INTEGRATED APPROACHES TO HEALTH: CONCEPTS AND EXPERIENCES IN FRAMING, INTEGRATION AND EVALUATION OF ONE HEALTH AND ECOHEALTH

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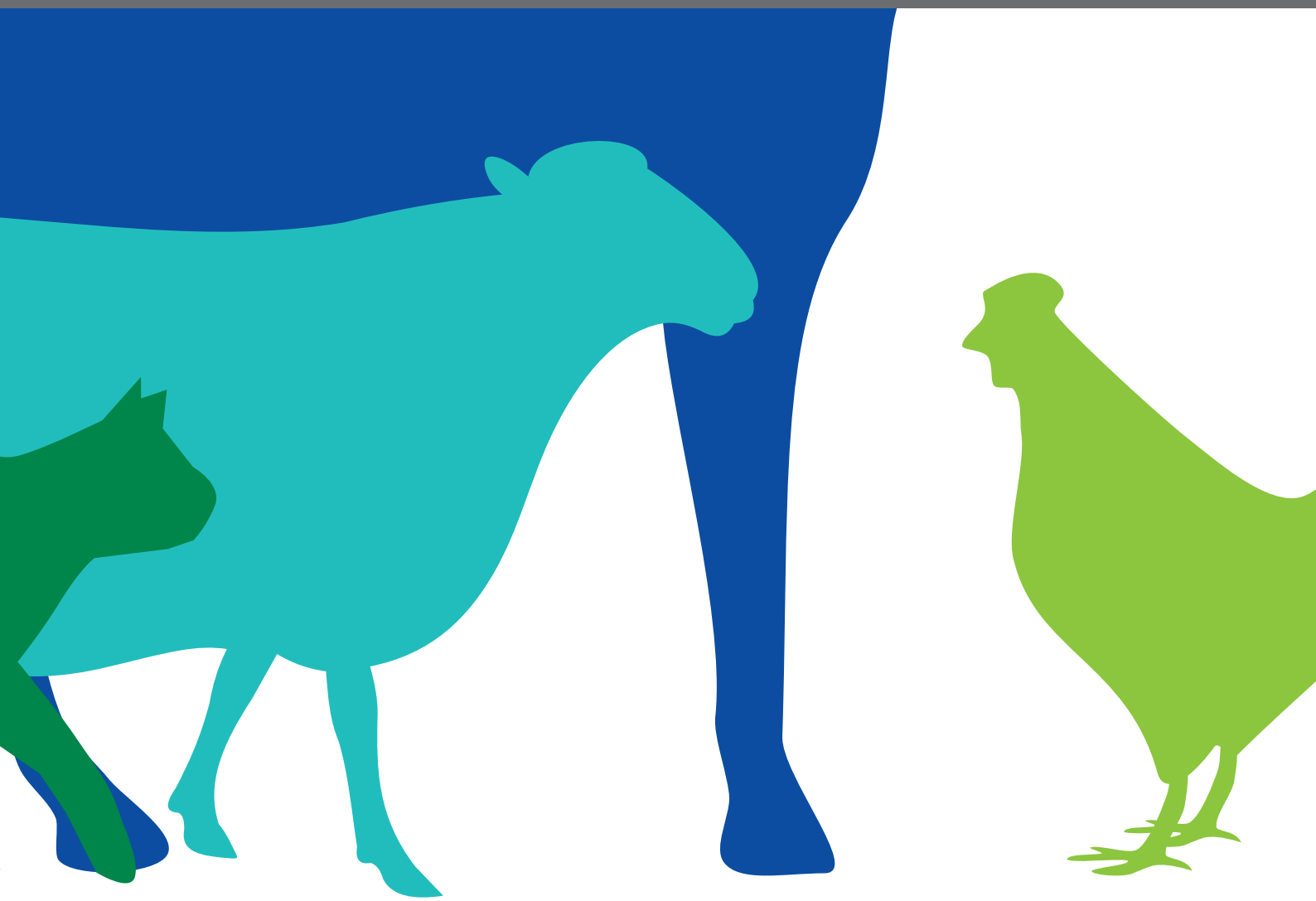

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INTEGRATED APPROACHES TO HEALTH: CONCEPTS AND EXPERIENCES IN FRAMING, INTEGRATION AND EVALUATION OF ONE HEALTH AND ECOHEALTH

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Integrated approaches to health aim to promote sustainable health for people, animals and ecosystems. Photos by: Martha Betson (UK), Kevin Queenan (UK), Chinwe Ifejika Speranza (CH), Toni Velkov (MK), Martin Hitizger (CH), Georgina Limon (UK) and Barbara Häsler (UK).

