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Abstract: Background: Emerging and re-emerging infectious diseases that infect wildlife, such as African swine fever, avian influenza, and SARS-CoV-2, have highlighted the necessity for wildlife health surveillance (WHS) due to their direct and indirect impacts on wildlife species, ecosystems, domestic animals, and human health. While global policies and guidelines exist, a critical gap remains in local-to-national implementation of WHS systems. A group of local, national, and global actors in WHS have formed a working group to address this gap. **Methods and Findings:** The working group reports on a theory of change (ToC) developed to implement WHS from local to global scales. Through brainstorming, plenary exercise, and building on peer-reviewed science and existing surveillance systems, we identified six transformative pathways to be implemented via collaborations across scales and contexts: mindset change, policy and investment, user-driven science, user-driven technologies, capacity enhancement, and mobilization of a global community of practice. **Interpretation:** This ToC serves as a roadmap to develop effective WHS systems that support adaptive management and implementation. WHS is fundamental to understanding the impacts of health threats to biodiversity and human and domestic animal health. This ToC presents an approach to operationalize integration of wildlife health into collaborative One Health surveillance. **Funding:** The Science for Nature and People Partnership.

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Introduction

Healthy wildlife populations are the foundation for wildlife conservation, ecosystem services maintenance, income generation (e.g., ecotourism), food security, and the achievement of One Health

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(OH) objectives [1–3]. Wildlife serve as important reservoir for many endemic or (re-)emerging infectious diseases that affect people and livestock. For example, the recent emergence and global spread of the high pathogenicity avian influenza H5N1 virus from clade 2.3.4.4b, has greatly impacted the poultry sector and wild birds and mammals globally [4]. Large-scale amplification and circulation of this virus within and between poultry and wildlife has increased spillovers to mammalian hosts, including humans, illustrating a complex ensemble of conservation, livestock health, and public health issues [5]. Human activities and continued encroachment into natural areas affect climate, landscape structures and connectivity, habitat availability, water and soil quality, and patterns of species interactions, challenging the existence of wildlife species [6,7]. This loss of ecological integrity can threaten human health, with wildlife species often acting as early indicators and sentinels, but information is often lacking on biotic, abiotic, and anthropogenic drivers of wildlife and human health. In fact, a proposed "continuum of care" socio-ecological model of public health includes ecosystem integrity as a key upstream determinant, and nature protection as an essential intervention point for public health [8–10].

A fuller understanding and appropriate management of these complex OH issues require integrated wildlife health (WH) intelligence, especially across political borders. However, coordinated and systematic wildlife health surveillance (WHS) is globally lacking. Countries have significant disparities in the development of their WHS systems. Among 107 countries surveyed, 58% demonstrated no evidence of a functional WHS program [11]. Only a few high-income countries maintain established, nationwide, and centralized programs, and even in those cases, funding for WHS fluctuates in response to successive livestock or public health crises. Most low-and-middle income countries (LMIC) have limited capacity beyond sporadic surveillance with foreign funding or support often restricted in scope and duration [12].

Since 2011, the World Organisation for Animal Health (WOAH) and its WOAH Working Group on Wildlife, has shepherded the global standardization and coordination of WHS, through the designation of national wildlife focal points who report wildlife disease events to WOAH's 'WAHIS Wild' database via national delegates [1,13]. In 2021, WOAH released a WH framework that reinforced its commitment to supporting WHS globally, and to further integrate WHS into OH strategies. Moreover, WHS would further support WHO's pandemic preparedness framework that identifies actions for pre-epidemic preparedness, alert, outbreak response and post-epidemic evaluation. Despite these and other activities, WOAH has been limited in supporting WHS implementation at sub-national to national scales, due to the lack of field-level networks to support implementation of WHS. Most countries have not allocated human and financial resources for WH and institutional mandates for WHS either do not exist or fail to maximize intelligence across institutions. This represents a major gap in the ability to generate WH intelligence globally [14]. Therefore, current top-down approaches should be complemented with bottom-up processes and other grounded approaches (side-to-side and inside-out approaches) to enhance national coordinated initiatives and mainstream WHS systems [11].

