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ENVIRONMENTAL SCAN

Rapid synthesis of environmental antimicrobial resistance (AMR) knowledge and surveillance in Canada

6 February 2025

Acknowledgments

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Context

On 26 September 2024, the United Nations General Assembly called antimicrobial resistance (AMR) "one of the most urgent global health and development challenges" requiring action to protect healthcare, food safety, and economic growth (UNGA, 2024). The rise of AMR endangers modern medicine and economies by rendering essential medicines and life-saving treatments obsolete, driving up healthcare costs, and lowering workforce productivity. For example, between 1990 and 2021, bacterial AMR caused 1.14 million deaths annually, and this is expected to rise by 75% by 2050 if unchecked (Naghavi et al., 2024). In Canada, the Public Health Agency of Canada (PHAC, 2024) estimates that 1 in 220 patients in acute-care hospitals has a resistant infection and AMR could shrink the GDP by over $20 billion CAD by 2050.

The UN General Assembly recently reaffirmed its commitment to a One Health approach, emphasizing the need to manage air, water, plants, soil, food, and disease vectors to strengthen health systems through preventative AMR efforts (UNGA, 2024). This highlights the importance of a systemic One Health approach to holistically address human, animal, and environmental AMR threats. To date, most stewardship efforts have focused on reducing antimicrobial use (AMU) and misuse in human and veterinary medicine and across the food chain. The Quadripartite Alliance of the Food and Agriculture Organization (FAO), World Health Organization (WHO), World Organization for Animal Health (WOAH) and United Nations Environment Programme (UNEP, 2022, 2023) is working together to "strengthen environmental action" in One Health responses.

While the impact of environmental AMR on public health is unclear, the environment is widely recognized as playing a critical role in the selection and dissemination of resistant microorganisms, genes, and antimicrobial residues (Bengtsson-Palme et al., 2023; Bertagnolio et al., 2024; Finley et al., 2013; Larsson and Flach, 2022; Wellcome Trust, 2020). Preventing anthropogenic pollution – especially in hotspots heavily polluted by wastewater treatment, factories, healthcare facilities, and agriculture – is considered essential to prevent AMR spread (UNEP, 2023; WHO et al., 2020), which also helps avoid a negative feedback loop of increased antimicrobial use to prevent AMR-related diseases and biodiversity loss (UNEP, 2022).

Limited monitoring of environmental AMR risks remains a major barrier to realizing a One Health response, as it hampers efforts to manage resistance across the interconnected human, animal and environmental health domains. In Canada, there is an urgent need to understand the status of environmental AMR monitoring in its provinces and territories, as well as understand global approaches that can potentially inform the development of a Pan-Canadian environmental AMR surveillance program.

The rapid synthesis focuses on AMR in the environment. It follows the UK Environment Agency's (2024a: 13) framing, which involves sampling from water, soil, air, or wildlife (plants or animals) in natural settings.

Environmental AMR refers to the presence and proliferation of antimicrobial-resistant microorganisms and their genes in nature via soil, water, air, and wildlife (animal and plant) pathways.

Occurrence, selection, dissemination, and transmission describe interconnected AMR processes:

- Occurrence is the presence of AMR microorganisms or genes in the environment (WHO, 2021).
- Selection is when antimicrobial agents and environmental conditions create pressure that allows resistant strains or genes to develop, survive and multiply (Environment Agency, 2020; UNEP, 2022).
- Dissemination is the spread of AMR microorganisms or genes through pathways like water, soil, air, or animal activity (Environment Agency, 2020; UNEP, 2022; WHO, 2021).
- Transmission is the transfer of AMR pathogens or genes from the environment to humans, animals, or ecosystems (Environment Agency, 2020; Larsson and Flach, 2022).

Questions

- What are current recommendations and approaches in scientific research and international guidelines and plans for monitoring and assessing environmental AMR development, dissemination and transmission risks from a One Health perspective?
- What environmental surveillance data/information is publicly available for AMR pathogens, ARGs and antimicrobials in the environment in Canada?
- What actions are currently being taken in Canada to monitor the development and spread of AMR in the environment in Canada and where are the key environmental AMR surveillance knowledge gaps?

Approach and supporting materials

This rapid synthesis on AMR surveillance in the environment is comprised of three components: a Canadian jurisdiction scan of current knowledge, actions and publicly available databases; a global jurisdiction scan of current recommendations from multilateral institutions leading global AMR stewardship and environmental surveillance approaches of G7 countries; and a global evidence scan on environmental AMR monitoring from 2019-2024.

The synthesis draws from jurisdictional experiences, grey literature, and databases through Google Advanced Search and by reviewing government and stakeholder websites for information from Canada's provinces and territories, as well as France, the United Kingdom (UK), and the United States (US). We identified evidence by searching PubMed and Web of Science on 23 October 2024 to identify primary studies, pre-prints, modelling papers, and grey literature. Based on the UK Environment Agency's (2024a: 13) framing of environment, the main inclusion criterion was sampling from "the natural environment," such as water, soil, air, or wildlife (plants or animals) found in nature. Studies focused solely on built or anthropogenic environments, like wastewater treatment plants or farms, without sampling from the surrounding natural environment were excluded. The search strategies used are included in Appendix 1. Additionally, we interviewed subject matter experts at WHO on October 22, 2024 for further grey literature and information on the status and future directions of environmental AMR in a One Health context.

For evidence syntheses, methodological quality was appraised using the Assessing the Methodological Quality of Systematic Reviews (AMSTAR) tool. AMSTAR rates overall quality on a scale of 0 to 11, where 11/11 represents a review of the highest quality, medium-quality evidence syntheses are those with scores between four and seven, and low-quality evidence syntheses are those with scores less than four. The AMSTAR tool was developed to assess reviews focused on clinical interventions, so not all criteria apply to evidence syntheses pertaining to delivery, financial or governance arrangements within health systems or implementation strategies.

Outlined next in narrative form are key findings related to the questions from relevant evidence identified from the jurisdictional scan of 10 Canadian provinces, 3 Canadian territories, 7 G7 countries, and global scientific literature scan. A separate appendix document includes the following:

- Appendix 1: Methodological details
- Appendix 2: Organizing framework
- Appendix 3: Global jurisdiction scan
- Appendix 4: Global evidence scan summary
- Appendix 5: Canadian jurisdiction scan of environmental AMR surveillance
- Appendix 6: Canadian scientific evidence data extraction
- Appendix 7: Evidence syntheses data extraction
- Appendix 8: Documents excluded from the review

High-level summary of key findings

Current global scientific research and guidance: Environmental AMR monitoring

- 165 evidence documents published between 2019 and 2024 were found relevant to the global scientific research component (see Appendix 4), which included 14 evidence syntheses and 151 single or modelling studies.
- 30 grey literature documents and 39 journal publications were relevant to the guidance and action plans component of the global jurisdiction scan (see Appendix 3). Of the 30 grey literature, there were seven AMR National Actions Plans (NAPs) from G7 countries, 11 discussion papers, technical guidelines or reports from global actors such as United Nations organizations, and 12 research reports from the UK's Environment Agency. The 38 journal publications comprised of ten policy and qualitative studies, 14 evidence syntheses (see Appendix 7), eight single studies and seven reviews or commentaries from experts and environmental regulatory authorities.
- 21 evidence documents were included in the Canadian evidence scan (see Appendix 6), of which seven were identified from the global evidence scan and 14 from hand searches. There were 18 single studies, one modelling study, and two meta-analyses. Additionally, two grey literature documents, two single studies and two commentaries from environmental experts are cited to provide background or contextual information.
- Global One Health dimensions: Research and global guidance show that the One Health approach to AMR is expanding beyond the traditional focus on humans, animals, and the environment to include food and plant health. In Canada, this is reflected in the emphasis on food safety across agri-food systems, from farm to fork.
- Environment in a One Health context: Environment and environmental AMR in a One Health context lack clear definitions distinct from human, animal, and food/plant dimensions. And while it is clear that AMR threatens the health of people and animals by rendering antimicrobials ineffective, it is still uncertain whether AMR has a negative impact on the environment's natural ability to function (Larsson et al., 2023).
    - Evidence suggests that environmental AMR generally refers to AMR associated with natural media (water, soil, air, and wild biota) that is contaminated by human activities and is typically untreated.
    - Monitoring environmental AMR is important because it poses risks to human, animal, and crop health as both a source and transmission pathway for resistance.
    - A hotspot approach was universally applied, in which focus is on contaminated media in areas with significant AMR pollution and hazards, and conditions found favorable for AMR exposure and transmission.
- Developing an environmental component in an integrated national AMR surveillance program:
    - Environmental dimension: No country is implementing an environmental component of an integrated AMR surveillance program that holistically addresses water, soil, air and wild biota at a national scale.
    - Global guidance: WHO (2021) Tricycle Protocol is currently the only recommended global guidance that simultaneously addresses bacterial resistance in humans, across the food chain, and in the environment. It recommends using Extended Spectrum Beta-Lactamase producing *Escherichia coli* (ESBL-Ec) as a cost-effective indicator to monitor resistance trends. However, it thus far has had limited uptake by high-income countries that are at various stages of integrating environmental components in more advanced human and animal or food safety AMR surveillance systems.
- G7 National Action Plans and implementation parallels:
    - Objective: All G7 countries expressed environmental AMR priorities in terms of prevention and control, mainly to mitigate antimicrobial exposure and contamination in the natural environment.
    - Phased approach: While the focus and level of implementation for environmental AMR surveillance is diverse across contexts, a phased approach focused on priority environmental indicators significant to human or food systems safety was commonly adopted in national integrated AMR surveillance programs.
    - Leveraging extant monitoring programs: 5 of 7 countries (Canada, France, US, UK, Germany) pragmatically are leveraging existing programs for environmental AMR surveillance for reasons that included cost efficiency and rapid deployment.
    - Hotspot focus: Each focused on identifying hotspots, such as areas with high contaminant sources (*e.g.*, wastewater, organic waste) and conditions that promote AMR spread.