Integrated approaches to health address health challenges arising from the intertwined spheres of humans, animals and ecosystems. This eBook is the product of an interdisciplinary effort to establish how One Health, EcoHealth and other integrated approaches to health are conceptualized, framed, implemented and evaluated today. It supplements the handbook for the evaluation of One Health, published by the COST Action "Network for Evaluation of One Health (NEOH)" with in depth reflections on the theory behind integrated approaches to health and One Health more specifically, a brief version of the NEOH evaluation framework, a supplementary evaluation approach, and eight case studies in which the NEOH framework was applied. The eBook is intended for practitioners, researchers, evaluators as well as funders of integrated approaches to health and beyond.

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SECTION III

CASE STUDIES OF THE "NETWORK FOR EVALUATION OF ONE HEALTH (NEOH)"

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EDITORIAL
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Editorial: Concepts and Experiences in Framing, Integration and Evaluation of One Health and EcoHealth

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Editorial on the Research Topic

Concepts and Experiences in Framing, Integration and Evaluation of One Health and EcoHealth

The work presented in this research topic shows that the context of initiatives in One Health (and other integrated approaches to health) is crucial and plays an important role for their implementation. Consequently, conceptualization, as well as evaluation should take into account the wider system in which such endeavors are set and cater for multiple perspectives. The featured manuscripts provide a wealth of concepts for implementation and evaluation of integrated approaches to health, which are exemplified with real cases.

Collaborative approaches across disciplines and sectors are recognized as necessary to address *wicked* problems, which prove difficult to solve singlehandedly. The recent financial, economic, social, environmental and health crises further added to the challenges of providing tangible solutions to these problems. In the health domains, classical examples are antibiotic resistance or outbreaks of highly infectious diseases, e.g., Highly Pathogenic Avian Influenza (HPAI), Ebola, Severe Acute Respiratory Syndrome (SARS), Zika virus disease, which gave fresh impetus to integrated approaches to health. However, it must be recognized that these concepts have a long history and have been named with a variety of terms such as One Health, EcoHealth, Global Health, Planetary Health, Ecological Public Health, Environmental Health, Health in scaled Social-Ecological Systems, or others, depending on the specific perspective. They all share the characteristics of integrating knowledge and skills from multiple stakeholders within and across a variety of disciplines and sectors, aiming to collectively find sustainable health solutions.

Lerner and Berg investigated the similarities and differences of three currently very influential holistic concepts: One Health, EcoHealth, and Planetary Health. They found that One Health has been described as either a narrow collaboration of public health and veterinary medicine or as wide-spread interdisciplinary field with a focus on vertebrate health. EcoHealth appeared to emphasize more on including all living creatures down to microscopic levels, while Planetary Health seemed more concerned with human health at global scale. This article documents that despite all being holistic approaches, they emerge from different core values. Interestingly,

a bibliometric study investigating studies on dynamic disease modeling, substantiated similar silos previously, even within the One Health community (1). Duboz et al. inferred that the common holism is grounded in systems thinking and enabled by participatory modeling, which is why they advocate for the systematic incorporation of specialists in systems science and social engagement for all integrated approaches to health. The apparent difference in scope of One Health and EcoHealth has been alluded to converge already previously (2), and in their respective contributions, Destoumieux-Garzón et al. and Wilcox et al. elaborate and analyse theories and practical examples to explain this convergence. The first team highlights the value of ecological, evolutionary, and environmental sciences in understanding factors underlying stress responses and developing novel strategies to achieve manageable equilibria and dynamics in ecosystems to foster health for all. The second team shows how the social-ecological systems and resilience theory contribute to the One Health approach by illustrating two examples in the Greater Mekong subregion and their contribution toward the UN Sustainable Development Goals.

Focussing on perceptions from the public, Padda et al. investigated how One Health was conceptualized by regular visitors of the St. Louis Zoo (USA). They demonstrated that in contrast to infectious diseases, which are often cited as field of application for One Health, the zoo public appeared to be primarily concerned by chronic, non-communicable diseases. The findings reflect the epidemiologic transition experienced in that region and underline that zoos, particularly in the industrialized nations, are expected to play an important role in promoting One Health locally. In a different urban setting, Alarcon et al. studied livestock keeping and food supply chains in Nairobi. They showed that very diverse and predominantly small-scale farming in a densely populated environment is a challenge for managing animal health and protecting humans from food-borne diseases. However, they identified critical agents in the system and provided baseline information to develop effective policies.