The Science for Nature and People Partnership (SNAPP) funded the creation of a working group (WG), to strengthen WHS globally through a collaborative and evidence-based approach [10]. This WG comprises representatives of international, national, and local organizations with the goal of addressing the gap between global coordination and local implementation and identifying ways to encourage consistent and effective WHS practices at the national and global levels. This WG was founded on the premises that growing national WHS across the globe is beyond the scope of a single institution, a consortium approach would better address these challenges, and cross-sectoral and trans-disciplinary methods are needed to implement sustainable WHS systems. One of the main objectives of this WG is to identify practical pathways to implementation. Here, we present a Theory of Change (ToC) to address the gaps between global policy and local-to-national implementation of WHS.

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Methods

The development of a ToC is a participatory process in which a group of stakeholders and rightsholders reflect on their collective aims and the expected outcomes and impacts of their actions and describe how their activities will eventually lead to these desired outcomes and impacts [15]. The ToC is a roadmap illustrating our working group's assumptions about how a set of interventions will lead to specific changes. The WG developed a ToC to address the WHS implementation gap following six steps (Figure 1).

Figure 1. Steps to develop a Theory of Change for WHS implementation.

The WG developed the final ToC (Figure 2) over two virtual workshops (4-hours each), a 3-day in-person workshop facilitated by a professional and experienced facilitator (CK), additional online debriefing sessions, and multiple rounds of drafting. Each step involved various activities including individual reflection, group discussions, or plenary exercise.

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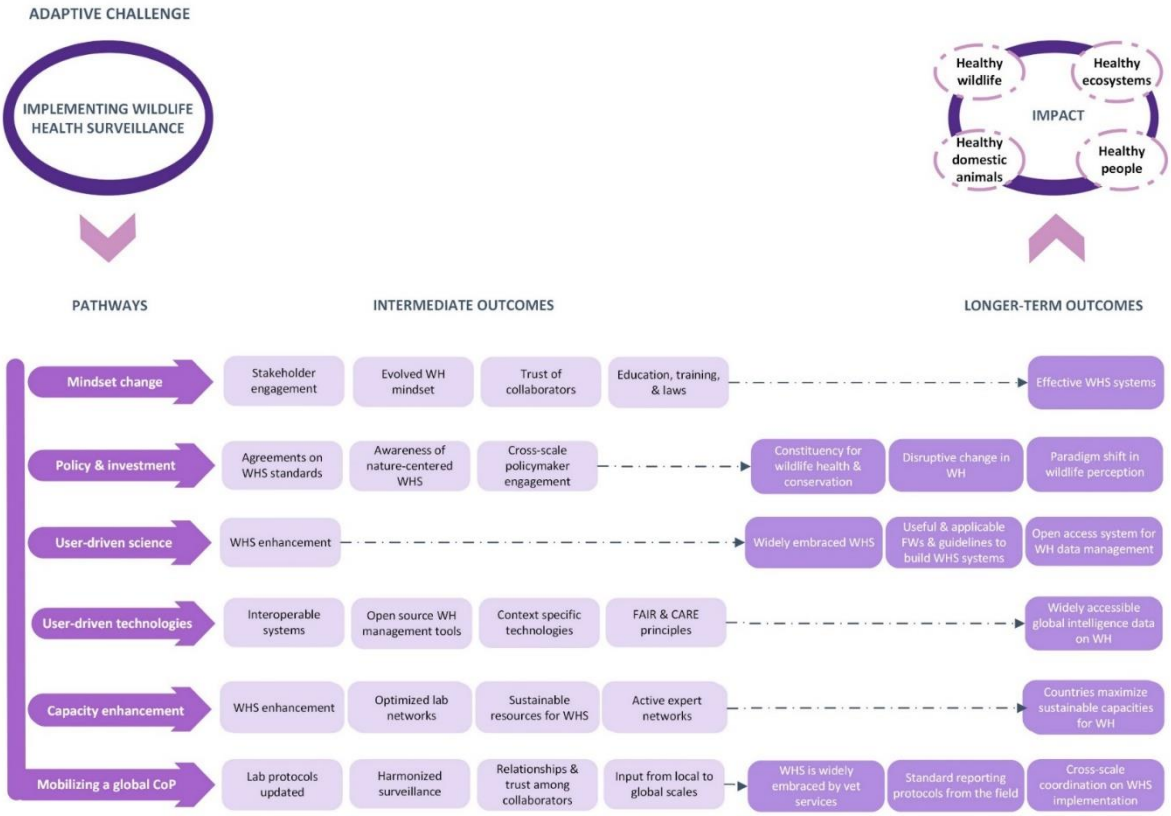

Figure 2. Theory of Change for implementing global wildlife health surveillance (CoP: community of practice, WH: wildlife health, FW: framework, OH: One Health; FAIR: Findable, Accessible, Interoperable and Reusable; CARE: Collective benefit, Authority to control, Responsibility and Ethics).

