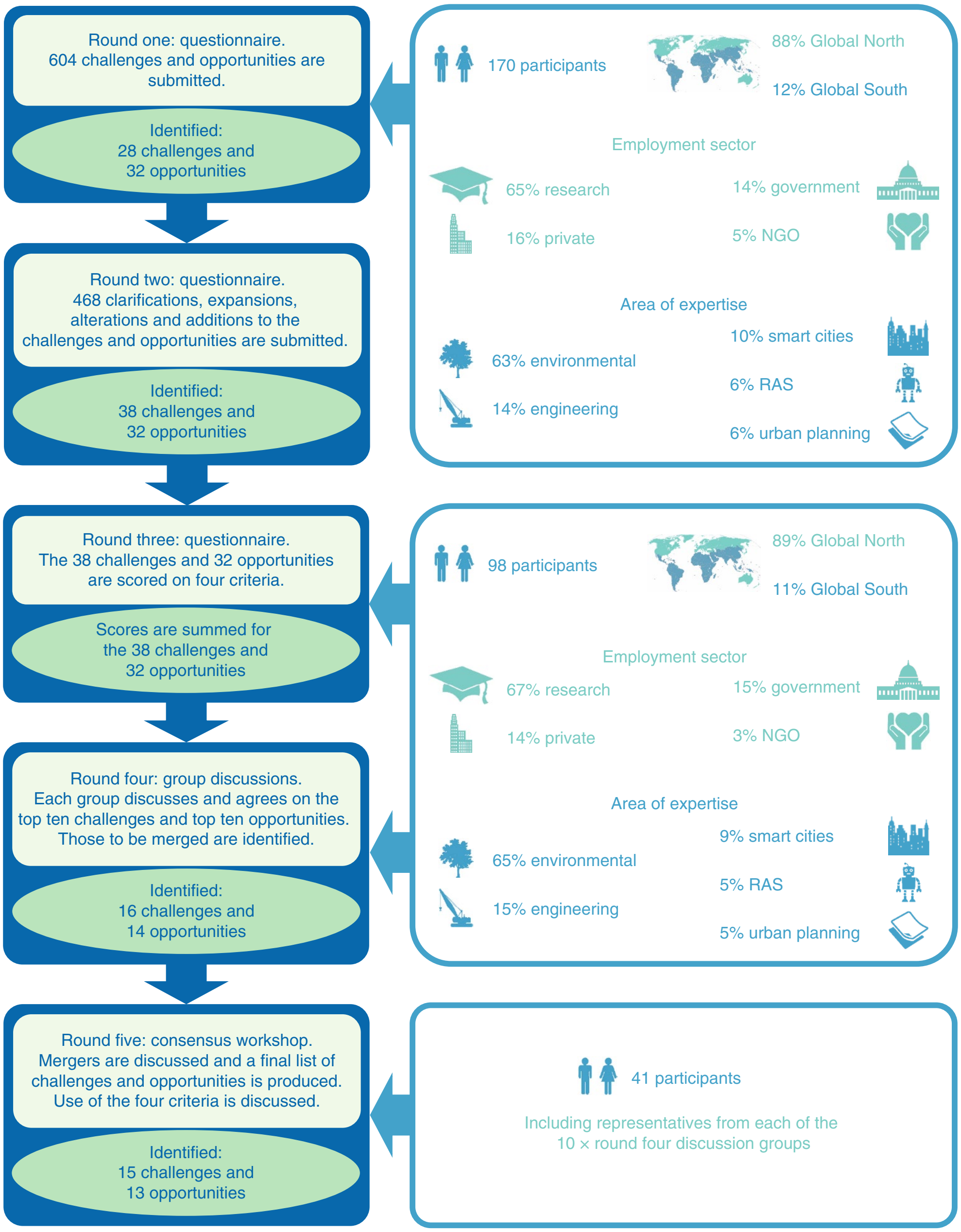

Fig. 2 | Horizon scan process used to identify and prioritize opportunities and challenges associated with RAS for urban biodiversity and ecosystems. The horizon scan comprised an online survey, following a modified Delphi technique, which was conducted over five rounds. NGO, non-governmental organization.

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 homogenized 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% confidence interval (CI) = 2.37–882.61; $P=0.0007$; Extended Data Fig. 2). The discussions in rounds four and five (Fig. 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 (for example, through automated reflectors), reducing urban temperatures and providing less harsh microclimatic conditions for biodiversity under ongoing climate change' (item 10). Both items would tackle recognized issues in rapidly expanding cities. Discussions indicated that Global South participants prioritized the opportunities for RAS in mitigating pollution and urban heat island effects more than their