The next set of manuscripts moved from understanding and conceptualizing to evaluating the implementation of integrated approaches to health. While in the discourse above, systems theory is an important tenet, Valeix focussed on the concept of "integration" as a pivotal aspect of implementing One Health approaches. She framed integration as "complementary to" or "composed of" collaboration, cooperation and coordination. The framework she developed probes the social dimensions and power dynamics among professional participants that affect One Health implementation. She emphasized the importance of local and national levels for the successful realization of One Health and exemplified the approach for zoonotic disease management in Ghana focussing on the veterinary actors. Rüegg et al. presented the framework developed by the EU COST Action "Network for Evaluation of One Health" (NEOH, https://neoh.onehealthglobal.net), an international, open network with more than 240 participants from 30 countries. It pursued a systems approach to evaluation and comprised a One Health-index and -ratio as a semi-quantitative measure to assess systems thinking, planning, transdisciplinary, and participatory working, sharing and learning infrastructures, as well as adaptive leadership in One Health initiatives. The framework was tested in various case studies from the network: Buttigieg et al., Paternoster et al., Fonseca et al., Hanin et al. and their co-workers evaluated One Health approaches for infectious disease surveillance and control. Comparing the One Health-indices and -ratios revealed that time is a relevant factor for the implementation of such initiatives, with older efforts becoming more holistic. The case study on preventing the misuse of acaricide containers for food and water storage after an animal health intervention underpins this observation, as it shows a very good balance between all six evaluated aspects of One Health and was implemented as a satellite project of a well-established field program. The case study on the Southern African Centre for Infectious Disease Surveillance also indicates that national borders are challenging for the sharing of data. Looking at the evaluations of an academic One Health research program to tackle antimicrobial resistance and a study on obesity in European dogs and their owners suggests that the professional context of a One Health initiative determines much of its capability to implement a holistic approach and that the prevailing competitive mentality in the academic field may pose a serious obstacle to the endeavor. Finally, Radeski et al. demonstrate how the target of improving animal welfare aligns surprisingly well with the One Health concept. All case studies conclude that systems thinking is challenging for many natural scientists but that the NEOH framework is a helpful tool for feedback, accountability and even conception of One Health initiatives.

In the time this special issue was collected, the World Bank published its "operational framework for strengthening human, animal, and environmental public health systems at their interface"(3), the Food and Agriculture Organization (FAO), the World Organization of Animal Health (OIE) and the World Health Organization (WHO) have jointly published "a tripartite guide to addressing zoonotic diseases in countries"(4), and the UN Convention on Biological Diversity (CBD) has issued its "guidance on integrating biodiversity considerations into one health approaches" (5). Also, in other communities the wealth of literature on systemic approaches is growing rapidly and there are countless opportunities to cross-fertilize between different fields of application. This confirms the timeliness of this Research Topic, which we believe, contributes valuable resources for practitioners, policy-makers, and funders. It also highlights a diversity of core values rooted in different systems and temporal–spatial scales that give rise to a gap between policy and practice. Closer examination of the articles raises the concern that nature based benefits as well as cross-cultural perspectives (6) are underrepresented in the multiple One Health narratives and their management. In the search for generic validity, it goes unnoticed that we know very little about the lives of those who experience these complex entanglements between humans, animals, and ecosystems on a daily basis, and whose stewardship is decisive for change to occur. We also suspect that sustained projects foster a more holistic view than short term investigations and that professional idiosyncrasies may hamper integration of knowledge, which both challenge

the current academic and research practice. But now that we have paused to consolidate our knowledge and experiences with integrated approaches to health, we shall open our minds to tackle these obstacles.

AUTHOR CONTRIBUTIONS

All authors have served as editors of the research topic. SR has written the draft of the editorial and it was amended and revised by the other authors.

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PERSPECTIVE
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A Comparison of Three Holistic Approaches to Health: One Health, EcoHealth, and Planetary Health