Results

Adaptive Challenge

Adaptive challenges are issues resulting from complex dynamics that require a collaborative learning process and a mindset shift, rather than an expertise-guided technical solution [16]. The group focused on the adaptive challenge of bridging the WHS implementation gap (Figure 3) to "enhance capacity for coordinated and effective WHS systems to support adaptive management across scales and sectors."

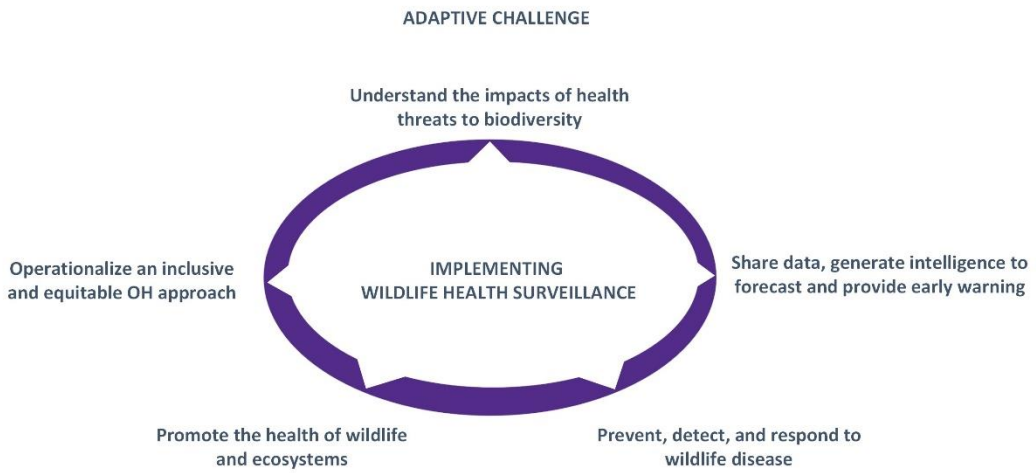

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Figure 3. The impacts of addressing the adaptive challenge to implement wildlife health surveillance systems.

Barriers to Implementation

Barriers are a result of conflicting priorities between government sectors or worldviews, as well as resource and data complexity challenges (Figure 4). Government entities' abilities to lead WHS may be limited because of legal or funding restrictions, or the absence of an underlying mandate for WHS or appropriate expertise. Animal health mandates are usually within veterinary services, whose main priorities are determined by a limited number of economically important species. On one hand, this results in low WHS prioritization compared to other animal health priorities. On the other hand, it reduces incentives to transparently report WH intelligence because of perceived negative economic consequences and trade impacts. In this context, wildlife is perceived as a threat (source of diseases), rather than a resource to be conserved for the greater good. Traditionally the environmental sector has had limited awareness of and influence on livestock and public health decisions. As a result, WHS priorities have mainly been defined from a human and agriculture-centered standpoint without considering the inherent value of wildlife, biodiversity, and ecosystems. The lack of institutional support for WHS has caused poor prioritization of sustained WHS efforts despite its critical importance to operationalizing One Health.

As single institutions rarely hold the sole mandate for WHS, multi-institution collaborative approaches are needed for implementation, which requires adequate communication coordination, and collaboration mechanisms [12]. This can be further complicated when national and subnational levels of government operate under different regulations and policies. The complexity of WHS data and the lack of standards result in inconsistent systems that hinder the sharing of information, and coordination across sectors and scales. As a result, significant barriers prevent generation of coordinated WHS intelligence that supports One Health action.