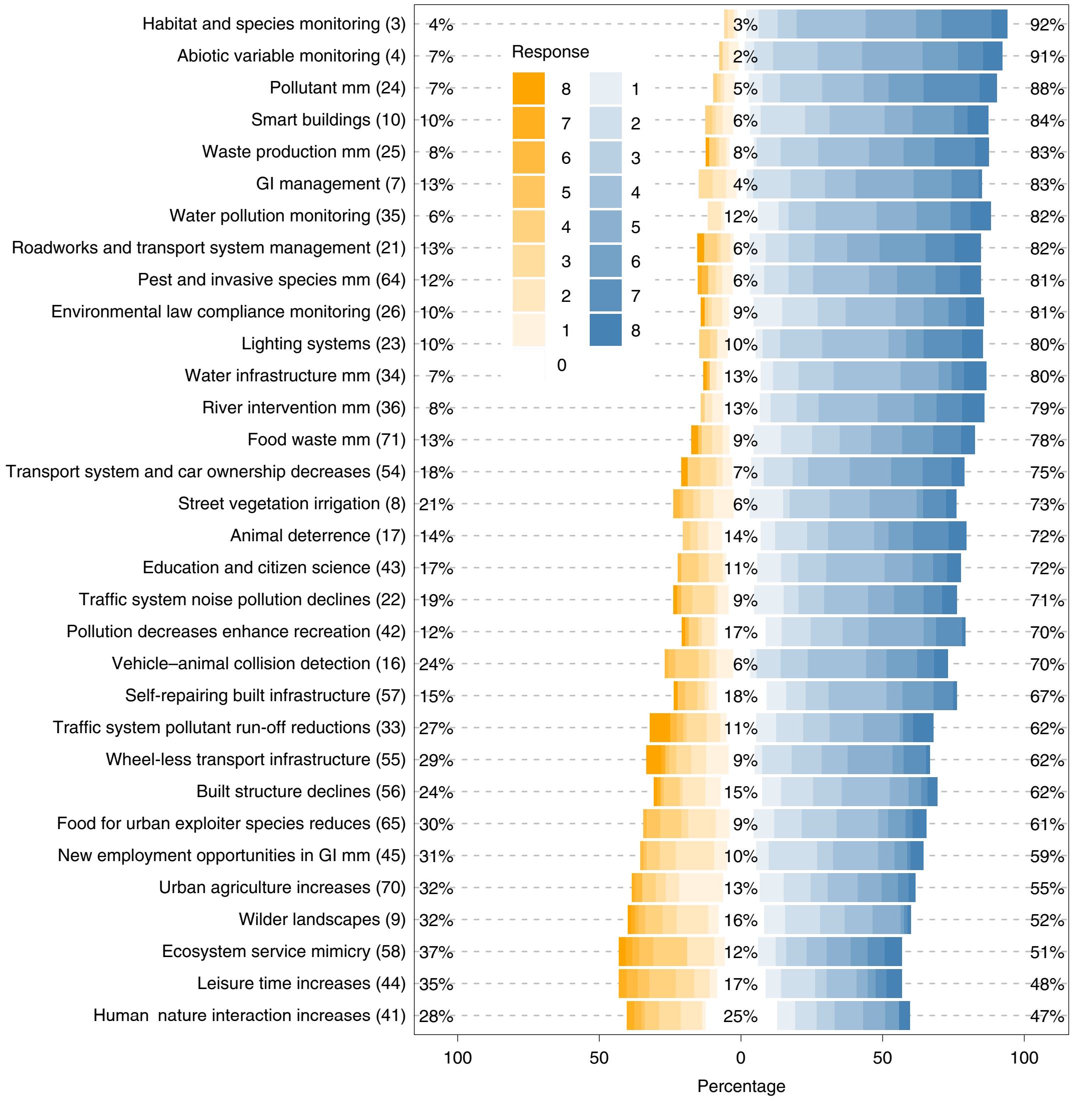

Fig. 3 | Opportunities associated with RAS for urban biodiversity and ecosystems, ranked according to round three participant scores. The distribution of summed participant scores (range: −8 to +8) across four criteria (likelihood, impact, extent and novelty) is shown for each of the 32 opportunities. 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 to and right hand side of the shaded bars, respectively). The full wording agreed by the participants for each opportunity is given in Supplementary Table 1. Item numbers are given in parentheses for cross-referencing between figures and tables. mm, monitoring and management. GI, green infrastructure.

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 prioritized 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 with 38% ($n=20/52$) of those with environmental expertise (Fisher's exact test: odds ratio = 0.20; 95% CI = 0.06–0.60; $P=0.02$). 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 with 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 (for example, batteries, heavy metals and 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 with 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 the challenge 'Pollution will increase if RAS are unable to identify or clean up accidents (for example, spillages) that occur during automated maintenance/construction of infrastructure' (item 32) above zero compared with 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

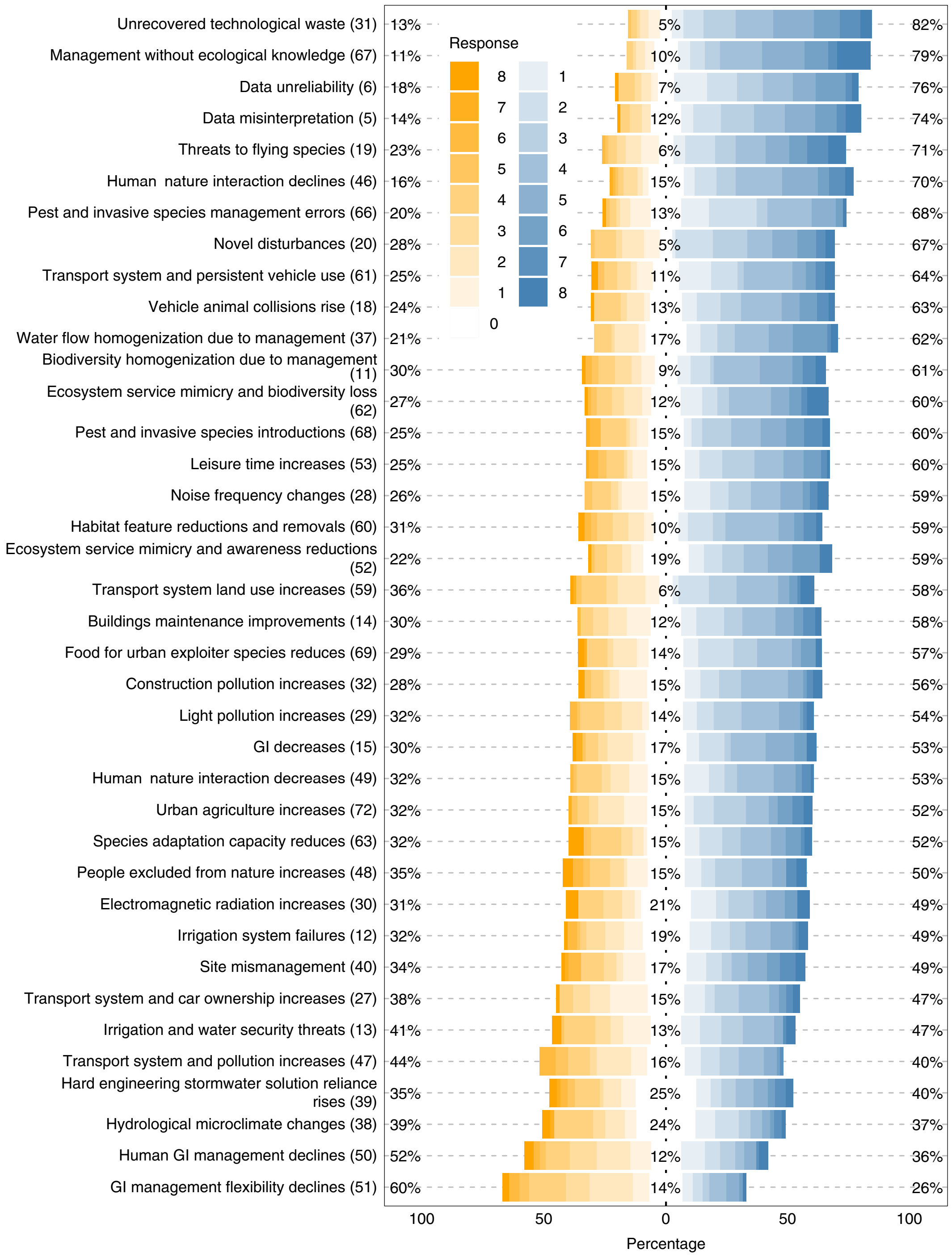

Fig. 4 | Challenges associated with RAS for urban biodiversity and ecosystems, ranked according to round three participant scores. As in Fig. 3, but for the 38 challenges.

similar pattern was observed for item 38 'RAS will alter the hydrological microclimate (for example, temperature and light), altering aquatic communities and encouraging algal growth'. A significantly greater proportion of non-environmental compared with 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 indicates that the full benefits of RAS for urban biodiversity and ecosystems may not be realized. Experts responsible for the development and implementation of RAS could prioritize 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 (Fig. 2). A final set of 13 opportunities and 15 challenges were selected by the participants, which were grouped into eight topics (Table 1).