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Several holistic and interdisciplinary approaches exist to safeguard health. Three of the most influential concepts at the moment, One Health, EcoHealth, and Planetary Health, are analyzed in this paper, revealing similarities and differences at the theoretical conceptual level. These approaches may appear synonymous, as they all promote the underlying assumption of humans and other animals sharing the same planet and the same environmental challenges, infections and infectious agents as well as other aspects of physical—and possibly mental—health. However, we would like to illuminate the differences between these three concepts or approaches, and how the choice of terms may, deliberately or involuntary, signal the focus, and underlying values of the approaches. In this paper, we have chosen some proposed and well-known suggestions of definitions. In our theoretical analysis, we will focus on at least two areas. These are (1) the value of the potential scientific areas which could be included and (2) core values present within the approach. In the first area, our main concern is whether the approaches are interdisciplinary and whether the core scientific areas are assigned equal importance. For the second area, which is rather wide, we analyze core values such as biodiversity, health, and how one values humans, animals, and ecosystems. One Health has been described as either a narrow approach combining public health and veterinary medicine or as a wide approach as in the wide-spread "umbrella" depiction including both scientific fields, core concepts, and interdisciplinary research areas. In both cases, however, safeguarding the health of vertebrates is usually in focus although ecosystems are also included in the model. The EcoHealth approach seems to have more of a biodiversity focus, with an emphasis on all living creatures, implying that parasites, unicellular organisms, and possibly also viruses have a value and should be protected. Planetary Health, on the other hand, has been put forward as a fruitful approach to deal with growing threats in the health area, not least globally. We conclude that there are actually important differences between these three approaches, which should be kept in mind when using any of these terms.

Keywords: concept of health, ecology, ecosystems, interdisciplinarity, philosophy of medicine, medicine, value, veterinary medicine

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INTRODUCTION

Several holistic and interdisciplinary approaches that work with the human–animal–environment interface exist in order to safeguard health. Three of the most influential concepts at this moment, One Health, EcoHealth, and Planetary Health, are analyzed in this paper, revealing similarities and differences at the theoretical, conceptual level. Of these three concepts, Planetary Health is a more recent and therefore possibly less developed concept, and it may hence appear somewhat arbitrary to choose this concept and compare it to the two more well-established ones. However, based on the fact that Planetary Health has rapidly become an approach mentioned in very well-renowned and high-ranked global publications and furthermore seems to attract attention among politically influential groups we still find it highly relevant to include this concept in the discussion on an equal basis.

Someone approaching these concepts from the outside may easily perceive these concepts as relatively synonymous, as they all promote the underlying assumption of humans and other animals sharing the same planet, and to large extent the same habitats and with this the same environmental challenges, infections, and infectious agents as well as other aspects of physical—and possibly mental—health. Since a couple of years back, there has been an ongoing effort to merge at least two of these approaches, namely One Health and EcoHealth (1, 2). Among the papers promoting a merge some differences are acknowledged although downplayed, issues that might question the idea that the two approaches are synonymous. Also during this period, at least one new approach, Planetary health, has been proposed as an alternative to the other two (3).[1] We believe that a more thorough analysis of the differences between the approaches is needed for two different reasons. Either the analysis gives an argument to halter the merge or the analysis might help keeping the diversity in a merged approach.

It should be kept in mind that there are no universal, agreed definitions of any of these three approaches (6, 7). Attempts have been made to pinpoint the central aspects of each of these, but these aspects are not centrally agreed on and different people, within different professions, and with different backgrounds, may use the approaches differently. Gibbs (7), for example, argues that definitions of One Health seem to reflect the aim of the organization proposing it. In this paper, we have chosen some proposed and well-known suggestions of definitions. In our theoretical analysis, we will mainly focus on two areas. These are (1) potential scientific areas which could be included and (2) core values present within the approach. In the first area, our main concern is how wide or narrow the view on interdisciplinarity is (i.e., which and how many scientific fields included) and whether the core scientific areas are assigned equal importance. For the second area, which is rather wide, we analyze core values such as biodiversity, health, and how one values humans, animals, and ecosystems.

[1] See Lerner and Berg (4) for an analysis of another approach, Zoobiquity (5), which has also been introduced during this period but resembles One Health.

The aim of this paper is to illuminate the differences between these three approaches, and how the choice of terms may, deliberately or involuntary, signal the focus, and underlying values of the approaches.

METHOD

Identifying the demarcation of an interdisciplinary approach is not an easy task. In this study, which is a study in philosophy of science, we have focused on the scientific parts of the approaches and not on the political aspects, although the latter aspect may also warrant deeper analysis by experts in the field. The scientific demarcation of each of these three approaches, which is the question in focus here, relies on underlying values, theories of science, and the scientific fields included. In order to analyze this aspect, one cannot make a straightforward key-word-based bibliometric exercise where any publication in any scientific peer-reviewed journal is read and analyzed. Instead, we have chosen a selective approach where papers and books dealing with theoretical aspects of this field of science, such as theoretical foundation of the approach, how the approach is defined, demarcation of the approach toward other approaches, and possible conflicts of value due to scientific standpoints, are analyzed philosophically. It is based on active searches in several databases and reading of key publications, thorough reading of reference lists, web pages, and newsletters dedicated to the approaches as well as in-depth discussions with experienced colleagues in the fields studied.