  - Environmental media: The UK Environment Agency has extensively published on its approach to the environmental aspects of AMR and the rationale behind the design of its environmental AMR surveillance program. It offers various research reviews and tools addressing risks related to waterborne, soilborne, airborne, and wild biota.
  - Interagency working model: The US has established a strong collaborative interagency working model that monitors an environmental media (surface water) at a national scale (Franklin et al., 2024).
- Limited transmission understanding: Despite awareness of environmental transmission risks associated with inadequate water, sanitation and hygiene infrastructure and wastewater treatment (UNEP, 2022; Walsh et al., 2011; WHO et al., 2020), global evidence on AMR transmission risks from the environment remains limited. Most global research focused on AMR occurrence, followed by dissemination and selection.
- Taxonomic focus: Overall, there was greater attention to waterborne environmental AMR risks in global guidance and by G7 countries. This aligns with the global evidence scan results, as 60% (n=99) analysed water-related media, especially in relation to wastewater discharge and receiving surface waters, as compared to soilborne (20.6%, n=34), airborne (3.0%, n=5) or wildlife samples (40.0%, n=66). Research from global researchers indicate greater interest in detecting and understanding transmission risk associated with bioaccumulation of surrounding soil and sediments from agricultural activities and wastewater discharge, aerosol emission from AMR hotspots, and wild animals as bio-sentinels of environmental exposure in impacted human environments.
- Variable methods: Sampling campaigns of environmental media varied, including the frequency and time periods used to collect the range of environmental samples. Two thirds (n=104) applied an opportunistic sampling campaign, while nearly 13% (n=21) applied routine measures of collection – from daily to bimonthly or seasonally over half a year to several years.

Current actions: Environmental AMR monitoring and publicly available surveillance data/information in Canada

- Monitoring: No active surveillance programs or publicly available datasets or databases were found that focused on AMR development, amplification and spread in environmental contexts in Canada (see Appendix 5).
- Antimicrobial use (AMU) or human-agri-food focus: AMR monitoring at present primarily focuses on AMU or is monitoring resistance in the human, animal and food supply chain dimensions of a One Health framework.
- Environmental monitoring:
  - Water, soil, air, and wildlife are monitored in various national, provincial and territorial programs, but they did not have an AMR component. The Department of Fisheries and Oceans reports AMU for transparency around industry practices, not AMR monitoring.
  - Surface water research: PHAC noted its exploration of surface water pathways as part of FoodNet Canada in pilot studies that found occurrence of resistant isolates in river and recreational waters in Ontario (Kadykalo et al., 2020), and that waterborne exposure routes for *salmonella* were low compared to foodborne pathways (Christidis et al., 2020; Hurst et al., 2023).
- The evidence synthesis identified 11 national AMR and non-AMR surveillance programs that can potentially be leveraged when developing environmental AMR selection, dissemination and transmission monitoring in Canada, two of which already are being explored by PHAC.
  - The programs include three national AMR surveillance programs that integrate human, animal and/or food data, one focused on animal health, two non-AMR programs with a strong public health focus, and five national environmental programs monitoring pollutants.
  - 21 publicly available environmental monitoring datasets from Canadian provinces and territories were also identified.

Current research: Environmental AMR occurrence, selection, dissemination, or transmission in Canada

- 21 scientific articles published by Canadian researchers from 2019-2024 were identified during the provincial jurisdiction and global evidence scans (see Appendix 6).

- Geographic scope: Most studies (85.7%, n=18) used Canadian data, while six analysed samples from Wales, France, Germany, US, India, and China. One meta-analysis analyzed global metagenomes.
- Thematic AMR focus: Dissemination was a key theme for more than half of the studies, while a quarter addressed transmission. Selective factors were the least studied.
  - Nearly two thirds of Canadian scientific articles examined multiple AMR processes, with the most common combination being occurrence and dissemination.
  - The four transmission-focused studies were generally PHAC-associated and compared environmental sources to human or agri-food sources, with findings emphasizing surface water and soil as potential transmission pathways.
- Genes and bacteria of interest: Two thirds focused on genetic markers, with antimicrobial resistant genes (ARGs). For microorganisms, only bacteria were monitored, with *Salmonella* and *Escherichia coli* being the most monitored (36.8%, n=7 each). Two measured ESBL-Ec.
- Environmental media focus: Water was the most frequently sampled medium (61.9%, n=13), ranging from wastewater and surface water, including catch basins (drainage for surface water runoff) and recreational waters (water bodies specifically designated for leisure activities).
  - Research also included aerosol studies (28.6%, n=6), soil studies (14.3%, n=3), and wildlife as sentinel species (15.8%, n=3).
  - The three soil studies sampled farm soils impacted by wildlife (animal droppings) and lake sediment in watersheds with significant anthropogenic pollution.
- Comparative approach: All studies featured a comparative component, most often between AMR sources (71.4%, n=14) or to assess how sampled sites might be differently impacted by anthropogenic activities (28.5%, n=6).
- Aerosol research: While aerosol AMR risks are often overlooked in national action plans and most of the global aerosol scientific evidence were reviews, Frontiers-NSERC-funded Canadian research is addressing a key knowledge gap in elucidating the roles of bioaerosols in ARG dissemination and transmission. Initial research includes exploring the links between anthropogenic pollution and long-distance ARG transport (Rossi et al., 2023, 2024), ARG dispersal in diverse environments such as Arctic habitats (Provencher et al., 2024), and assessing novel methods for ARG tracking (George et al., 2024; P George et al., 2022).

Key knowledge gaps: Environmental AMR surveillance in Canada

- Canada lacks a national surveillance program for environmental AMR, limiting a One Health understanding of environmental reservoirs in AMR selection, dissemination and transmission. WHO and PHAC especially align on the need for more data on public health risks from environmentally acquired AMR to guide integrated surveillance.
- Other knowledge gaps include exposure pathways and transmission control points, and environmental pollutants and conditions driving AMR persistence and dissemination. Climate change, while beyond the scope of this review, is recognized as an important factor influencing AMR dynamics.
- The synthesis identified significant gaps in defining and monitoring environmental AMR, as no clear or universally accepted definition exists in scientific literature or global guidance. This lack of standardization complicates environmental monitoring and surveillance efforts, underscoring the need for cross-sectoral alignment and consistent methodologies to support integration of environmental activities in broader One Health AMR efforts.
- Mapping resistomes across microbial reservoirs is critical for early warning systems to mitigate AMR threats. ARGs and mobile genetic elements (MGEs) are increasingly used globally and in Canada to track AMR evolution and spread within the One Health continuum. Knowledge gaps remain in detecting ARG diversity, understanding their evolution, and tracking their transfer between pathogens.
- The lack of standardized indicators and harmonized sampling methods remains a key challenge in environmental AMR monitoring, though progress can be made by establishing priority baseline indicators and integrating environmental surveillance data with human and veterinary health information through cross-sector data systems and isolate libraries.

- Environmental sampling for AMR prioritizes public health risks in anthropogenic hotspots, such as sampling wastewater influent or agricultural settings, rather than effluent or receiving environments. Clear distinctions between sample types (e.g., influent for population risk and effluent for environmental risk) are crucial for understanding the environmental dimension of AMR as it relates to human, animal and crop health risks.
- Canadian wildlife AMR research is limited, with studies primarily focusing on raccoons in rural Ontario and seals in the Maritimes. Effective wildlife monitoring targets species with broad distribution and presence in both impacted and pristine environments to evaluate AMR transmission dynamics associated with food safety concerns and overlapping habitats.
- The WHO recommends using ESBL-Ec as a cost-effective indicator for resistance trends, but its use is minimal in Canada. Historical Canadian data shows low ESBL-Ec prevalence in food animals and humans, but experts recommend ongoing monitoring to detect emerging trends as research has shown that the prevalence of ESBL-Ec increased dramatically during a 10-year study period (Denisuik et al., 2019; Karlowsky et al., 2021).
- Diverse sampling methods and indicators complicate efforts to standardize environmental AMR monitoring globally and in Canada. Indicators can reflect widely distributed organisms, commonly used antimicrobials, and/or environmentally persistent agents. Monitoring requires cost-effective, risk-based approaches tailored to specific contexts, like those implemented by France, the US, and the UK.
- Antimicrobial residue monitoring is a critical but under-researched area in Canada. Further research in this area can help identify AMR hotspots, guide surveillance efforts, and inform the development of more sustainable agricultural and industrial practices.
- While agricultural and pharmaceutical manufacturing pollution from sectors like animal/crop production and drug manufacturing are recognised as key AMR pollution point sources, oversight remains limited in Canada and globally. Recent WHO guidance (2024) on curbing antibiotic pollution from manufacturing offers a useful framework for monitoring and regulating Canada's pharmaceutical sector. Greater monitoring of the world's 8th largest market (ISED Canada, 2024) is important because data on environmental emissions from manufacturing remains a knowledge gap as releases are not covered by quality assurance standards.