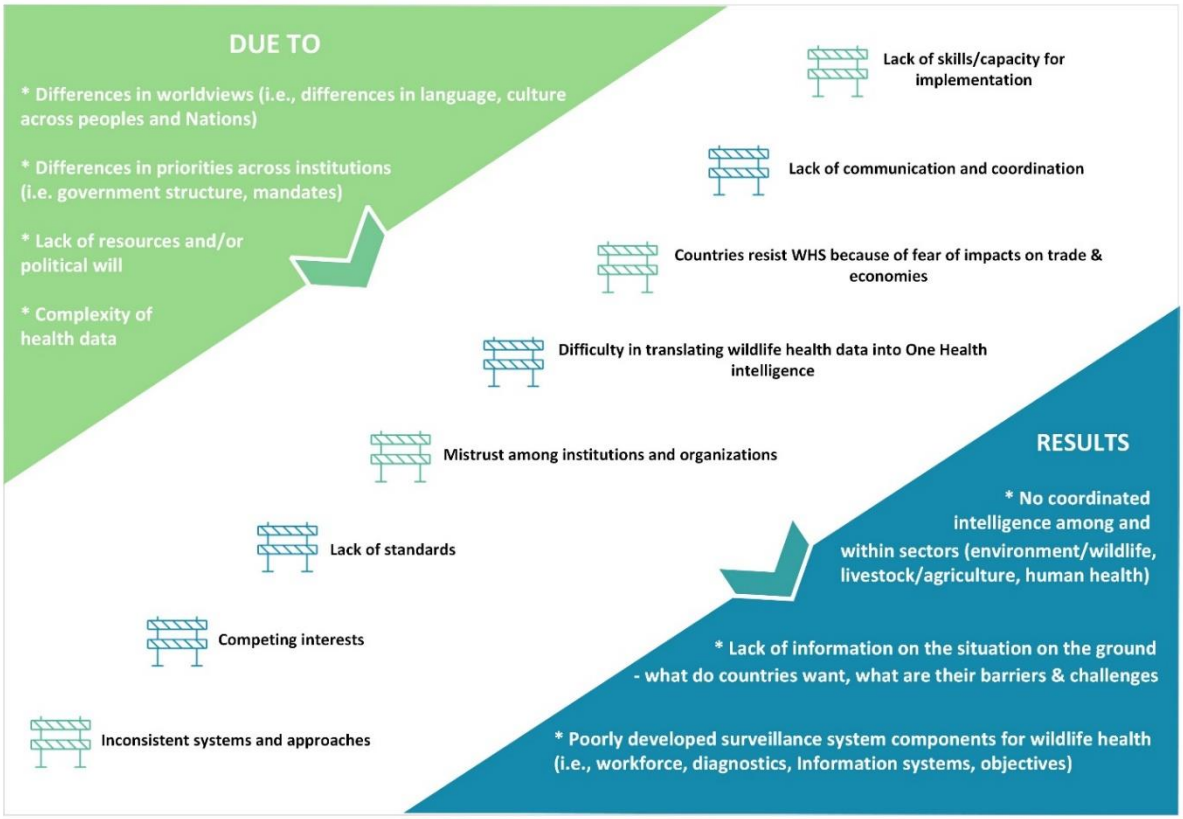

Figure 4. Barriers to implementation of WHS.

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Pathways of Change

Six pathways were identified: mindset change, policy and investment, user-driven science, user-driven technologies, and capacity enhancement, all supported by the mobilization of a global community of practice. Activities identified for each pathway are shown in Table 1.

Table 1. Activities identified for each pathway of Theory of Change.

Pathways		Activities
Mobilizing a global community of practice • Ongoing community engagement • Governance of WHIN to support growth of national WHS efforts • Task forces (e.g. Standards and Guidelines, Data and Technology, Training and Capacity, Advocacy and Outreach, Field implementation User-driven knowledge synthesis, Indigenous and Local Communities, etc.) • Clearinghouse of resources, assessment of guideline needs/gaps, develop SOPs and resources when indicated	**Mindset change**	• Social science on shifting how people value and perceive wildlife • Outreach investment: build stories around benefits of WHS relevant to countries • Communication strategy for different audiences • Outline the business case for WHS (e.g. cost-benefit analysis) • Successes and failures of WHS demonstrating the OH benefits of WHS
	Policy & investment	• Grow political will for WHS investments and policies in high level agreements and funding mechanisms • WHS policy gaps: a review of policy impediments to WHS implementation from global to local scale • Assessment of wildlife health surveillance impacts on public health, agriculture, and conservation policy • Study of policy/governance (including needs and barriers) • Measuring the cost-effectiveness of WHS systems (actual cost, risk/costs avoided, revenue, other economic value, e.g., willingness to pay)
	User-driven science	• Systematic review of existing WHS, including scale, structure, sustainability, scalability • Review of impediments to WHS implementation from local to global scale (including data management systems) • Measuring the cost-effectiveness of implementing and enhancing WHS systems (costs, risk/costs avoided, revenue, other economic value, e.g., willingness to pay) • Map global WHS targets • Decision tool for surveillance objectives prioritization addressing public health, livestock health, and conservation priorities • Performance metrics - develop or refine a WHS system evaluation and assessment tool • Integrate surveillance and ecological data (e.g., host genetics, social structure, demographics, movement, distribution, community composition, pathogen community composition) • WHS Biobanking: needs, costs, risks, implementation • Formal network analysis as indicator of performance