We have focused on published scientific texts which have been regarded as either rich in theoretical substance on these matters or that are influential for the approaches. Often these texts have explicitly mentioned how they demarcate the approach or presented a definition of the approach. However, most of the papers and books that are published within these approaches are focused on other important issues such as policy making, implementation of the approaches, solving practical health problems, or basic scientific research. As a consequence, this review consists of relatively few references.

For each of the three approaches, we have analyzed the definitions applied, described the main contributing sciences, and identified the core values, based on these key publications within each approach.

ONE HEALTH

Definitions of the Approach

One Health has been described as both a narrow and wide approach. The narrow approach is mainly biomedical, focusing on animal, and human health while combining human and veterinary medicine (2, 5, 8). Gibbs (7) has compiled central definitions of One Health. The two widest of these are from the One Health Commission and the One Health Global Network. The One Health Commission defines One Health in the following citation:

> One Health is the collaborative effort of multiple health science professions, together with their related

> disciplines, and institutions—working locally, nationally, and globally—to attain optimal health for people, domestic animals, wildlife, plants, and our environment.[2]

The One Health Global Network defines One Health as an approach:

> To improve health and well-being through the prevention of risks and the mitigation of effects of crises that originate at the interface between humans, animals, and their various environments.[3]

For both definitions, focus appears to be on what the One Health Global Network calls a "whole of society" approach where all health sciences and their related disciplines works across borders collaboratively to improve health at an optimal level. Lately, there has been increasing emphasis within the One Health scientific community on the need for widening the One Health concept to encompassing not only human and animal health, but also biodiversity, ecology, climate change, agricultural systems, and various social sciences (8).

Contributing Sciences

In the narrowest description, One Health combines public health and veterinary medicine (9). In one of the widest approaches as in the wide-spread "umbrella" depiction it includes environmental health, ecology, veterinary medicine, public health, human medicine, molecular, and microbiology, as well as health economics (4). The narrow approach is the oldest one, and has been developed from what was earlier termed "One Medicine." The approach of One Medicine was mainly developed by veterinarians and physicians (10) and hence very centered on conventional medical issues. The term "One Medicine" was later perceived as too clinical, as the approach to health became widened to also include public health issues and ecology (4, 11). However, a more narrow interpretation of One Health, rather similar to that of One Medicine, can still sometimes be found. This narrow approach is, however, not much further discussed in this paper.

As an example, the Manhattan Principles was an ecological approach that expanded the field and belongs to the initial foundation of One Health (1). Also, health is nowadays regarded as something more than just clinical biology, although the outer limits of health as a concept have not been settled within the approach. Critics have pointed out the lack of social sciences including research related to rural development, population dynamics, anthropology, urbanization, and so on within the approach (2). However, there is much effort at the moment to include social scientists, and this aspect was also highlighted at a recent European workshop on One Health (8), together with the already more well-established aspects such as ecology, agricultural systems, food safety and security, and so on.

Core Values

From our analysis, we find that the core values of the One Health concept still relate to public human health and the health of animals influencing the health of humans. Hence, safeguarding the health, and especially individual health, of vertebrates is usually in focus although ecosystems are also included in the wider model (4). Ecology, microbiology, and biodiversity are nevertheless generally perceived as parts of the core sciences, in their own right. Later publications, such as the report by Keune et al. (8) emphasize the importance of widening the One Health concept also to social sciences and agricultural sciences. It can be argued that two core values of One Health are (a) the respect for scientific specialties whilst emphasizing the need for cooperation between such disciplines and (b) the emphasis application of multidisciplinarity in research and advisory projects.

EcoHealth

Definitions of the Approach

EcoHealth has been described as involving the health of humans, animals, and ecosystems, including also environmental sustainability and socioeconomic stability in the framework. In some cases, the EcoHealth approach seems to have more of a biodiversity focus, with an emphasis on all living creatures, implying that parasites, unicellular organisms, and possibly also viruses have a value and should be protected. Waltner-Toews suggests that EcoHealth aims for "sustainable human and animal health and well-being, through healthier ecosystems" [(12), p. 519]. The leading journal of the approach, which has published several papers on these theoretical matters, is the EcoHealth journal. At present, the EcoHealth approach at the EcoHealth Journal website is defined as:

> EcoHealth is committed to fostering the health of humans, animals, and ecosystems and to conducting research which recognizes the inextricable linkages between the health of all species and their environments. A basic tenet held is that health and well-being cannot be sustained in a resource depleted, polluted, and socially unstable planet.[4]

Contributing Sciences

In the start of the journal EcoHealth possible scientific fields that could contribute to the approach was suggested. These were conservation and ecosystem management, veterinary medicine, human medicine, public health practice, rural and urban development, and planning, and more not specified (13). EcoHealth has included more of social science and the humanities than One Health and the approach includes anthropologists with a focus on indigenous people. Indigenous and local knowledge are also acknowledged as a source of knowledge besides the western scientific knowledge (14). Scientific papers could have a more

[2] https://www.onehealthcommission.org/en/why_one_health/what_is_one_health/ retrieved August 14, 2017.