1. 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,

Table 1 | The most important 13 opportunities and 15 challenges associated with RAS for urban biodiversity and ecosystems

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 (for example, roads, car parks and driveways), allowing an increase in the extent and quality of urban green space and associated ecosystem services (item 54)	The replacement of ecosystem services (for example, air purification and pollination) by RAS (for example, artificial trees and 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 will be damaged through direct collision (item 60)
		Autonomous transport systems will require new infrastructure (for example, charging stations, maintenance and control facilities and vehicle depots), leading to the loss/fragmentation of green spaces (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 (for example, through automated reflectors), reducing urban temperatures and providing less harsh microclimatic conditions for biodiversity under ongoing climate change (item 10)	Biodiversity will be reduced due to generic, simplified and/or homogenized management by RAS. This includes over-intensive green space management, improved building maintenance and homogenization of water currents and timings of flow (items 11, 14 and 37 merged)
	Irrigation of street trees and other vegetation by RAS will lead to greater resilience to climate change/urban heat stress (item 8)	
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, as well as decreasing awareness of the surrounding environment while travelling (item 46)
	RAS will provide novel ways for people to learn about and experience biodiversity and will 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 (for example, artificial trees and robot pollinators) will reduce awareness of ecological functions and undermine public support for/valuation of green infrastructure 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/artificial intelligence 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, and so on; for instance, pest control programmes threaten unpopular species (for example, wasps and 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 difficult-to-identify species groups (for example, invertebrates) or less tangible ecosystem elements (for example, landscape and aesthetic benefits), leading to under-valuing of 'invisible' species and elements (item 6)
5. Managing invasive and pest species		When managing/controlling pests 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, and so on (item 20)
7. Pollution and waste	RAS will improve the detection, monitoring and clean-up of pollutants, benefitting ecosystem health (item 24)	Unrecovered RAS and their components (for example, batteries, heavy metals and plastics) will be a source of hazardous and non-degradable waste (item 31)

Continued

Table 1 | The most important 13 opportunities and 15 challenges associated with RAS for urban biodiversity and ecosystems (continued)

Topic	Opportunities	Challenges
	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 the detection of breaches of environmental law (for example, fly-tipping, illegal site operation, illegal discharges, consent breaches, and so on) (item 26)	
	Automated and responsive building, street and vehicle lighting systems will reduce light pollution impacts on plants and nocturnal and/or migratory species (item 23)	
	Automated transport systems (including roadworks) will decrease vehicle emissions (by reducing the number of vehicles and improving traffic flow), leading to improved air quality and ecosystem health (item 21)	
8. Managing water and flooding	Monitoring and maintenance of water infrastructure by RAS will lead to fewer pollution incidents, improved water quality and reduced flooding (item 34)	Maintenance of stormwater by RAS will increase reliance on hard engineering solutions, decreasing the uptake of nature-based stormwater solutions that provide habitat (item 39)

The opportunities and challenges were prioritized as part of an online horizon scan involving 170 expert participants from 35 countries (Fig. 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 parentheses are for cross-referencing between the figures and tables.

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 affect both species[32] and people's wellbeing[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 (for example, roads, car parks and 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 (for example, charging stations, maintenance and control facilities and 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].

2. 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 optimizing 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 such as 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 and leaf litter and herbicide application substantially 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]. Therefore, 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. For hydrological systems in particular, participants noted that automated management could result in the homogenization 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 (for example, for house sparrows *Passer domesticus*[55]), especially for cavity and ground-nesting species.

3. 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 marginalized[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[63,64] 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[65] and mental health[66]. Changes in noise levels could also improve experiences of biophonic sounds such as bird song[67]. Driving through green, rather than built, environments can provide human health benefits[68]. 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 chose greener routes[69]. Autonomous vehicles could alter how disadvantaged groups, such as children, older and disabled people travel[70]. 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[71] that can foster connectedness to nature[72]. Participants suggested that 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[73].

Alternatively, participants envisaged scenarios whereby RAS reduce human–nature interactions. One possibility is that autonomous deliveries to households may minimize 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[74]. RAS that mimic or replace ecosystem service provision (for example, Singapore's cyborg supertrees[75], and robotic pollinators[76]) may reduce people's appreciation of ecological functions[77], potentially undermining public support for, and values associated with, green infrastructure and biodiversity conservation[78]. This is in line with what is thought to be occurring as people's experience of nature is increasingly dominated by digital media[79].

4. 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[12]. 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 was one that participants identified as an important opportunity[80]. 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 difficult-to-detect species[81,82]. RAS also offer the potential to detect plant diseases in urban vegetation and, subsequently, inform control measures[83,84].

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 prioritize easy-to-identify and charismatic species in well-studied regions could intensify[85]. Participants emphasized 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 (for example, landscape, aesthetic and spiritual benefits) that cannot be captured or quantified autonomously may be overlooked in decision-making[86]. 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 city-wide responses[87].

5. Managing invasive and pest species. The abundance and diversity of invasive and pest species are often high in cities[88]. 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[89,90]. However, participants were concerned about the implementation of such novel approaches, citing the potential for error, whereby misidentification could lead 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.

6. RAS interactions with animals. The negative impact of unmanned aerial vehicles on wildlife is well documented[91], but evidence from some studies in non-urban settings suggests that this impact may not be universal[92,93]. 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 habitats by creating a three-dimensional barrier to animal movement, which might disproportionately affect migratory species. Similarly, ground-based or tree-climbing robots[52] may disturb nesting and non-flying animals.

7. Managing pollution and waste. Air[94,95], noise[96] and light[97,98] 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[63,64]. 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[99]. RAS that monitor air quality, detect breaches of environmental law and clean up pollutants are already under development[100,101]. Waste management is a major problem for urban sustainability, and participants noted that RAS[102] 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[103].