Canadian university and government partners are assessing AMR risk associated with water and soil pollution in areas with food animal production, but the risks from antimicrobial use in crops and pharmaceutical manufacturing remain underexplored for their impact on human and agri-food safety in Canada. The recently published WHO (2024) guidance addresses managing wastewater and solid waste from antibiotic manufacturing and offers recommendations for developing indicators and identifying surveillance partners. This includes regulatory bodies, pharmaceutical manufacturers, and waste management actors across the production chain. Currently, globally and in Canada, manufacturing AMR pollution is largely unregulated, as these environmental emissions are excluded from quality assurance standards.

- Policymakers need guidance on designing cost-effective surveillance programs that balance coverage breadth and depth. Implementation studies on integrating surveillance at scale can enhance Canada's approach to environmental AMR monitoring.
- Environmental AMR is an emerging field with evolving methods and terminology. This synthesis highlights current gaps and calls for periodic updates to integrate new science and insights into One Health and environmental AMR surveillance.

Limitations

- The jurisdiction scans relied only on data, information, and documents that were publicly accessible. Government data, however, is often not publicly available or shared between departments or agencies, which likely constrained the review.
- An initial focus on environmental surveillance approaches for AMR yielded limited results due to a lack of available government data and information. The scope was consequently expanded to include hand searches of research-

intensive universities in Canada and integrated or One Health surveillance approaches that incorporate environmental considerations, both in Canada and globally.

- This is a deeply complex and broadly framed topic with a lack of standardised language and approaches across sectors and jurisdictions. The complexity complicated the design of the scoping methods and restricted the ability to apply a consistent structural approach across different types of environmental pollutants and institutions.
- Focus: There was significantly more found on water and wild animals over soil, air and wild plant AMR risks. This might have led to potential overrepresentation of associated health risks. Google Translate was used, when necessary, to translate documents into English, which can limit critical analysis.

Key findings: Current global scientific research and guidance for environmental AMR monitoring

This section summarizes current recommendations and approaches in scientific research and international guidelines and plans for monitoring and assessing environmental AMR development, dissemination and transmission risks from a One Health perspective. See appendices 3 and 4 for data from the global jurisdiction and global evidence scans. For the latter, a total of 2,180 scientific research articles were retrieved through PubMed and Web of Science searches, with 165 studies (14 evidence syntheses (see appendix 7) and 151 single or modelling studies) selected for their relevance to AMR monitoring in natural or surrounding environmental settings.

Environmental AMR definition and focus areas: While there is consensus over a working definition of One Health (Adisasmito et al., 2022), no clear definition for environment or environmental AMR in a One Health context was found. The environment's role is generally discussed within a One Health context as safeguarding public health and food safety. Similarly, global environmental AMR experts identify the environment as an AMR reservoir and a transmission pathway, particularly those exposed to heavily polluted environments, posing risks to human, animal and crop health (Larsson et al., 2023). Global leaders of the Quadripartite integrated surveillance AMR task force are thus exploring the potential of using environmental indicators to measure AMR in human and animal populations (Global Leaders Group on Antimicrobial Resistance, 2024).

There is also a lack of clarity about how the environment is defined in the context of AMR, which leads to uncertainty about what specifically should be measured and sampled. This ambiguity extends to the types of environmental media and settings considered relevant for environmental AMR monitoring. This synthesis followed the UK Environment Agency's (2024a) characterization of the environmental dimension of AMR: contaminated environmental media (water, soil, air and biota) in natural settings, as opposed to an industrial or anthropogenic environment. It also distinguished surface, ground, and marine waters from drinking water, noting that the former are untreated, a distinction that can apply to other media as well.

A hotspot approach was universally applied, in which focus is on contaminated media in areas with significant AMR pollution and hazards (Franklin et al., 2024; WHO, 2021), and conditions found favorable for AMR exposure (Environment Agency, 2024a) and transmission (Haenni et al., 2022). The latter is of particular concern, as mobile resistance determinants that can facilitate AMR evolution, spread and horizontal transfer to humans are most prevalent in hotspots (D'Costa et al., 2006; Kunhikannan et al., 2021; Larsson et al., 2023; Larsson and Flach, 2022).

Integrated surveillance: Rather than establish dedicated environmental AMR surveillance systems, high-income countries such as the UK and US are exploring how existing environmental monitoring activities can be integrated into broader human, animal and food AMR surveillance. For example, the US' interagency enteric bacteria monitoring program for human and food-animal systems is presently piloting the Surface Water AMR Monitoring (SWAM) program, which builds from an existing environmental monitoring program (the National Rivers and Streams Assessment (NRSA)) on the ecological condition of rivers and streams for watershed-level AMR surveillance.

In terms of global guidance for One Health or integrated AMR surveillance systems, the FAO & WHO (2021) Codex Alimentarius and WHO (2021) Tricycle Protocol are currently the only guidance documents recommended by the Quadripartite to enable the generation of comparable geographic data. The former focuses on foodborne AMR and does not include direct surveillance of contaminated environmental media (water, soil, air and biota) in natural environments, and thus was considered outside the scope of this review. The WHO (2021: vi) Tricycle Protocol is included because it "simultaneously" addresses bacterial resistance found in humans, the food chain, and the environment. WHO officials noted that they are currently in the final stages of disseminating additional guidance for the Tricycle.

Based on the Tricycle understanding of simultaneous AMR risk monitoring across human, animal, food and environmental dimensions, no country has an integrated AMR surveillance system with a fully developed environmental AMR component. To date, the Tricycle Protocol has largely been implemented in low- or middle-income countries with limited cross-sector surveillance capacity (Ruppé, 2023). The Tricycle Protocol's limited high-income country application is likely two-fold:

- The Tricycle Protocol was primarily designed for low- and middle-income (LMIC) countries with limited capacity and resources (IACG, 2018).
- High-income countries such as G7 countries with advanced surveillance systems are starting to incorporate environmental aspects, either within existing AMR human-agri-food surveillance programs (UK, US, Germany, Japan) or through routine environmental monitoring measures (France).

Limited uptake of Tricycle monitoring of ESBL-Ec in high-income countries aligns with reviews of the G7 countries' AMR National Action Plans (NAPs) and the global evidence scan findings: only two countries (Germany and Japan) cited commitments to research and apply (Bundesministerium für Gesundheit, 2023; Government of Japan, 2023); and about a tenth of the included scientific literature from the global evidence scan (9.6%, n=16) tested for ESBL-Ec. Of these 16 articles, 62.5% (n=10) were from G7 countries (France, Germany, Italy, Japan, US). WHO officials noted that there is interest to adapt the Tricycle in the US, and that the Netherlands is currently defining indicators based on it at the country and EU level.

G7 National Action Plans: While G7 countries note commitments to one health approaches and environmental dimensions in their National Action Plans for AMR, there overall was a lack of environmental focus as compared to human, animal or food safety dimensions, especially in addressing key pathways and drivers of AMR through different environmental media. Singer et al. (2016a) attributed this to limited scientific evidence available to guide policy development. Although countries like France, the UK, and the US have initiated environmental AMR strategies, their National Action Plans were high-level and failed to capture the full scope of ongoing scientific research or the practical expertise of collaborative researchers and government agencies working to address One Health knowledge and intervention gaps. For example, France's National Action Plan (Ministere des Solidarites et de la sante, 2022) did not capture marine research on AMR environmental contamination and indicator genes from university and governmental collaborators in the English Channel and North Sea (Bourdonnais et al., 2022, 2024a, 2024b). Table 1 provides an overview of the G7 NAPs and respective environmental surveillance approaches.

G7 environmental media: Overall, there is not a uniform focus on environmental media.

Water is the primary environmental media all G7 countries focused upon. With regards to monitoring, Sabbatucci et al. (2024) reported that France, the US, and Italy have systems for regular monitoring of surface water quality, including resistant bacteria, ARGs, antimicrobial compounds, and/or residues. However, the surveillance programs for France and Italy, as well as the US datasets, were not found online in this review. US government officials have published a detailed narrative describing the objectives, design rationale and methods applied in SWAM, an interagency effort that monitors environmental water AMR risks at a watershed and national scale (Franklin et al., 2024). While the US, France and Italy have a surface water focus, Canada and Germany reported building from their SARS-CoV-2 wastewater monitoring program in their respective NAPs, though neither specify if they are monitoring influent for population risks or effluent for environmental risks.

Four G7 countries (Canada, Germany, Japan, UK) highlighted soil as an environmental reservoir. Research has been undertaken in the UK on antifungal risk linked to biosolid spread in terrestrial environments (Martin and Hart, 2023).

While no G7 NAP highlighted airborne AMR risks as a concern, the UK is reportedly working towards a national surveillance strategy to address AMR bioaerosol exposure (Environment Agency, 2023a). Additionally, collaborative research from Canada and global experts indicates possible aerosol monitoring of atmospheric AMR transport via clouds (Rossi et al., 2023, 2024) or snow (Zhu et al., 2021), as well as biomonitoring via conifer needles, is nascent.

The Italy, Japan, and UK NAPs recognised AMR wildlife risks in association with food safety, zoonotic health and general environmental health. The global evidence scan indicated that wildlife sentinel research is of interest to researchers in all G7 countries, with wild boar being of particular interest to Germany and Italy likely due to food safety, and deer in Germany, Italy, the UK and raccoons in Canada and the US likely due to exposure risk of shared human-wildlife landscapes. Policymakers from the UK have produced biomonitoring guidance for species in freshwater, coastal/marine and terrestrial environments (Environment Agency, 2023b).