[3] http://www.onehealthglobal.net/what-is-one-health/ retrieved August 14, 2017.

[4] https://ecohealth.net/en/ retrieved August 14, 2017.

esthetic or essay approach. Among the natural scientists, ecologists seem to have higher influence.

Core Values

Focus is on the relationship between health, ecosystem, and sustainable development, where the latter is based on equity (1, 6, 13–15). Participation from different sectors in the society such as policymakers, scientists, and those performing the fieldwork are favored (6, 14). That participation is consensus and cooperation-based (15) and aims for action (6). The concept of health is mainly used at the population level of health and is also used as a metaphor (6). Biodiversity is an important value within the idea of sustainability.

PLANETARY HEALTH

Definitions of the Approach

Planetary Health has in recent years been put forward as an alternative to One Health and EcoHealth. The concept has been developed by The Rockefeller Foundation-*Lancet* Commission on planetary health. However, the concept seems to be less interdisciplinary than One Health and EcoHealth and primarily focus on human health, although the environment is acknowledged. In one of the key papers from the commission they state that:

> Our definition of planetary health is the achievement of the highest attainable standard of health, well-being, and equity worldwide through judicious attention to the human systems—political, economic, and social—that shape the future of humanity and the Earth's natural systems that define the safe environmental limits within which humanity can flourish. [(3), p. 1978]

One can clearly see that this definition of planetary health, the Brundtland view of sustainability (16) is present that humans are valued more than other animals or ecosystems. For example, Horton et al. (17) state that Planetary Health is focused on mitigating and responding to threats to human health and well-being, and on the sustainability of the entire human civilization. In addition to this, the authors acknowledge the importance of biodiversity as it is the basis of the natural systems on which humans depend, without discussing the intrinsic values of these ecosystems (17). This approach is extremely anthropocentric, focusing only on human health outcomes. One of the main critiques toward the Brundtland report has been linked to its anthropocentric approach, limiting the discussions to sustainability from human utility perspective, not emphasizing the inherent values of ecological systems and biodiversity (18).

Although also Whitmee et al. (3) to a large extent adopt an anthropocentric approach they bring up effects of ecological changes, climate change, land use alterations, and food production changes in relation to the risks of transmission of zoonotic and vector-borne diseases to humans, thereby involving also animals in the line of thought. Having said this, the health and consequently the welfare of animals for the animals' own sake is not mentioned, and it is evident that animal health is only perceived as relevant in terms of potential disease transmission to humans, and in terms of their capacity as food production units.

Contributing Sciences

Approaching the concept of Planetary Health in its most narrow form of interdisciplinarity, Horton et al. (17) clearly state that this field of science involves health professionals, public health practitioners, policy makers, and similar categories. The term "health professionals" in this context only refers to human health professionals, i.e., not veterinarians or other animal health professionals. Neither does this list cover ecologists nor others biologists.

In the key paper from the Rockefeller Foundation and The Lancet (3), the focus is somewhat wider, mentioning a broad spectrum of scientific disciplines such as human medicine, ecology, and other environmental sciences (including climate and biodiversity research), economy, energy, agricultural sciences (including plant and animal production sciences), marine sciences, and more. Hence, these authors appear to acknowledge the need for interdisciplinary collaboration to a larger extent.

Core Values

From our analysis, the core values within the Planetary Health approach is the health of living and future human generations, applied to individuals, communities, and populations (3). A main goal is equity in health, which is related to socioeconomic, regional, and gender factors (17). Furthermore, the Planetary Health concept requires sustainability, which is in turn based on natural resources and biodiversity (3).

DISCUSSION

The approach used in this paper was to apply a methodology originating from the field of philosophy science on three interdisciplinary approaches to health among people, animals, and the environment. This approach does have its limitations, as it does not involve a total scrutiny of all publications in these three fields. The choice of papers, books, and informants can always be challenged, but this method is an efficient way of rapidly pinpointing the core values and contributing sciences in a systematic way. Nevertheless, we fully acknowledge that future further and deeper analyses may reveal slightly different results. It should also be mentioned that within the scientific community the values and demarcations of various concepts may change over time, and we would hence like to emphasize that our conclusions only reflect the present state.