8. Water and flooding. Freshwater, estuarine, wetland and coastal habitats are valuable components of urban ecosystems worldwide[104]. Maintenance of water, sanitation and wastewater infrastructure is a major sustainability issue[105]. It is increasingly acknowledged that RAS could play a pivotal role in how these systems are monitored and managed[106], including improving drinking water[107], addressing water quality issues associated with sewerage systems[108] and monitoring and managing diverse aspects of stormwater predictions and flows[109]. 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[110,111]. Furthermore, 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[112]. However, participants identified that the opposite scenario could materialize, whereby RAS-maintained stormwater infrastructure increases reliance on hard engineered solutions, decreasing the uptake of nature-based solutions (for example, trees, wetlands, rain gardens, swales and retention basins) that provide a habitat and other ecosystem services[113].

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 is maximized. Here, we identified and prioritized 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 from 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 minimize 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 difficult to predict, early examination is essential to avoid detrimental and unintended consequences on urban biodiversity and ecosystems while fully realizing the benefits.

Methods

Horizon scan participants. We adopted a mixed approach to recruiting experts to participate in the horizon scan, to minimize the likelihood of bias associated with relying on a single method. For instance, snowball sampling (that is, 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 difficult-to-reach groups[114]. We therefore contacted individuals directly via an email inviting them to join the horizon scan, as well as using social media and snowball sampling. The 480 experts working globally across the research, private, public and non-governmental organization sectors who were contacted directly were identified through professional networks, mailing lists (for example, groups with a focus on: urban ecosystems; the research, development and manufacture of RAS; or urban infrastructure) and author lists of recently published papers, as well as the editorial boards of subject-specific journals. Of the 170 participants who took part in round one, 143 (84%) were individuals who had 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: (1) environmental (including ecology, conservation and all environmental sciences); (2) infrastructure (including engineering and maintenance); (3) sustainable cities (covering any aspect of urban sustainability, including the implementation of smart cities); (4) RAS (including research, manufacture and application); or (5) 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 and the Caribbean[115]). Participants specified their employment sector according to four categories: (1) research; (2) government; (3) private business; or (4) non-governmental/not-for-profit organization.

Participants were asked to provide informed consent before 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 minimizes 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. These could either be opportunities (that is, RAS would have a positive impact on biodiversity and ecosystem structure/function) or challenges (that is, RAS would have a negative impact) (Fig. 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. M.A.G. subsequently collated and categorized the statements into major topics through content analysis. A total of 60 opportunities and challenges were identified.

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

In round three, we used a questionnaire to ask participants to prioritize the 70 opportunities and challenges in order of importance (Fig. 2). We asked participants to score four criteria[25,116] using a five-point Likert scale ranging from −2 (very low) to +2 (very high): (1) likelihood of occurrence; (2) potential impact (that is, the magnitude of positive or negative effects); (3) extensiveness (that is, how widespread the effects will be); and (4) degree of novelty (that is, 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 minimize the influence of scoring fatigue[117]. 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 of their scores for that opportunity or challenge. We generated score visualizations in the Likert package[118] of R version 3.4.1 (ref. [119]). 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 (that is, 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) (Fig. 2 and Supplementary Table 1). For round four, we allocated participants into one of ten groups, with each group comprising experts with diverse backgrounds. We asked the groups to discuss the ranked 32 opportunities and 38 challenges and to 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 the 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).

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Anonymized data are available from the University of Leeds institutional data repository[120] at https://doi.org/10.5518/912.

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Author contributions

M.D. conceived the study. M.D., M.A.G., Z.G.D., S.G., J.C.F. and M.J.F. developed and tested the questionnaire and webinar materials. A.A., T.A., P.M.L.A., F.A., C.A., A.J.B., A. Barkwith, A. Berland, C.J.B., C.C.R.-B., L.B.B., D.C., R.C., T.C., S. Connop, S. Crossland, M.C.D., D.A.D., C.D., C.T.D., E.C.E., F.J.E., P.G., N.M.G., B.G., A.K.H., J.D.H., C.H., M.H., D.F.H., T.I., I.-C.I., D.K., T.K., I.K., S.J.L., S.B.L., I.M.-F., P. Manning, P. Massini, S.M., D.D.M., A.O., G.P.L., L.P.-U., K.P., G.P., T.J.P., K.E.P., R.A.R., U.R., S.G.P., H.R., J.P.S., S.d.S., S.S., C.E.S., A.S., T.S., R.P.H.S., C.D.S., M.C.S., T.V.d.V., S.J.V., P.H.W., C.-L.W., M.W., N.S.G.W., J.Y., K.Y. and K.P.Y. contributed data. M.A.G. collated and analysed these data. M.A.G., M.D. and Z.G.D. led writing the paper. A.A., T.A., P.M.L.A., F.A., C.A., A.J.B., A. Barkwith, A. Berland, C.J.B., C.C.R.-B., L.B.B., D.C., R.C., T.C., S. Connop, S. Crossland, M.C.D., D.A.D., C.D., C.T.D., E.C.E., F.J.E., N.M.G., B.G., A.K.H., J.D.H., C.H., M.H., D.F.H., T.I., I.-C.I., D.K., T.K., I.K., S.J.L., S.B.L., I.M.-F., P. Manning, P. Massini, S.M., D.D.M., A.O., G.P.L., L.P.-U., K.P., G.P., T.J.P., K.E.P., R.A.R., U.R., S.G.P., H.R., J.P.S., S.d.S., S.S., C.E.S., A.S., R.P.H.S., C.D.S., M.C.S., T.V.d.V., S.J.V., P.H.W., C.-L.W., M.W., N.S.G.W., J.Y., K.Y. and K.P.Y. contributed and agreed to the final version.

Competing interests

The authors declare no competing interests.

Additional information

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Supplementary information is available for this paper at https://doi.org/10.1038/s41559-020-01358-z.