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• Fund raise to support countries to develop WHS • Work with subset of countries to build/refine WHS systems • Coordination among stakeholders and organizations • Scaling the use of citizen science and local and Traditional Knowledge in WHS: applications, challenges, and solutions	**User-driven technologies**	• Establish data standards: codification, set case definitions for WH, standards for WHS • Stakeholder mapping and needs assessment for technologies • Build and distribute tools (e.g., sampling, data, lab assays) • Product development, testing and refinement • Support flexible, scalable technologies that are fit for purpose with an open-source mindset
	Capacity enhancement	• E-learning platform modules linked to existing e-modules and platforms (i.e. WOAH, FAO) • In-person training with clear impact assessment • Country case studies of WHS use cases - sharing of lessons learnt • Wildlife emergency management task force • Simulations based on wildlife disease scenario • PhD thesis grant call • Experts ready to consult and provide expertise for response

Mindset Change

Mindset changes underpin every pathway of the ToC. Three strategies of mindset change were highlighted. First, there is a need to understand and communicate the value of WHS as a benefit and not just as a cost (e.g. cost of trade impacts). Economic analyses should be a core activity of this pathway (e.g., Natural Capital Project), making a business case for WHS, including the non-market value of wildlife like willingness to pay for WH or ecosystem services that incorporate the intrinsic value of wildlife. Second, there is a need to move beyond the utilitarian and human-centered perception of wildlife and WHS, and fully integrate the intrinsic value of wildlife in decisions and prioritization of WHS. In that nature-centered paradigm, WHS incorporates drivers of disease and their effects on wildlife populations and encourages the connection of WHS systems with ecological monitoring programs for comprehensive monitoring of environmental changes. Third, the WG reflected on decolonizing our approach to global cooperation on WHS, and the requirement for cultural humility in addressing questions of wildlife value and WHS [18,19]. Creating relationships among diverse groups, peoples, and Nations is critical to create the ethical space where multiple worldviews can be represented, heard, and respected. This is essential as national governments engage with Indigenous Nations on the co-design and co-management of WHS programs, under the guiding principles of the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) [20].

Policy and Investment

This pathway focuses on growing political will for WHS by fostering policy changes, allocating adequate funding and investment, and incentivizing health hazard detection. Political support for sustainable WHS can benefit from both top-down and bottom-up approaches. At the global level, the wildlife health framework developed by WOAH and other tools (e.g. Joint External Evaluation [JEE], the WOAH Performance of Veterinary Service [PVS]) encourage and guide countries to implement WHS but are not legally binding and do not provide a clear pathway to national and local implementation. The WOAH guidelines on wildlife surveillance offer practical recommendations for

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national implementation, albeit without an enforcement mechanism. Opportunities exist (e.g., the Pandemic Prevention Treaty, the pending 2005 WHO International Health Regulation [IHR] updates) to more strongly mandate the development and maintenance of WHS as part of coordinated multisectoral surveillance, such as those in place for livestock and human health [11,21,22]. At the national level, the adoption of standard operating procedures is essential to provide bottom-up policy incentives to sustainably implement such surveillance.

Locally relevant prioritization of WHS objectives (i.e. engaging local stakeholders and rightsholders, making them responsible "stake sharers") along with stronger assessment of the value of functional WHS systems would further incentivize local implementation and investments. However, the global nature of drivers of WH warrants a strong role for global cooperation in the funding of country-level WHS systems and moving away from short-term project funding. A challenge to address is ensuring that both spatial and temporal scales of national and global investments are compatible with the generation of WH intelligence that benefit local and global communities.