Of the three approaches that seemed to be similar, One Health, EcoHealth, and Planetary Health, we have regarded Planetary Health to differ the most regarding how they value humans, animals, and ecosystems (**Table 1**). This approach is clearly anthropocentric and focuses primarily on human health. In One Health and EcoHealth, humans and animals are more on par. Therefore, we consider Planetary Health as more similar to a concept such as Global Health, than One Health and EcoHealth. One strand of definitions of Global Health is based on a broad collaborative and transnational approach to establish health for all. This "health for all" concerns only humans but is wider than public health (19).

TABLE 1 | Comparison of the three approaches.

		One Health		EcoHealth	Planetary Health	
		Narrow	**Wide**		**Narrow**	**Wide**
Core contributing sciences	Human	Public health	Public health Human medicine Molecular and microbiology Health economics Social sciences	Public health Human medicine Rural and urban development and planning Social sciences Anthropology	Public health Human medicine	Human medicine Economy Energy Natural resources
	Animal	Veterinary medicine	Veterinary medicine	Veterinary medicine	–	Agricultural sciences (including plant and animal production sciences)
	Ecosystem	–	Environmental health Ecology	Conservation and ecosystem management	–	Ecology Other environmental sciences (including climate and biodiversity research) Marine sciences
Knowledge base		Western scientific	Western scientific	Western scientific Indigenous knowledge	Western scientific	Western scientific
Core values	Health	Individual health	Individual and population health	Population health	Individual and population health	Individual and population health
	Groups	Humans Animals	Humans Animals Ecosystems	Humans Animals Ecosystems	Humans	Humans
	Other			Biodiversity Sustainability (for humans, animals, ecosystems)	Sustainability (for humans)	Sustainability (for humans)
Reference		(2, 5, 8, 9)	(4, 7, 8, 11)	(1, 6, 12–15)	(17)	(3)

The main difference between Global Health and Planetary Health is the emphasis on the need for sustainability based on natural resources in the latter approach.

Regarding the more interdisciplinary and holistic approaches One Health and EcoHealth, both approaches share similarities such as advocating interdisciplinarity, and promoting health. Therefore, some authors argue for a merge of the two approaches despite the existing differences (1, 2). In international reports made by intergovernmental agencies, a practice of treating them as related to each other has already been established [see (20)]. However, there still seem to be some aspects that might differ between the approaches, and we will below discuss the concept of health and the differences in interdisciplinarity. For comparison, we will analyze all three approaches. Finally, as a consequence of the fact that at least One Health and EcoHealth seems to expand in their interdisciplinarity we will also discuss where the outer limits of these approaches might lie.

Health

One of the most obvious differences is in the view of health. Planetary Health focuses mainly on human health (3), while the other two approaches have a broader perspective. Zinsstag et al. (1) state that One Health mainly treat animal and human health while EcoHealth mainly focuses on the relation between health and ecosystems. The difference between One Health and EcoHealth might be more troublesome to bridge than suggested. Lerner and Berg (4) showed that there are three levels where health can be defined and these are individual level, population level, and ecosystem level. The difference between individual health and the two other levels is similar to the reason why animal ethics and environmental ethics are seen as different from each other. With help from philosophical value theory, one can see that One Health attributes health to individual bearers in the same manner as one strand of animal ethics ascribe values to individual animals and humans, while EcoHealth attributes health to aggregations, systems, and processes similar to when environmental ethics ascribe value to ecosystem processes or species. Could a process have health in the same way as an individual have? Could an ecosystem have health? Or does health become metaphorical in these latter senses, as Charron (6) suggests? On the other hand, if one concerns the human body as an ecosystem, one could rather argue that human individual health should be similar to the ecosystem level. This issue, the relation between and importance of the levels of health, must be solved in order to merge the two approaches.

One initial step may be to decide on treating health as a property of the individual, rather than of the group, population, or ecosystem. This approach is quite possible, without denying the fact that the health of one individual (regardless of species) may of course in many cases directly or indirectly influence the health of others.

Given this, one might want to consider whether there needs to be a similar definition of health for all individuals involved in the merged approach. Should the health promoted be of the

same definition for humans, animals, and plants (with relevant adjustments for different kinds of species)? Lerner (21) has shown that this might be possible and several alternatives already exist. For example, the WHO definition of health for humans is currently applied also on animals, especially in organic agriculture. Other categories of health definitions that are applied to both animals and humans are balance theories, health as biological function (such as homeostasis) and health as the ability to realize an individual's vital goals. When it comes to mental health and its definitions, however, there are still considerable discrepancies in how this scientific field is approached in humans and animals, respectively. Furthermore, the study of health definitions in animals is less thorough than in humans and when one turns to plants or ecosystems even less research and analysis has been carried out. As a conclusion, much philosophical concept analysis still needs to be carried out to find definitions of health suitable to a merged approach [see also (4, 21)].