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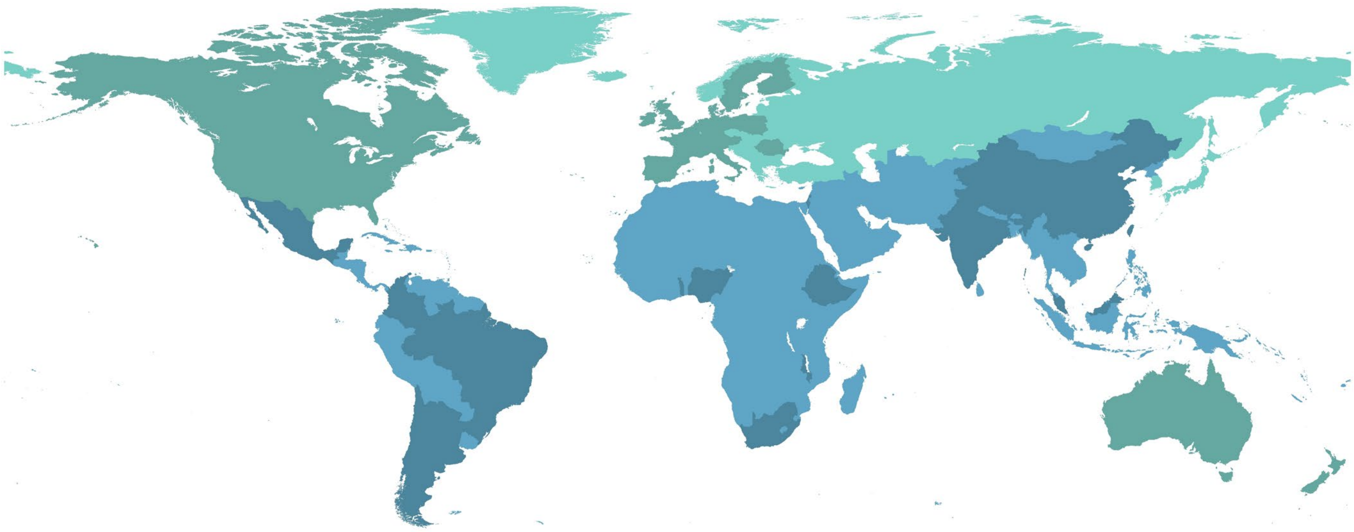
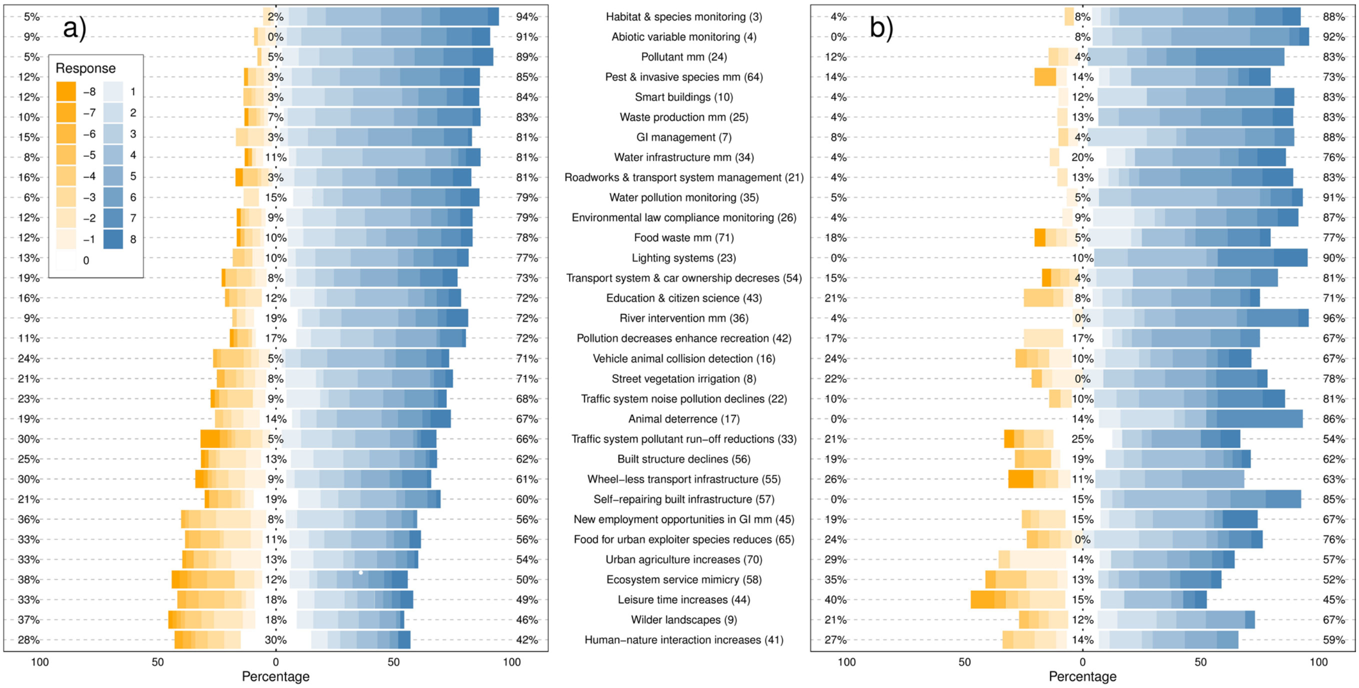
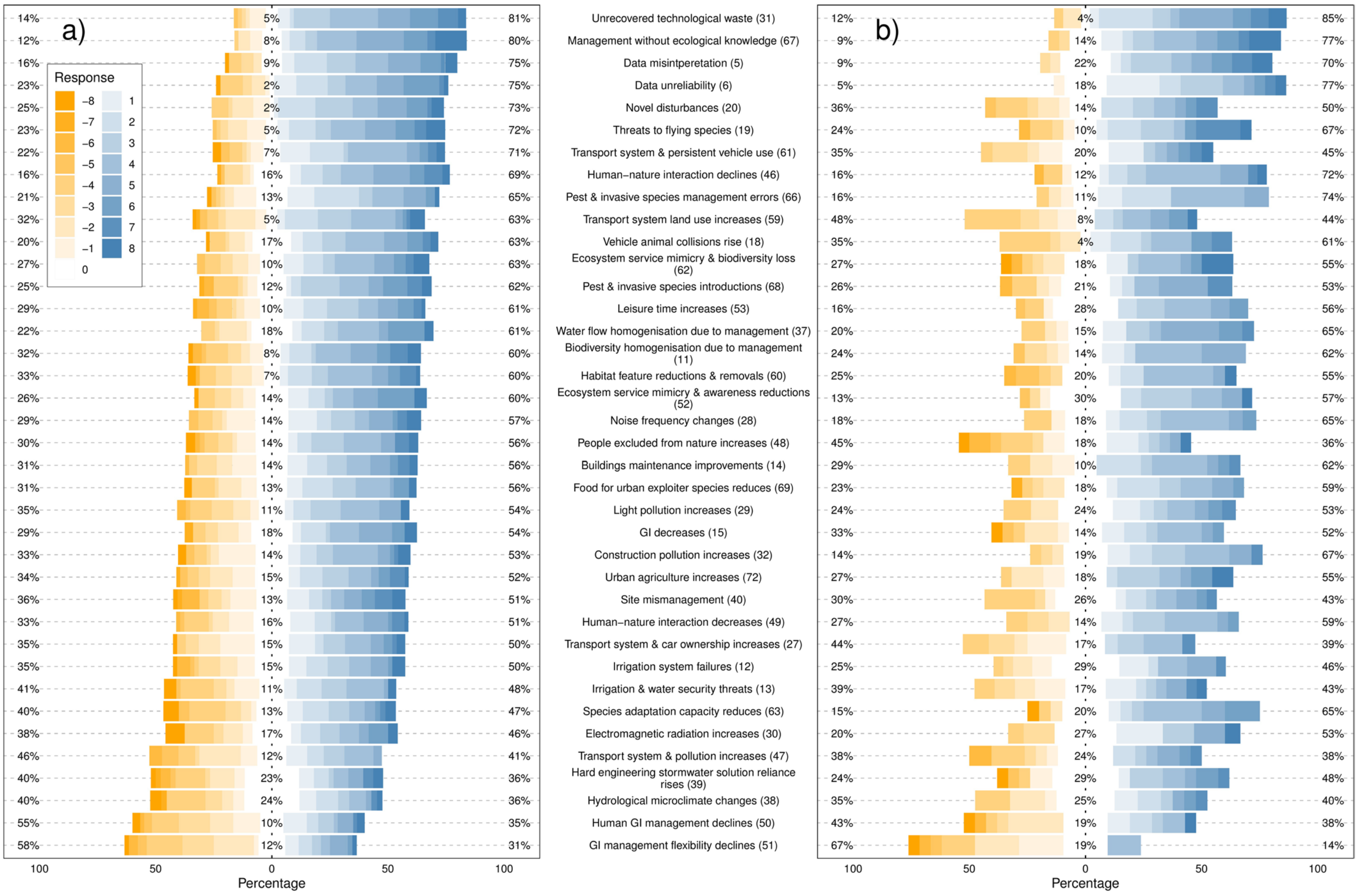