Table 1: Overview of G7 National Action Plans (Bundesministerium für Gesundheit, 2023; Government of Japan, 2023; HM Government, 2024; Ministere des Solidarites et de la sante, 2022; Ministero della Salute, 2022; PHAC, 2023a; US Federal Task Force on Combating Antibiotic-Resistant Bacteria, 2020), with additional environmental approach information cited in-text

	Canada	France	Italy	US	UK	Germany	Japan
Year range	2023-2027	2022-2025	2022-2025	2020-2025	2024-2029	2023-2030	2023-2027
AMR focus	Antimicrobial	Antibiotic	Antibiotic	Antibiotic, antifungal	Antibiotic, antifungal	Antibiotic	Antimicrobial
Tricycle surveillance						One Health approach example	Research commitment
Env. AMR: Water	Water	Water, groundwater	Water	Water	Water	Water	Water
Soil	Crops, sediment				Crops, land	Soil	Soil
Air							
Wildlife: Animals			Linked to food safety, zoonotic disease risk		Linked to animals (food, companion)		Associated with environment
Plants							
Env. AMR priorities	Focus on water quality monitoring, water use management and wastewater treatment, as well as marine sediments	Strong pharma. and clinical focus, from responsible manufacturing to supply chain monitoring and community dispensation; mitigating clinical waste risk	Waste-related microbial population focus (e.g. wastewater, sewage, livestock or aquaculture waste); zoonotic disease risk; food residues	Surface water focus and science-driven approach, from advanced molecular testing of ABR pathogens to deeper understanding of ABR one health transmission	Science-driven approach focused on waste minimisation and effective waste management to mitigate AMR and AMR-driving chemicals env. dissemination	Env. release, including factors like biofilms and soil AMR impact post-wastewater and slurry discharge	One health surveillance and research of AMR organisms and residual antimicrobials in aquatic and terrestrial environments, and wild animals
Env. AMR surveillance	• Exploring leveraging FoodNet Canada's surface water data collection for AMR and antimicrobial testing (PHAC, 2023b) • Leveraging Pan-Canadian SARS-CoV-2 wastewater surveillance to help with early AMR detection, including	• Leveraged environmental monitoring of surface water for AMR surveillance (Collineau et al., 2024) • NAP environmental pollution measures: antibiotic production and use, and controlling liquid (effluent) or solid waste production or	Establishing monitoring of: • antibiotics, ABROs, and ARGs in env. • antimicrobial producers with significant discharge • zoonoses prevention: main zoonotic microorganisms and ARGs in food supply chain, and protecting biodiversity	Developing interagency env. component of National AMR Monitoring System (NARMS) called surface water AMR monitoring program (SWAM), which monitors watershed-level pollution (Franklin et al., 2024)	• Leveraging existing env. monitoring capacity for agri-food tracking of foodborne human pathogens and AMR • Defined env. dimensions and developed risk assessment / prioritization tool, and wildlife and biomonitoring strategy (Environment	Undertaking "phased approach" integrating human, veterinary, agriculture, env. monitoring, drawing from resistance monitoring in federal and regional government vet. sector, and SARS-CoV-2 wastewater monitoring	Establishing a One Health Surveillance system linking data from multiple ongoing programs, including the Japan Nosocomial Infections Surveillance (JANIS) and Japanese Veterinary Antimicrobial Resistance Monitoring System (JVARM)

	three city pilot (PHAC, 2023b)	from care activities			Agency, 2023b, 2023c, 2024a)		

Table key:	Data was found and recorded	No data was captured

The UK Environment Agency has published extensively on its framing of environmental dimensions of AMR and rationale underpinning the design of its environmental AMR surveillance program, with various research reviews and tools available on waterborne, soilborne, airborne and wild biota risks via its website.

G7 phased approach: No country had a purpose-designed surveillance program in which environmental AMR risks was a core focus. Each country seemed to be at different stages of integrating environmental AMR surveillance into ongoing monitoring programs, whether by incorporating an environmental component into a program already monitoring antimicrobial use and resistance in public health, agricultural and food safety systems, or linking it to ongoing water, soil, air quality or wildlife monitoring. Five of seven G7 countries (Canada, France, US, UK, Germany) indicated planning to leverage existing monitoring programs to better understand environmental AMR risks in their jurisdictions. For instance, Canada (Canadian Integrated Program for Antimicrobial Resistance Surveillance (CIPARS)), the UK (Pathogen Surveillance in Agriculture, Food and Environment (PATH-SAFE)) and US (National Antimicrobial Resistance Monitoring System (NARMS)) indicated they are developing environmental components that expanding their human-agri-food safety surveillance. Reflections from the UK and US noted this is in part due to cost efficiency (Franklin et al., 2024; Hart et al., 2023), and rapid deployment (Environment Agency, 2023a).

Experts and policymakers in French, UK and US agencies have detailed their approaches in a wide range of publications—from reviews, policymaking reflections and official agency publications. Table 2 draws from recommendations (Collineau et al., 2024; Haenni et al., 2022), tools and strategies (Environment Agency, 2023b, 2024a, 2024b), or next steps (Franklin et al., 2024) to describe their respective environmental AMR approaches and key knowledge gaps they aim to address in the immediate future.

Table 2: Descriptions of surveillance approach and knowledge gaps – France (Collineau et al., 2024; Haenni et al., 2022)**, US** (Franklin et al., 2024)**, and UK** (Environment Agency, 2023b, 2024a, 2024b)

	France	US	UK
One health surveillance	• Create a One Health operational body for national coordination facilitating cross-sectoral collaboration and operations. • Create a national cross-sectoral working group to define common indicators and integrate data analysis.	• Established a national interagency working group, which presently aims to produce standard measurement protocols, sampling design parameters, and reporting guidelines for monitoring AMR in surface waters. • Generate isolates library to facilitate multi-scale comparison and cross referencing with NARMS library.	• Develop surveillance of AMR in environmental settings driven by Environmental risk assessment approaches (Hazard-Source-Pathway-Receptor). • Environmental AMR data should be interpreted with human, veterinary and other environmental data.
Environmental indicator selection	• Identify a baseline list of priority indicators based on widely distributed organisms or widely used antimicrobials, and/or agents that are environmentally persistent.	• Surface water watershed-level pilot and national survey: Select baseline indicators that facilitate investigations into AMR transmission within and among human and animal populations.	• Develop indicators based on who and what should be protected (human, animal or ecosystem health). • For wild fauna, indicator selection should account for abundance and wide distribution in country; and presence across impacted and non-impacted environments, allowing for anthropogenic spillover comparison.
Environmental AMR knowledge gaps	• Identify environmental conditions facilitating persistence and dissemination. • Determine Predicted No-Effect Concentrations for Resistance (PNEC-	• Comprehensively examine AMR dynamics through varied sampling strategies and environmental conditions to inform risk assessment and identify critical control points.	• Assess risk pathways of most likely direct exposure routes affecting human health exposure, and research on environmentally acquired infections (Environment Agency, 2024b). • Standardise AMR analysis techniques.

	R) or Persistence (PNEC-P) thresholds for highly prescribed antibiotics. • Monitor spatial and temporal dissemination to evaluate variability over time and geographic diversity. • Monitor the resistance patterns of ubiquitous pathogens found in the environment and humans.	• Assess how spatial variation and water quality parameters correlate with AMR. • Assess public health risks associated with AMR pathogens in environment. • Assess how anthropogenic drivers and intervention strategies impact AMR transmission.	• Establish open-access sample and raw data archiving.

Limited transmission understanding: There continues to be limited global evidence on AMR transmission risks from the environment. Most global research had an AMR occurrence (87.3%, n=144) focus, followed by dissemination (29.7%, n=49) and selection (15.2%, n=25). Only 6.7% (n=11) of the global scientific articles focused upon transmission. The limited transmission research can be explained, in part, because most research to date has focused on AMR occurrence or prevalence. They hence do not identify pollution point sources in most of the articles. About a third of global studies reported AMR in environmental reservoirs linked to human health sources (37.6%, n=62), mainly wastewater discharge. Fewer studies (17%, n=28) linked AMR to animal sources, mostly from agri-food exposure. These articles largely addressed dissemination concerns from AMR hotspots.

Taxonomic focus: Evidence from the global jurisdiction and evidence scans indicate taxonomic focuses in policy and research. In the latter, over half of the scientific evidence focused on water (60%, n=99) as compared to soil (20.6%, n=34), aerosol (3.0%, n=5) and wildlife-related AMR risks (40%, n=66). Research from global researchers indicate greater interest in detecting and understanding transmission risk associated with surrounding soil and sediments from agricultural activities and wastewater discharge, and wild animals. Notably, wild plants were not identified as an indicator in the global jurisdiction or evidence scans. Environment Agency (2023b) explained this bias as largely due to wild plant exposure risk being perceived as low compared to wild animals that are mobile or consumed.

Key findings: Environmental surveillance data and information for AMR pathogens, ARGs and antimicrobials in Canada

PHAC indicated a need for a rapid evidence synthesis of existing publicly available AMR surveillance information in Canada's environment, and an identification of surveillance gaps that will serve as input for:

- Informing the development of Public Health Agency of Canada's 's (PHAC) AMR environmental surveillance strategy.
- An ongoing living evidence synthesis for areas of emerging science where additional evidence/research may be required to inform the PHAC approach.