User-Driven Science

Data synthesis, research, and knowledge sharing activities are fundamental to supporting science-based decisions and tools for WHS. A concerted focus on developing evidence and sharing scientific resources for WHS is needed, particularly in the following subject areas: economics or cost-benefit analyses, prioritization of surveillance efforts, assessment of existing WHS resources, development of performance metrics, and political science research for policy gaps and governance. There is also a need for science to facilitate the building of useful public data collection tools to better incorporate local knowledge sourced from community, citizen, or student-based networks, which can enhance data from government-led efforts [23].

User-Driven Technologies

This pathway addresses flexible and scalable technologies needed to improve WHS implementation. The need for standardized and open-source data collection and management tools has been a strong force driving collaboration between WG members. WH information sharing remains hamstrung by institutions largely operating data systems in isolation and constrained by sensitivities related to data sharing. Reducing data siloes will help operationalize WHS and One Health. Here, appropriate technology developed through participatory and collaborative approaches can provide reliable standard open-source data management solutions that enable information sharing and greater interoperability of existing systems. Advancements in artificial intelligence could also contribute to making information more accessible. The ultimate goal is for user-driven technology to provide richer information and intelligence about WH for decision makers and managers of wildlife.

Capacity Enhancement

This pathway explores how to mobilize existing workforces and enhance the skills, knowledge, and capacity for WHS. Developing and consolidating training materials that are locally relevant and tailored to the different roles within the WHS system are critical to implementation. Delivery of training requires institutions and actors that are firmly embedded in the local context. As such, connecting international and local WHS actors and organizations will be instrumental in the development of sustainable capacity building models. Facilitating access to training materials through e-learning platforms in multiple languages would benefit WHS implementation. Finally, even with adequate training, responding to large-scale wildlife health emergencies can be a challenge for newly formed WHS systems, and this capacity can be enhanced by the support and mentoring of a global network.

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Mobilizing a Global Community of Practice (CoP) – a Wildlife Health Intelligence Network (WHIN)

The expansion of this WG into a larger CoP, the WHIN, provides the main pathway to implementing this ToC. It addresses a fundamental gap in the current implementation of national WHS by leveraging multiple organizations and actors operating at different scales, and with different expertise. WHIN acts as a support system, linking expertise and addressing gaps to design, guide, and support the implementation of comprehensive, coherent, and sustainable WHS by individual countries. WHIN will mobilize organizations and individuals from multiple sectors and levels, including intergovernmental organizations (e.g., WOAH, FAO, WHO, UNEP, IUCN), key global implementation actors (e.g., WCS), regional networks, national WHS coordinators and actors, field practitioners, educators, and researchers (e.g., protected area managers, citizen science groups, scientists, Indigenous communities, local conservation organizations, universities), and laboratories. A WHIN charter and governance structure is currently being developed. The network will promote collaborations, lateral and South-South (LMIC) cooperation, and bottom-up processes to develop new norms and policies. This model will support a decolonized approach to global cooperation, by recognizing and facilitating input from different contexts and worldviews, such as actors in LMIC, and Indigenous communities.

By working together as a WHS CoP we can synergistically address implementation challenges more effectively.

For example, the establishment of minimum requirements and standards for WHS systems, practical step-by-step guides on operationalizing WHS, standard operating procedures for network and laboratory activities, and evaluation and assessment tools can be strengthened if co-developed by the CoP. By bringing people together, the CoP's collective knowledge and experience, such as local successes and solutions, can be harnessed to achieve a more efficient and effective rollout of WHS.

Aims and Expected Impacts

The mission of WHIN is to establish a CoP that works collaboratively on WHS so that it is implemented everywhere, at all times, particularly where it matters most, such as vulnerable populations, and threatened biodiversity. WHIN seeks to grow the CoP and over the longer-term WHIN aims for the majority of countries to have effective WHS systems, supported by comprehensive guidance and standards, open access to WH data management tools, and broad support for OH and conservation driven WHS. The impact of enhanced capacity for WHS at national scales, combined with effective coordination between global and local-national organizations and institutions, will be facilitated by WHIN's CoP. The ultimate impact seeks sustainable and healthy ecosystems supporting abundant and diverse wildlife and sustainable human societies.