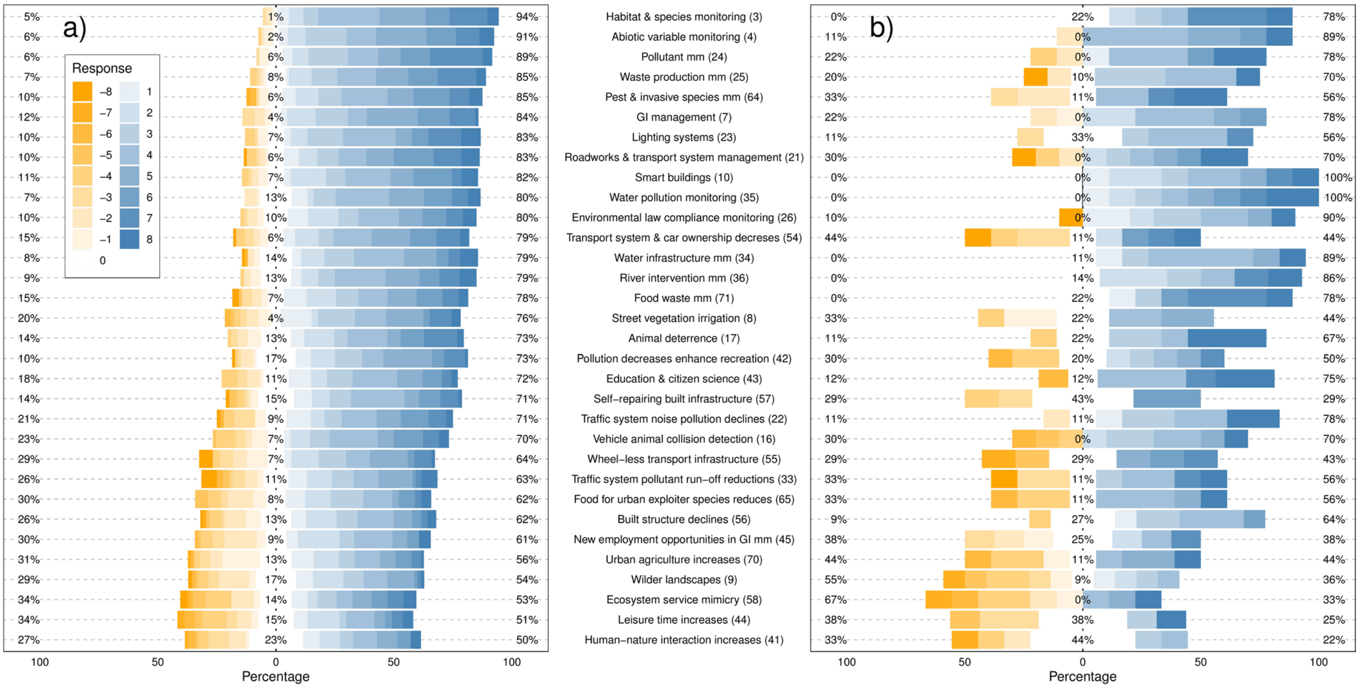
Extended Data Fig. 1 | The Global North (green) and Global South (blue), with countries represented by participants in round one of the horizon scan indicated with darker shading. Countries represented from the Global North were: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Ireland, Israel, Italy, Netherlands, New Zealand, Poland, Portugal, Romania, Spain, Sweden, Switzerland, United Kingdom and United States of America. Countries represented from the Global South were: Argentina, Brazil, Chile, China, Colombia, Ethiopia, India, Malawi, Malaysia, Mexico, Nigeria, South Africa and Togo.