The next sections describe the review's main findings of:

- **Current actions** being undertaken in Canada to monitor the development and spread of AMR in the environment by assessing publicly available national, provincial and territorial datasets for AMR hazard and risk assessments, including research projects,
- **Current research** on Environmental AMR selection, dissemination or transmission, and
- **Key knowledge gaps** to address in environmental AMR surveillance.

Current actions: Environmental AMR monitoring and publicly available surveillance data/information

Environmental AMR monitoring: No publicly available datasets that track antimicrobial resistant pathogens, antimicrobial resistance genes (ARGs), or antimicrobials in Canada's environment for environmental AMR surveillance were found. Although the Canadian government has committed to a One Health approach to antimicrobial resistance (AMR), the environmental aspect is has not been addressed in its Pan-Canadian surveillance programs. For example:

- the CIPARS tracks trends in antimicrobial use (AMU) and resistance (AMR) in specific bacteria within human and agri-food systems.

- AMRNet, a lab-based surveillance program that evaluates human and animal AMR data from seven provinces/territories.

PHAC is exploring the collection surface water data for AMR and antimicrobial testing as part of FoodNet Canada. Prior pilots found occurrence of enteric pathogens and resistant isolates in river and recreational waters in Ontario (Butler et al., 2021; Kadykalo et al., 2020); and waterborne *salmonella* exposure routes were low compared to foodborne routes (Christidis et al., 2020; Hurst et al., 2023). Additionally, the Department of Fisheries and Oceans includes self-reported data on antibiotics and antiparasitics from industry owners and operators in its National Aquaculture Public Report for five provinces (British Columbia, New Brunswick, Newfoundland and Labrador, Nova Scotia and Quebec). This is tracked as broader transparency around industry practices, not to monitor AMR.

The jurisdiction scan identified national AMR and non-AMR surveillance programs that can potentially be leveraged when developing environmental AMR selection, dissemination and transmission monitoring in Canada (see Tables 3 and 4):

- three national AMR surveillance programs that integrate human, animal and/or food data (CIPARS, AMRNet, FoodNet),
- one focused on animal health (Animal Health Canada's Canadian Animal Health Surveillance System (CAHSS),
- two non-AMR wastewater based epidemiology programs with a strong public health focus (Respiratory Virus Activity Wastewater Monitoring Dashboard and Canadian Wastewater Survey (CWS)),
- five national environmental programs monitoring aquaculture pollutants (Department of Fisheries and Oceans' National Aquaculture Public Report data) industrial pollutants (National Pollutant Release Inventory), air pollution (National Air Pollution Surveillance (NAPS)), sustainability indicators (Canadian Environmental Sustainability Indicators (CESI)), and marine habitats in the Maritimes (Community Aquatic Monitoring Program (CAMP)), and
- Table 3 summarizes publicly available datasets on environmental monitoring across the provinces and territories identified during this review. 84.6% (n=11) had a publicly available jurisdictional datasets for water, 23.1% (n=3) for soil and 38.5% (n=5) for ambient air; 15.4% (n=2) for wildlife.

Table 3: Publicly available datasets: Provincial or territorial environmental monitoring

Jurisdiction	Water	Soil	Air	Wildlife
AB	Ambient			Biodiversity
BC	Surface		Ambient	
MB				
NB	River, lake			
NL	Drinking			
NS	Surface			
ON	Drinking, ground	Agricultural	Ambient	Fish contaminants
PE	Drinking, surface, estuary	Stream, suspended	Ambient	
QC	Drinking, surface, ground, pollutants		Ambient	
SK	Surface, ground	Soil, sediment	Ambient	
NT	Ambient			
NU				
YT	Ambient			

Table key:	Data was found and recorded	No data was captured

Table 4: Publicly available datasets: National AMR and Non-AMR surveillance programs

Table key:	Data was found and recorded	No data was captured

		AMR				Non-AMR: Pub. Health focus		Non-AMR: Environment focus				
Monitoring program (abb.)		**CIPARS**	**AMRNet**	**FoodNet**	**CAHSS**		**CWS**	**NAPR**	**NPRI**	**NAPS**	**CESI**	**CAMP**
Program name		Canadian Integrated Program for AMR Sur.	AMRNet	FoodNet Canada	Canadian Animal Health Sur. System	Res. Virus Activity WW Monitoring Dashboard	Canadian Wastewater Survey	National Aquaculture Public Report	National Pollutant Release Inventory	National Air Pollution Sur.	Canadian Env. Sus-tainability Indicators	Comm. Aquatic Monitoring Program
Lead institution		PHAC	PHAC	PHAC	Animal Health Canada	PHAC	Statistics Canada	Fisheries and Oceans Can.			ECCC	Fisheries and Oceans
Scale		National	National: 7 provinces or territories	National: AB, BC, ON, QC	National	National	National: AB, BC, NS, ON, QC, SK	National: BC, NB, NL, NS, QC	National	National	National	National: NB, NS, PE
Monitoring type		AMU, AMR	AMR	AMR	AMU, AMR	Respiratory viruses	Licit and illicit drugs, organisms	AMU	Industrial pollutants	Ambient air quality	Freshwater quality	Water, sediment, wildlife
AMR/Non-AMR indicator: Pathogens, ARGs and antimicrobials		Enteric bacteria, AMU: antibiotics	Bacterial pathogens	Enteric bacteria	Resistant pathogens, AMU: antibiotics	Polio, mpox, SARS-CoV-19, RSV, influenza	SARS-CoV-19	Antibiotics, antiparastics				
One health domain / pollution source		Human, Agri-food	Human, Animal	Human, Agri-food	Animal	Human	Human	Animal, Food	Human	Human	Human	Human, Env.
Environmental media (natural state)				Surface, recreational				Freshwater, marine, land			Water, air	Water, marine
Water, sanitation, and hygiene-related pollutant monitored	**Sewage, WW, or effluent**										Municipal WW	
	Run-off			Irrigation								
	Animal waste (not manure)											
	Solid waste or compost										Solid waste, plastic	
Soil-related pollutant monitored	**Soil**										Agric.	
	Sludge, biosolids, or manure											
	Sediment											
Air-related	**Bioaerosol**											
	Emissions										Emissions	
Wildlife-related	**Wild animal**										Biodiversity	Fish health
	Wild plant										Habitat	Ecosystem

Table 5: Canadian environmental AMR research published between 2019-2024 (n=21)

Paper (Author, Year)	Jurisdiction	AMR indicator: Pathogen, determinants and agents	Research type				AMR source				
			O	S	D	T	Water	Soil	Air	Wildlife	Comparative study
Adator et al. (2020)	AB	ESBL-Ec					Surface WW Catch basin				Sources: Human, cattle feces
Butler et al. (2021)	ON	*Campylobacter E. coli Salmonella Enterococcus Bacteroides*					Surface				Areas: Anthropogenic activity
Christidis et al. (2019)	PHAC data	*Salmonella*					Surface				Sources: Food, animal contact
George et al. (2022)	QC	ARG							C. needle		Areas: Anthropogenic activity
George et al. (2024)	QC Wales	ARG					WW		WW C. needle		Sources & Countries
Hurst et al. (2023)	AB BC ON	*Salmonella*					Surface				Sources: Retail meat, animal manure
Kadykalo (2020)	ON	*Salmonella E. coli*					Surface Rec.				Areas: Anthropogenic activity
Obieze et al (2022)	AB MB QC India	Diverse range of Bacteroidota and Proteobacteria bacteria					Surface				Countries & Areas: Anthropogenic activity
Provencher (2024)	NU	ARG					Surface				Sources & Areas: Anthropogenic activity
Rossi et al. (2023)	France*	ARG									Sources: Likely pollution source origin
Rossi et al. (2024)	France*	ARG									Sources: Likely pollution source origin
Saab et al. (2023)	NS NT QC	*Salmonella E. coli Listeria*								Seal	Sources: Different species
Sanderson et al. (2022)	Meta-analysis: ON UK	*Enterococcus faecium* ARG MGE					Surface WW (mun/ agric)				Countries & Sources: Human, agriculture
Subirats et al. (2023)	Meta-analysis: Global	ARG MGE Class 1 integron					Unclear	Unclear	Unclear	Unclear	Sources: Chemically polluted terrestrial and aquatic environments
Vogt et al. (2021)	ON	*Salmonella E. coli* ARG						Farm soil		Raccoon	Sources: Swine manure pits
Vogt et al. (2022)	ON	*Salmonella E. coli* ARG					Surface			Raccoon	Sources: Human, livestock
Wight et al. (2024)	NL	*E. coli ESBL-Ec* ARG MGE						Lake sediment			Sources & Areas: Anthropogenic activity
Zaheer et al. (2019)	AB	ARG Heavy metal and biocide resistant genes					Surface WW Catch basin				Sources: Cattle feces
Zaidi et al. (2022)	AB	*Enterococcus hirae* ARG					Surface WW Catch basin				Sources: Human, cattle feces, manure
Zaidi et al. (2023)	AB BC ON QC	*Enterococcus faecium* and *faecalis* ARG MGE					Surface WW			Unknown	Sources: Human, livestock, domestic animals
Zhu et al. (2021)	AB US China Germany	ARG MGE							Snow		Countries

Table key:	Data was found and recorded	No data was captured

*Please note: Although conducted in France, this study is included in Canadian research because half of its co-authors—including the lead author and a Canada Research Chair on bioaerosols—are affiliated with Université Laval, the study was partially funded by the Natural Sciences and Engineering Research Council of Canada, and the study focuses on ARG atmospheric transport, a major knowledge gap in Canada and globally.