Discussion

Our ToC for implementing WHS provides a roadmap for strengthening national, and subsequently global, capacity to effectively prevent, monitor, and respond to WH threats. Through a focus on six pathways (mindset changes, policy and investment, user-driven science, user-driven technologies, capacity enhancement, and mobilizing a global CoP), this ToC delineates activities that will contribute to operationalizing WHS, thereby promoting wildlife and ecosystem health and reducing health risks at source (i.e., primary prevention) [9]. This ToC highlights the importance of coordination and knowledge sharing across sectors among all stakeholders and rightsholders involved in WHS – from local field practitioners to global actors.

Establishing a CoP through WHIN can help achieve transformative change by bringing together multiple organizations, governments, local communities, and consolidating the expertise of scientists and practitioners at sub-national, national, and regional levels. Such a diverse group of institutions and voices working alongside each other to support WHS is best positioned to enhance the adoption and growth of WHS on the ground, by facilitating bottom-up, side-to-side, and inside-out approaches [24].

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This is the first ToC to articulate steps to support practical implementation of WHS across scales, bridging an important gap between global frameworks (e.g., WOAH's Wildlife Health Framework [23]) and local realities. Stronger WHS can help countries achieve coordinated multi-sectoral surveillance and capacity indicators across the IHR Joint External Evaluation (JEE) and WOAH's Performance of Veterinary Service (PVS) Evaluation tool to address zoonotic disease emergence. This ToC further supports broader OH strategies outlined in OHHLEP's One Health Theory of Change, the Quadripartite's One Health Joint Plan of Action, the Global Health Security Agenda (GHSA), and the Convention on Biological Diversity Global Action Plan on Biodiversity and Health [25–28]. One of the most immediate implications of our ToC is the need for social, political, and technological advances in data and knowledge sharing. Creation of WH intelligence requires efficiencies of structured data, including a universal language for complex WH data that integrates the collaborative input of stakeholders and rightholders, and incremental steps to achieve greater data sharing (i.e., FAIR and CARE principles, DataOne) [29].

There is a lack of transdisciplinary involvement, representation, and diversity in who currently advises and implements WHS, with the majority of established WHS systems and expertise in high-income countries [30]. Despite efforts to diversify perspectives, our WG composition and the ToC we developed face the same limitation of representation, diversity, and transdisciplinary involvement. However, WHIN's CoP approach aims to address these gaps in representation, reduce high-income country bias, and increase diversity and inclusion in global cooperation processes. WHIN is committed to cultural pluralism and supports the inclusion and leadership of Indigenous and LMIC members. We encourage readers interested in this initiative to get involved, as diverse and sustained support will be critical to success.

Moreover, WHIN's consortium approach will require member organizations to support the common good despite potentially overlapping or even competing institutional mandates. Competing mandates likely influenced the development of this ToC and will likely continue to be a challenge for WHIN, particularly when leadership in an area is associated with increased funding opportunities. However, we hope that this collaborative approach will facilitate efficient and concerted use of limited resources, demonstrating benefits over competitive models. Shifting funding priorities towards collaborative models will be necessary to reduce competition between key actors. Furthermore, current funding mechanisms are fragmented, both in time and space, leaving few opportunities for sustainable and scalable impacts. Continuous evaluation and adaptation of this ToC will be crucial in response to the ever-evolving landscapes of WH and global cooperation.

This ToC offers an exciting vision for WHS, one in which WHS is expanded to respond to nature-centered priorities. WHS is needed to understand environmental drivers of WH, and how they influence conservation, and animal and public health. This is essential to ensure continued progress in operationalizing OH as most wildlife health initiatives remain focused on zoonotic diseases [11]. The ToC underlines the importance of knowledge exchange, cooperation, and learning across all levels. Global WHS needs trust and collaboration among actors that engage and support countries in enhancing their WHS systems. The WHIN community of practice can link and leverage these efforts to scale WHS efficiently and globally. With a keen focus on capacity enhancement, standard development, research, data sharing, and advocating for wildlife, the ToC paves the way for tangible action to catalyze change. This proposal's success will rely on our willingness to lean into a new collaborative and decolonized model of international cooperation for WHS.

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Conflicts of Interest: The findings and conclusions in this manuscript are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy.

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