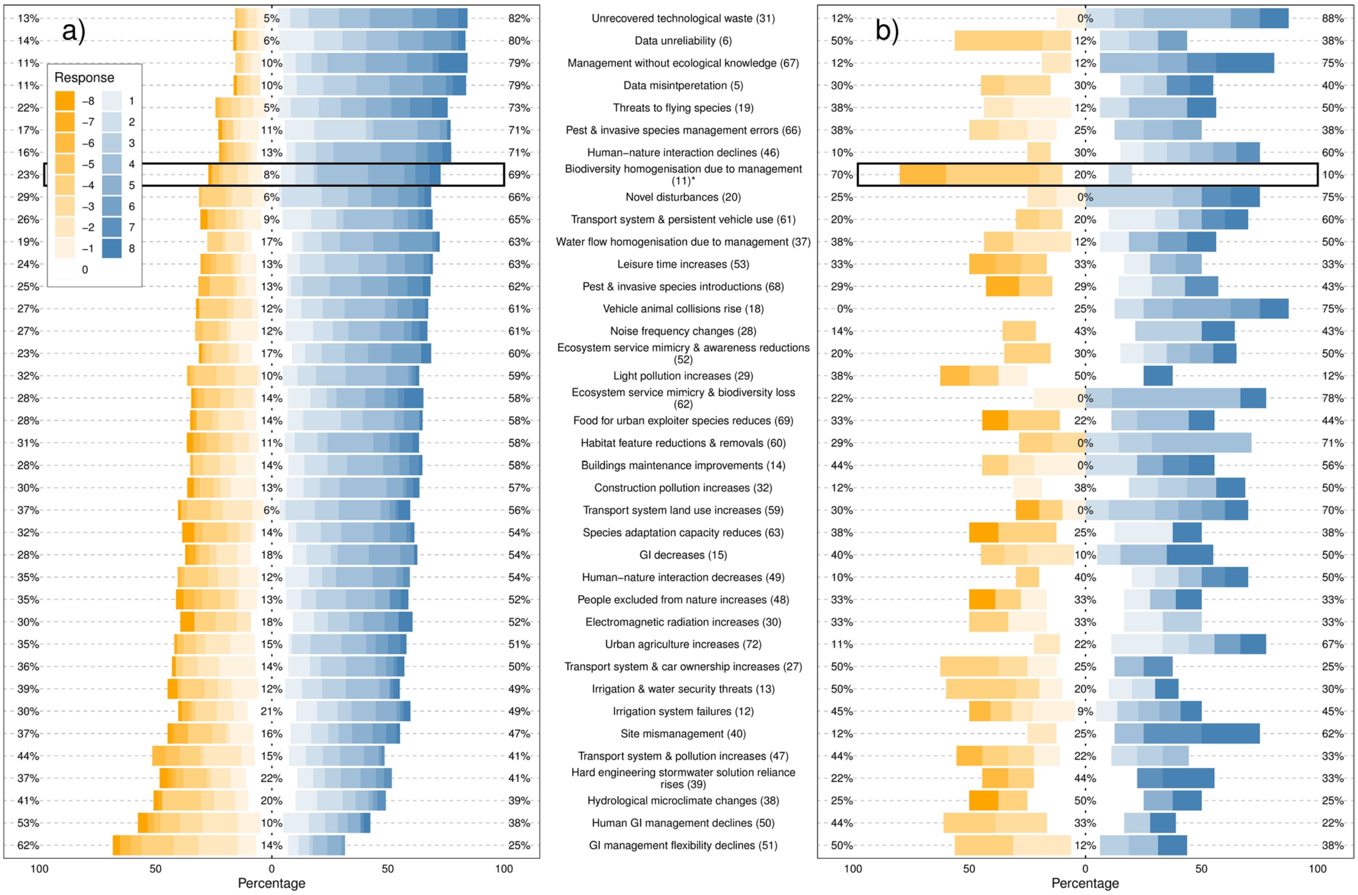
Extended Data Fig. 2 | Opportunities associated with robotics and automated systems for urban biodiversity and ecosystems according to participants working in the research sector and other sectors. a, Participants working in the research sector (*n* = 66). **b**, Participants working in other sectors (*n* = 32). The distribution of summed participant scores (range: -8 to +8) across four criteria (likelihood, impact, extent, novelty) for each of the 32 opportunities. Items are ordered according to percentage of participants in (**a**) who gave summed scores greater than zero. Percentage values indicate the proportion of participants giving negative, neutral and positive scores (left hand side, central and right hand side of the shaded bars respectively). The full wording agreed by the participants for each opportunity can be found in Supplementary Table 1: 'mm' is an abbreviation for 'monitoring and management'; item number given in parenthesis is for cross referencing between figures and tables.



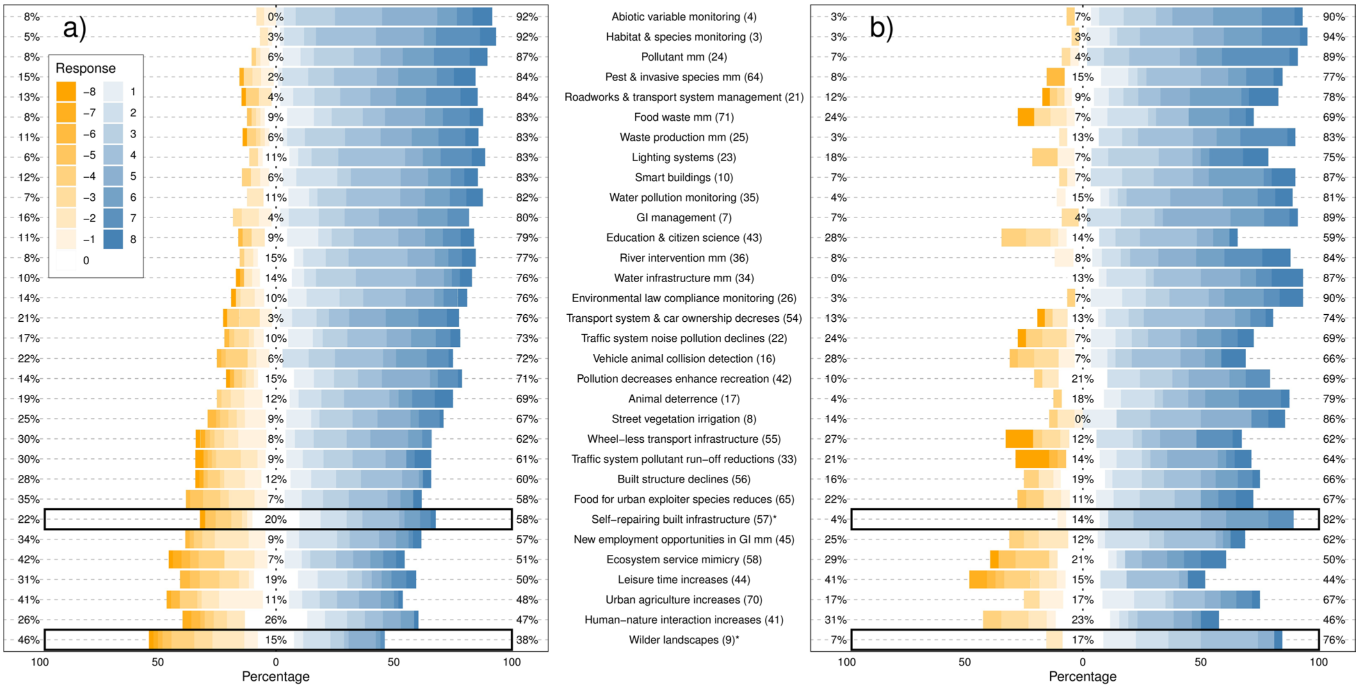
Extended Data Fig. 3 | Challenges associated with robotics and automated systems for urban biodiversity and ecosystems for participants working in the research sector and other sectors. **a**, Participants working in the research sector (*n* = 66). **b**, Participants working in other sectors (*n* =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