Current research: Environmental AMR occurrence, selection, dissemination, or transmission

Twenty-one scientific articles, published between 2019 and 2024, by Canadian researchers or featuring environmental data collected in Canada, were identified during the Canadian jurisdictional and global evidence scans. See Table 5 for a summary of the 21 documents, and Appendix 6 for more details.

Jurisdiction geographic distribution: 85.7% (n=18) drawing from data collected in Canada (Adator et al., 2020; Butler et al., 2021; Christidis et al., 2020; P George et al., 2022; Hurst et al., 2023; Kadykalo et al., 2020; Obieze et al., 2022; Provencher et al., 2024; Saab et al., 2023; Sanderson et al., 2022; Vogt et al., 2021, 2022; Wight et al., 2024; Zaheer et al., 2019; Zaidi et al., 2022, 2023; Zhu et al., 2021), 28.6% (n=6) analysed data from Wales, France, Germany, the US, India and China (George et al., 2024; Obieze et al., 2022; Rossi et al., 2023, 2024; Sanderson et al., 2022; Zhu et al., 2021), and 4.8% (n=1) based on a meta-analysis of metegenomes in the public domain (Subirats et al., 2023). AMR research spans multiple provinces, with Ontario (Butler et al., 2021; Hurst et al., 2023; Kadykalo et al., 2020; Sanderson et al., 2022; Vogt et al., 2021, 2022; Zaidi et al., 2023) and Alberta (Adator et al., 2020; Hurst et al., 2023; Obieze et al., 2022; Zaheer et al., 2019; Zaidi et al., 2022, 2023; Zhu et al., 2021) being the most studied (33.3%, n=7), followed by Quebec (23.8%, n=5) (George et al., 2024; P George et al., 2022; Obieze et al., 2022; Saab et al., 2023; Zaidi et al., 2023). Two studies assessed data collected in British Columbia (9.5%, n=2), and one each (4.8%, n=1) from Newfoundland and Labrador (Wight et al., 2024), Nova Scotia and the Northwest Territories (Saab et al., 2023; Wight et al., 2024), and Nunuvut (Provencher et al., 2024).

AMR research type: Three quarters of the research had a prevalence or occurrence focus (80.1%, n=17) (Adator et al., 2020; Butler et al., 2021; George et al., 2024; P George et al., 2022; Kadykalo et al., 2020; Obieze et al., 2022; Provencher et al., 2024; Rossi et al., 2023, 2024; Saab et al., 2023; Sanderson et al., 2022; Subirats et al., 2023; Vogt et al., 2021; Wight et al., 2024; Zaheer et al., 2019; Zaidi et al., 2022, 2023), and more than half focused on dissemination (61.9%, n=13; see Figure 1) (Adator et al., 2020; George et al., 2024; P George et al., 2022; Provencher et al., 2024; Rossi et al., 2018, 2023; Sanderson et al., 2022; Vogt et al., 2021; Wight et al., 2024; Zaidi et al., 2022, 2023; Zhu et al., 2021). While it was hypothesised that transmission research would be scarce, 19.0% of Canadian articles (n=4) focused on this (Christidis et al., 2020; Hurst et al., 2023; Vogt et al., 2021, 2022). Selective factors was also a focus of four studies (Obieze et al., 2022; Sanderson et al., 2022; Subirats et al., 2023; Zaheer et al., 2019).

Two thirds (66.6%, n=14) of the Canadian publications focused on multiple AMR processes, with occurrence and dissemination being the most common combination (42.6%, n=9) (Adator et al., 2020; George et al., 2024; Paul George et al., 2022; Provencher et al., 2024; Rossi et al., 2023, 2024; Wight et al., 2024; Zaidi et al., 2022, 2023). This was followed by occurrence and selection research (9.5%, n=2) (Obieze et al., 2022; Subirats et al., 2023) or understanding factors facilitating occurrence, selection and dissemination (9.5%, n=2) (Sanderson et al., 2022; Zaheer et al., 2019) or occurrence, dissemination and transmission (4.8%, n=1) (Vogt et al., 2021).

Of the 4 selection articles, one looked at selective factors associated with surface water's physicochemical properties and the non-point pollution impact of anthropogenic activities (Obieze et al, 2022), and Zaheer et al. (2019) compared environmental microbiomes and resistomes between animal production and urban systems. They found sewage influent had highest AMR diversity, indicated some metal and biocide resistance, and had drug classes associated with human use (Zaheer et al., 2019). Two were meta-analyses (Sanderson et al., 2022; Subirats et al., 2023) that compared sources, including of chemically polluted terrestrial and aquatic environments.

Of the 13 dissemination articles, six compared an environmental source to other sources from the human-agri-food dimension (Adator et al., 2020; Sanderson et al., 2022; Vogt et al., 2021; Zaheer et al., 2019; Zaidi et al., 2022, 2023). Five considered anthropogenic activities in a watershed (Adator et al., 2020; Provencher et al., 2024; Wight et al., 2024; Zaheer et al., 2019; Zaidi et al., 2022). Interestingly, three had an air pollution aspect, in which snow (Zhu

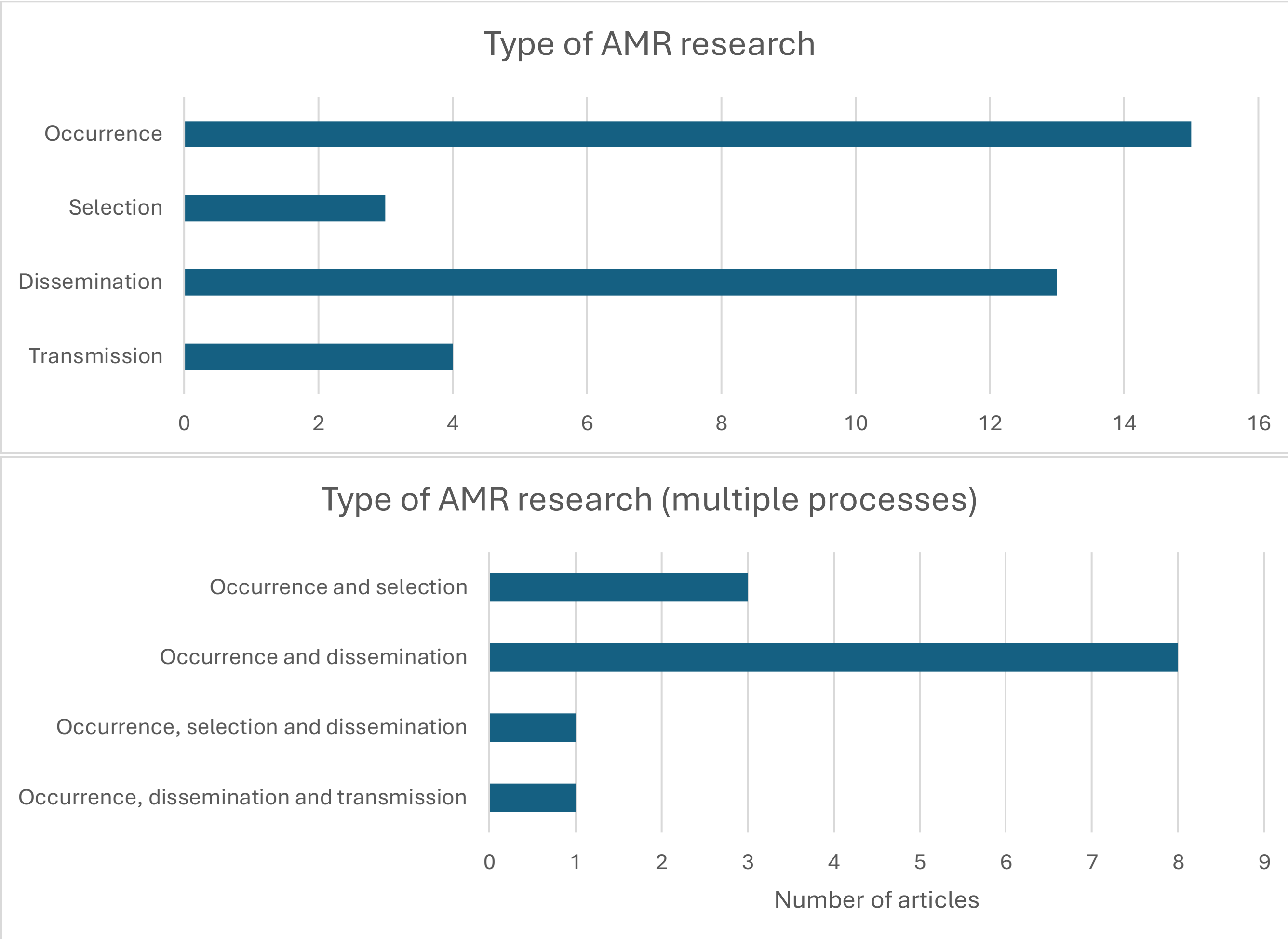

Figure 1: Type of AMR research (top, n=21), including multiple AMR processes (bottom, n=15)

et al., 2021) or clouds (Rossi et al., 2023, 2024) were considered for atmospheric transport. Two articles evaluated conifer needles as potential bioaerosol monitors (George et al., 2024; P George et al., 2022).