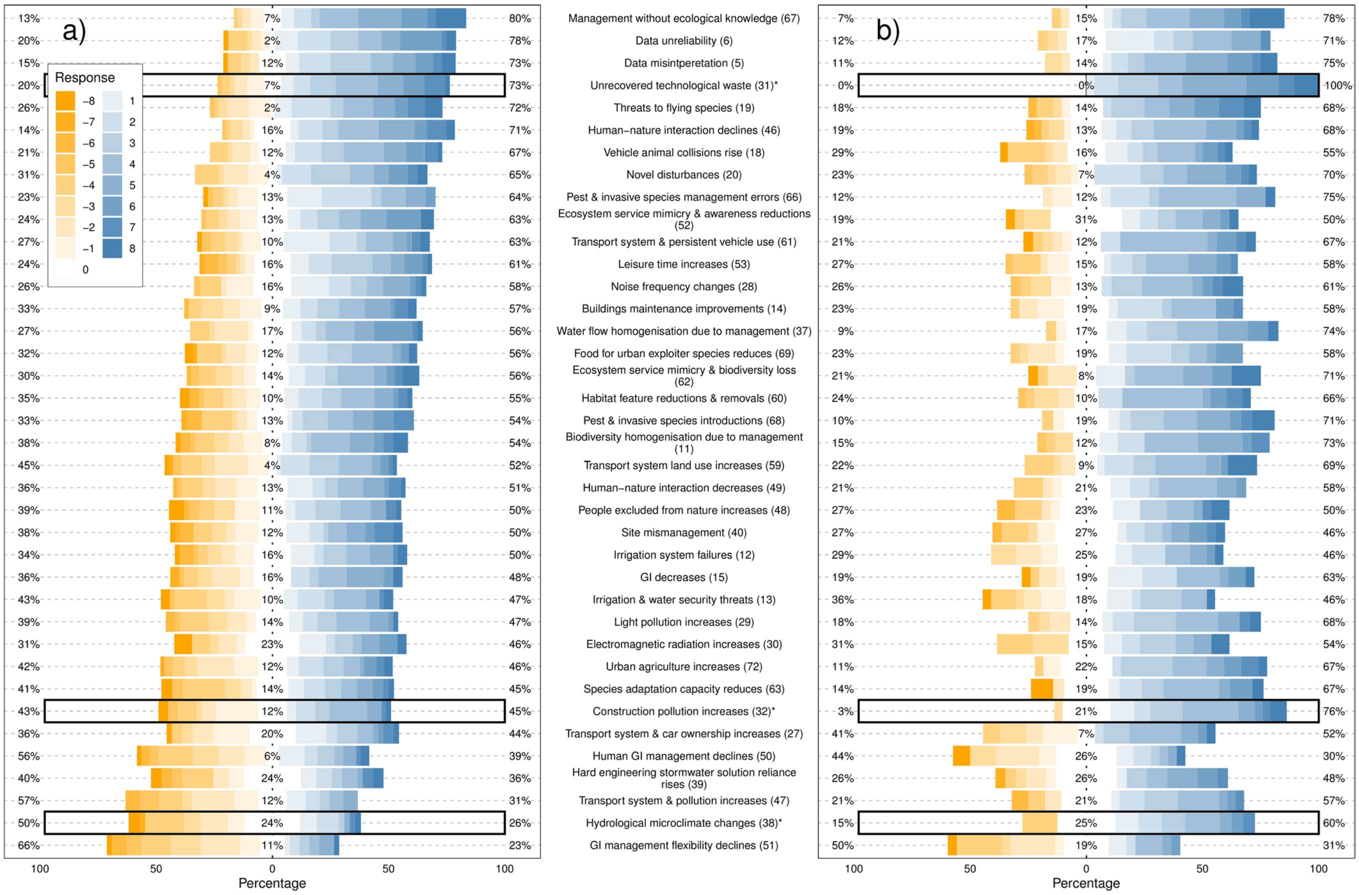
Extended Data Fig. 4 | Opportunities associated with robotics and automated systems for urban biodiversity and ecosystems according to participants based in the Global North and Global South. a, Participants based in the Global North ($n=87$). **b**, Participants based in the Global South ($n=11$). The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



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



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



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

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Questionnaire data were collected through Leeds Online Surveys https://leeds.onlinesurveys.ac.uk/
Data analysis	R version 3.4.1 for statistical tests and Likert plot drawing

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

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- Accession codes, unique identifiers, or web links for publicly available datasets
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Anonymised data are available from the University of Leeds institutional data repository at https://doi.org/10.5518/912.

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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Mixed methods study incorporating responses to closed and open ended questions, and outputs from an online workshop.
Research sample	Research sample: 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, mailing lists and social media. No demographic information was collected as this was not relevant to the study. Study sample was used as we only wished to engage with experts in specific fields of (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)
Sampling strategy	Sampling strategy was a mix of direct contacts, snowball and convenience sampling. All those contacted were sent one initial invitation, followed by two reminders to join the horizon scan. Sample sizes were not chosen, but were a result of how many invitees were willing to take part. We note that typical numbers of participants in horizon scan exercises are usually in the low tens.
Data collection	Data were recorded by participants on their own computers. The study was not experimental, so details on experimental conditions are not applicable.
Timing	The full horizon scan exercise took place between September 2018 and February 2019.
Data exclusions	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). This approach was decided a priori.
Non-participation	We had 170 participants in rounds one and two of the horizon scan. Rounds 3 and 4 had 98 participants. We did not collect motivations for round one and two participants not completing later rounds.
Randomization	No experimental groups were used

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology
☒	☐	Animals and other organisms
☐	☒	Human research participants
☒	☐	Clinical data

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging

Human research participants

Policy information about studies involving human research participants

Population characteristics	See above
Recruitment	We explicitly recruited experts into the study, initially inviting 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.
Ethics oversight	Ethical approval was granted by the University of Leeds Research Ethics Committee (reference LTSEE-077).

Note that full information on the approval of the study protocol must also be provided in the manuscript.