All the transmission articles (n=4) compared environmental source(s) to ones in the human and/or agri-food dimension. Three of these articles were associated with FoodNet (Christidis et al., 2020; Hurst et al., 2023; Kadykalo et al., 2020), with these studies aiming to understand the AMR risk of humans exposed to surface water or recreational water compared to clinical, animal or food pathways. While drinking water and recreational water were found to have roughly similar exposure (Christidis et al., 2020), Hurst et al. (2023) attributed surface water exposure as “very low” risk compared to retail meat in Canada. The fourth study (Vogt et al., 2021) assessed potential transmission by examining the whole genome sequence data of *Salmonella* and *E. coli* isolates from raccoons and farm environmental sources (soil and manure pits), finding that soil transmission to local raccoon populations is likely to occur.

Genes and bacteria of interest: Two thirds of articles focused on genetic markers (see Table 6), with antimicrobial resistant genes (ARGs) investigated in 66.7% (n=14) articles and MGEs in nearly a quarter (23.8%, n=5). With regards to pathogens, only bacteria were monitored. *Salmonella* and *E. coli* were most frequently monitored bacterium (33.3%, n=7), with ESBL-Ec monitored in two studies (9.5%).

There was a strong association between a research group and their selected indicators. FoodNet-associated research focused on enteric bacteria (Butler et al., 2021; Christidis et al., 2020; Hurst et al., 2023; Vogt et al., 2022), and research co-authored by the Canadian Research Chair on bioaerosols assessed ARGs

Table 6: Type of AMR microorganisms, AMR determinant or antimicrobial agent monitored (n=21)

Type of AMR microorganisms, determinant or agent monitored	Count	% of articles
Microorganism	**11**	**52.4%**
Campylobacter	*1*	*4.8%*
Escherichia coli	*7*	*33.3%*
Enterococcus	*3*	*14.3%*
Listeria	*1*	*4.8%*
Salmonella	*7*	*33.3%*
Diverse range of Bacteroidota and/or Proteobacteria bacteria	*2*	*9.5%*
Resistant microorganism	**2**	**9.5%**
ESBL-Ec	*2*	*9.5%*
Antimicrobial resistant genes (ARGs)	**14**	**66.7%**
Mobile genetic elements (MGEs)	**5**	**23.8%**
Class 1 integron	*1*	*4.8%*
Heavy metal and biocide resistant genes	**1**	**4.8%**

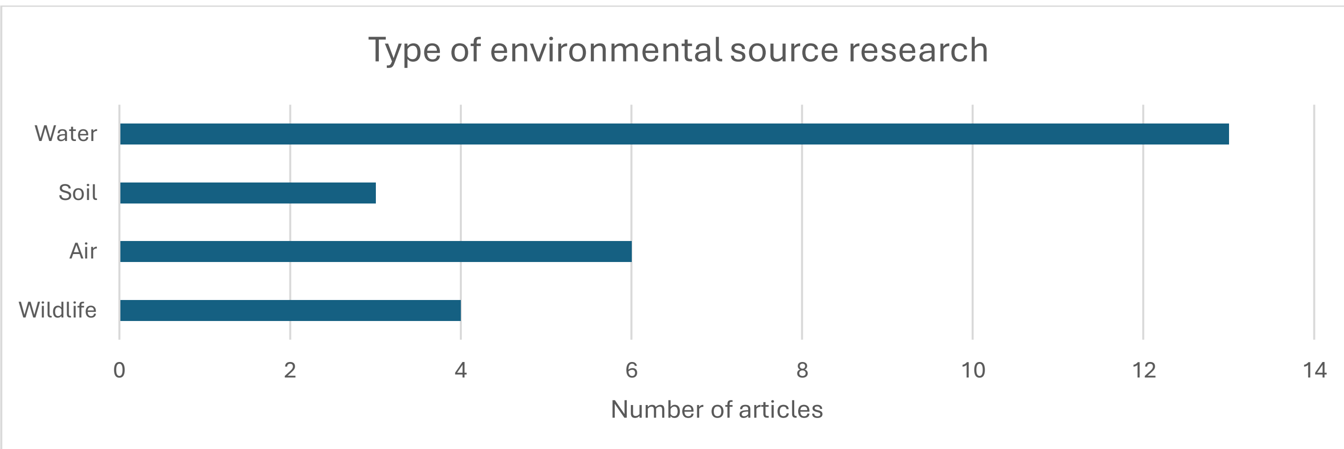

Figure 2: Type of environmental source research (n=19)

(George et al., 2024; P George et al., 2022; Provencher et al., 2024; Rossi et al., 2023, 2024). Scientific evidence linked to the Genomics Research and Development Initiative (GDRI) also focused on ARGs and *enterococcus* (Zaidi et al., 2022, 2023), heavy metal and biocide resistance (Zaheer et al., 2019) or MGEs (Subirats et al., 2023).

Environmental AMR source: **Water** was the most sampled of the environmental media (61.9%, n=13, see Fig. 2), with:

- eleven on **surface** water (Butler et al., 2021; Christidis et al., 2020; Hurst et al., 2023; Kadykalo et al., 2020; Obieze et al., 2022; Provencher et al., 2024; Vogt et al., 2022; Zaheer et al., 2019; Zaidi et al., 2022, 2023),
- six on **wastewater** – mainly municipal (Adator et al., 2020; George et al., 2024; Zaheer et al., 2019; Zaidi et al., 2022, 2023), though one also compared agricultural effluent (Sanderson et al., 2022),
- two on **catch basins** (Adator et al., 2020; Zaheer et al., 2019; Zaidi et al., 2022), and
- one on **recreational waters** in their studies (Kadykalo et al, 2020).

Three sampled **soils** in a nearby field adjacent to cattle feedlot and farm soil in relation to raccoon droppings, as well as **sediment** in urban lakebeds (14.3%). The six **aerosol** studies (28.6%) ranged from conifer needle biomonitoring (George et al, 2022, 2024) and atmospheric transport assessments (Rossi et al., 2023, 2024; Zhu et al., 2021), as well as to compare anthropogenic effects in three differently impacted High Arctic habitats (Provencher et al., 2024). Four (19.0%) articles featured **wildlife**, though one did not specify what species was considered in their cross-sector comparative genomic analysis (Zaidi et al, 2023). The three other articles focused on raccoons, with Vogt et al. (2022)

finding that raccoons are unlikely to be a major human AMR contributor in rural Ontario, and the last finding that seals in the Maritimes could be a sentinel species for AMR monitoring (Saab et al., 2023).

Comparative study: All articles had a comparative component, with different AMR sources (76.2%, n=16) (Adator et al., 2020; Christidis et al., 2020; George et al., 2024; Hurst et al., 2023; Provencher et al., 2024; Rossi et al., 2023, 2024; Saab et al., 2023; Sanderson et al., 2022; Subirats et al., 2023; Vogt et al., 2021, 2022; Wight et al., 2024; Zaheer et al., 2019; Zaidi et al., 2022, 2023) or different areas impacted by anthropogenic activity (28.5%, n=6) (Butler et al., 2021; Paul George et al., 2022; Kadykalo et al., 2020; Obieze et al., 2022; Provencher et al., 2024; Wight et al., 2024) most evaluated. Four studies analyzed data from different countries, with their findings reflecting either selective factors associated with anthropogenic pollution and local environmental conditions (Obieze et al., 2022) or geographic occurrence and dissemination (George et al., 2024; Sanderson et al., 2022; Zhu et al., 2021).

Of scientific research on different AMR sources, one (Kadykalo et al., 2020) focused on different types of water (surface and recreational purposes). George et al. (2024) and Provencher et al. (2024) compared water and air samples, the former to compare wastewater samples with conifer needle bioaerosol monitors, the latter as different samples showing anthropogenic impact in three remote arctic habitats. Soil studies considered exposure risk of environmental determinants in areas with high anthropogenic pollution, especially agricultural areas: a swine farm (Vogt et al, 2021), a cattle feedlot (Zaheer et al., 2019) and three urban watersheds (Wight et al., 2024). While Saab et al. (2023) compared AMR occurrence in two different seal species as possible regional AMR sentinels, the two raccoon studies compared them to other environmental samples (farm soil and swine manure pits in Vogt et al., 2021) or One Health data (human, livestock and surface water data in Vogt et al., 2022).

Key knowledge gaps: Environmental AMR surveillance

Critical surveillance knowledge and guidance gaps: Canada has not established a national surveillance program for environmental AMR and its drivers, which limits a One Health understanding of how AMR develops, amplifies, and spreads across the country. Ongoing global scientific knowledge gaps can affect the development of evidence-driven policy and monitoring (Bengtsson-Palme et al., 2023; Rytwinski et al., 2021; Singer et al., 2016b). Most environmental AMR research focuses on detecting AMR in natural environments, but there critically continues to be a lack of understanding of how resistance spreads and the risks it poses to humans, animals and within the broader environment. WHO officials highlighted the need for more data on public health risks from environmentally acquired AMR to focus integrated surveillance efforts. PHAC-associated studies indicate alignment with WHO on focusing on knowledge gaps of environmentally acquired AMR and exposure.

Globally and within Canada, critical knowledge gaps include identifying direct exposure pathways and critical transmission control points across the One Health continuum, identifying environmental conditions and concentrations that facilitate AMR persistence and dissemination, and analyzing spatial and temporal variability across diverse geographies and timeframes. Additionally, while climate change was beyond the scope of the present synthesis, it is recognised to be an important dimension affecting environmental systems (Haenni et al., 2022).

Environmental AMR definition gaps and monitoring implications: While the One Health definition is widely recognized (Adisasmito et al., 2022), this synthesis found no clear definition of environment or environmental AMR in a One Health context in scientific literature or global guidance. Experts agree that the environment is a major AMR reservoir and transmission pathway, particularly in heavily polluted areas, posing risks to human, animal, and crop health and that environmental indicators can be used to protect humans and animals (Global Leaders Group on Antimicrobial Resistance, 2024; Larsson et al., 2023; UNEP, 2023; WHO et al., 2020). The lack of a clear and universally accepted definition for environmental AMR can complicate monitoring efforts due to inconsistent usage of key terms, indicators, sampling sites and methods across research, policies, and jurisdictions. Standardized cross-sectoral and pan-jurisdictional environmental AMR monitoring is essential, particularly amid rising pollution and antimicrobial use in agriculture, industry, and healthcare, as sectors and policymakers require clear definitions and strategies to inform surveillance plans and support effective One Health AMR mitigation efforts.

Resistome mapping: Understanding AMR mechanisms and mapping the resistome of different microbial reservoirs was increasingly of interest globally and to Canada, as over two thirds of global and Canadian scientific research used ARGs as an indicator to understand how resistance spreads and evolves across a One Health continuum. ARGs and MGEs are especially seen as critical components of an early warning system for AMR threats, but significant gaps in understanding remain. Comparative whole genome sequencing and metagenomics research can address critical knowledge gaps that range from baseline information such as levels of AMR and MGEs in different environments and methods to detect the diversity of ARGs in pathogens (Adator et al., 2020; Bengtsson-Palme et al., 2023; Sanderson et al., 2022; Wight et al., 2024; Zaheer et al., 2019; Zaidi et al., 2022, 2023), to understanding the relative importance of the evolution and transfer of ARGs and MGEs between pathogens causing human infections (Matlock et al., 2023; Vogt et al., 2022; Zamudio et al., 2024).

Tricycle Protocol: The WHO recommends using ESBL-Ec as a cost-effective indicator to monitor resistance trends. However, only 9.7% of global studies and no Canadian research have included ESBL-Ec as an indicator organism. Lack of Canadian research might be explained, in part, by a previous finding of PHAC-associated analysis of 2012-2017 CIPARS data that found relatively low prevalence of potential ESBL-Ec and ESBL-producing *Salmonella* across humans and food animals (Primeau et al., 2023). While Primeau et al. (2023) did not assess environmental risk, they nevertheless recommended ongoing research and surveillance to detect emerging or changing trends in Canada. An example of this is clinical data from PHAC's CANWARD surveillance program indicating that ESBL-Ec and ESBL-producing *pneumoniae* had a significant increase between 2007 to 2018 (Denisuik et al., 2019; Karlowsky et al., 2021).

Standard indicators and harmonised methods: Global scientific and Canadian evidence highlights the diverse range of indicators and sampling methods applied in environmental AMR monitoring, underscoring the ongoing challenges in identifying reliable, standardized indicators and harmonising methods. The complexity and variability of environmental ecosystems and media complicate efforts to capture how resistance evolves and spreads, while a lack of consensus on the most appropriate biological, chemical, or molecular markers further hinders the development of robust surveillance systems. Addressing these gaps requires identifying a baseline list of priority indicators based on widely distributed organisms, commonly used antimicrobials, or environmentally persistent agents, tailored to specific contexts and informed by cost-effective, risk-based approaches such as those implemented by France, the US, and the UK. Moreover, environmental data should be interpreted with human, veterinary and other environmental data (Environment Agency, 2024a) through integrated data systems, such as a cross-sector library of isolates to allow for multi-scale One Health cross-referencing and comparison (Franklin et al., 2024).

Environmental sampling: While resistance naturally occurs in the environment (Wright, 2019), global and national research and policymaking often focus on public health AMR risks in anthropogenically impacted hotspots, such as wastewater, farm or indoor settings (Wight et al., 2024). For example, sampling locations for nearly all the 1,722 wastewater primary studies in Corrin et al.'s (2024) scoping review indicate that either raw sewage or influent was assessed. This is significant to note as the samples reflect a primary focus on population health risk, whereas effluent samppling would indicate an environmental focus. Understanding environmental AMR as it relates to human, animal and crop health risks requires broader investigation into receiving environments and the resistome within environmental reservoirs across the One Health continuum. This also includes distinguishing between anthropogenic and naturally occurring variability, evolution, and transmission (Bengtsson-Palme et al., 2023; Larsson et al., 2018; Pagaling et al., 2023). For example, recent pilot guidance from WHO and US Centers for Disease Control and Prevention on wastewater and environmental surveillance report importantly offer distinctions between environmental waters and wastewater (WHO and CDC, 2024), but more guidance is needed to clearly distinguish between different types of wastewater samples (*e.g.*, *inter alia* raw sewage, influent, effluent, or treated effluent) as public or environmental surveillance indicators.

Wildlife monitoring: Research from G7 countries on AMR in wild animals underscores significant risks to human health via food or habitat exposure. On the former, fish (Bollache et al., 2019; Bourdonnais et al., 2024b; Fang et al., 2019; Gross et al., 2022; Lagerstrom and Hadly, 2023; Mills et al., 2022, 2024), plankton (Bourdonnais et al., 2024a; Fioriti et al., 2021) and bivalves (Agnoletti et al., 2019; Environment Agency, 2023c; Fang et al., 2019; Hain et al., 2023), as well as game meats such as wild boar (Andriani et al., 2024; Chiaverini et al., 2022; Floris et al., 2024; Günther et al., 2022; Marotta et al., 2020; Pérez-Etayo et al., 2020; Plaza-Rodríguez et al., 2021a), can accumulate resistant bacteria and determinants, posing direct risks to humans through consumption. On the latter, animals like raccoons (Vogt et al., 2021, 2022; Worsley-Tonks et al., 2020, 2021), deer (Chiaverini et al., 2022; Elsby et al., 2022; Plaza-Rodríguez et al., 2021b), rodents (Vittecoq et al., 2023), seals (Gross et al., 2022; Watson et al., 2024), and migratory and non-migratory birds (Chiaverini et al., 2022; Drovetski et al., 2022; Formenti et al., 2021; Fukuda et al., 2021; G. C. Rodrigues et al., 2021; Kim et al., 2024; Plaza-Rodríguez et al., 2021b; Treskova et al., 2022; Vittecoq et al., 2022) can have overlapping habitats that may facilitate the spread of AMR between the environment, humans, and domesticated animals. The UK Environment Agency (2023b) recommends prioritizing abundant and widely distributed species found in both impacted and pristine environments as biomonitors to better evaluate AMR transmission dynamics.

Antimicrobial residues monitoring: While Canadian scientific evidence on antimicrobial residues and their selective drivers was limited in this rapid synthesis, this is a crucial area of research. Understanding selective drivers is essential in AMR dynamics, because antimicrobials are widely used for human, animal, and crop health, and their overuse or misuse can accelerate AMR development (UNEP, 2022). Investigating selective drivers helps identify factors that contribute to resistance, such as understanding how anthropogenic activities and geography might influence microbiota selection (Obieze et al., 2022). Additionally, exploring the potential for co-selection with heavy metals, biocides, and other pollutants can reveal how environmental contamination exacerbates AMR risks (Zaheer et al., 2019). By examining these complex interactions, researchers can better inform regulatory policies on antimicrobial use, waste management, and environmental protections to mitigate the environmental spread and development of AMR. Further research in this area could also help identify AMR hotspots, guide surveillance efforts, and inform the development of more sustainable agricultural and industrial practices.

Agricultural and pharmaceutical manufacturing pollution monitoring: Regulating agricultural and industrial pollution was outside the scope, but effluent and waste from these sectors—particularly animal and crop production and the pharmaceutical supply chain—are key sources of biological and chemical AMR pollutants (UNEP, 2022). Canadian university and government partners are assessing AMR risk associated with water and soil pollution in areas with food animal production, but the risks from antimicrobial use in crops and pharmaceutical manufacturing remain underexplored for their impact on human and agri-food safety in Canada. The recently published WHO (2024) guidance addresses managing wastewater and solid waste from antibiotic manufacturing and offers recommendations for developing indicators and identifying surveillance partners. This includes regulatory bodies, pharmaceutical manufacturers, and waste management actors across the production chain. Currently, globally and in Canada, manufacturing AMR pollution is largely unregulated, as these environmental emissions are excluded from quality assurance standards. The WHO guidance outlines regulatory targets to reduce AMR risks from liquid effluent, solid waste, and zero-liquid discharge systems for antibiotics used in humans, animals, and plants, which can serve as a potential blueprint for monitoring and addressing environmental AMR risks in industry.

Implementation science insights: Consultations with PHAC indicated an interest in understanding the rationale underpinning program design such as indicator selection, as well as how countries balance cost effectiveness with coverage breadth and depth to detect, monitor, and assess environmental AMR risks. While not a primary focus of the evidence synthesis, policy documents, scientific publications and commentaries from national policymakers helped to provide limited insights into how regulatory authorities from France, the UK and US have leveraged extant monitoring programs for environmental AMR surveillance. This underscores the importance of sharing implementation experiences in the complex, emerging field of environmental AMR and integrated One Health surveillance.

Evolving knowledge and guidance: Environmental AMR is an emerging field where terminology, guidance, and methods for integrated surveillance across the One Health continuum are still evolving. Consequently, the review required a combination of structured and unstructured approaches to address the broad research questions, and it may not reflect all current scientific and jurisdictional evidence. Given its dynamic nature, this synthesis can be regularly updated to reflect best available science and technology, and revised to incorporate new environmental AMR and One Health surveillance aims, guidance, information, and insights.

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