Interdisciplinarity

All three approaches are based on multi- or interdisciplinary research. The reason why these approaches have evolved was the understanding that the issues that needed to be solved needed contributions from several disciplines of science [see, for example, Ref. (15)]. To our interpretation, the Planetary Health approach has the narrowest focus on interdisciplinarity, with an emphasis on human health and related research areas. One Health has sometimes been criticized for focusing only on medicine (human and veterinary) (5, 9). Ecohealth seems to be the wider approach accepting more of the disciplines within the humanities and sociology (1) although the One Health approach has during recent years been used in a gradually wider context (4, 8).

Even within a discipline, there is a variety of scientific positions. Within human medicine, for example, some scientists work with microbiology, others with social science aspects and yet others with clinical trials. Therefore, it is reasonable to believe that One Health and EcoHealth could find a demarcation of disciplines that could cooperate in order to solve the problems. This might change due to novel problems, but a core group of disciplines that is wider than today might be easy to agree on (areas neglected or too little mentioned in the debate but could contribute strongly are philosophy and nursing science). Seen from this perspective, it may prove more difficult to incorporate the approach from Planetary Health into a merged approach because of its main focus on humans and human health.

Outer Boundary

One aspect, which we believe to be an issue, to consider is where the outer boundary should be drawn. A merged approach cannot deal with all aspects of the world without becoming a "theory of everything." For example, there are voices arguing for a much broader approach called One Welfare, focusing on human, animal, and social welfare including the environment (22–24). The relation of this new wide approach to the merged One Health-EcoHealth approach must be carefully analyzed. In our view, the risks of creating to wide and all-embracing disciplines should not be ignored. To create creative and fruitful interdisciplinary or transdisciplinary research groups and projects, there still has to be basic disciplines to connect between. This can still be the case also for wide concepts such as One Welfare, which must involve several other disciplines in addition to the ones mentioned above. There is a risk of the high number of disciplines involved then resulting in structural problems and conflicts.

At the conceptual level, the relation between the concepts of health and welfare can be seen in different ways depending on how we define them. They may be partially overlapping or more or less independent of each other. In animal welfare science, there has been an emphasis on finding a unifying concept, welfare, which covers all aspects of an animal's life (25). The problem with this approach is that if some aspects are poor and some are good the overall welfare might be hard to evaluate. Therefore, it is still useful to separate health and welfare conceptually. One can then be able to say that the animal's health is poor while the welfare is good (26). The same reasoning could be fruitful to apply to the approaches of One Health and One Welfare. One would then be able to focus on different aspects within each field. However, the joint One Welfare approach should not be dismissed until properly evaluated and tested.

CONCLUSION

Three of the currently most influential concepts in the area of human, animal, and ecosystem health are One Health, EcoHealth, and Planetary Health. Neither of these concepts have any generally, centrally agreed definitions, and are sometimes handled as almost synonymous, sometimes as overlapping and sometimes as quite distinctly separate. In our analysis, we have found that these concepts have a lot in common but do differ in contributing sciences, core focus, and values, which may influence how they are used and also what signals the choice of term sends. Considering especially the concept of health, the valuing of humans, animals, and ecosystems as well as the view on which disciplines to include within the approach, we conclude that there are actually important differences between these three approaches. This should be kept in mind when using any of these terms or in a process of merging one or more of these approaches together.

AUTHOR CONTRIBUTIONS

All authors have planned and contributed in writing the manuscript. All authors have critically reviewed and revised the manuscript and approved the final product.

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Systems Thinking in Practice: Participatory Modeling as a Foundation for Integrated Approaches to Health

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One Health (OH), EcoHealth (EH), and Planetary Health (PH) share an interest in transdisciplinary efforts that bring together scientists, citizens, government and private sectors to implement contextualized actions that promote adaptive health management across human, animal and ecosystem interfaces. A key operational element underlying these Integrated Approaches to Health (IAH) is use of Systems Thinking as a set of tools for integration. In this paper we discuss the origins and epistemology of systems thinking and argue that participatory modeling, informed by both systems theory and expertise in facilitating engagement and social learning, can help ground IAH theoretically and support its development. Participatory modeling is iterative and adaptive, which is necessary to deal with complexity in practice. Participatory modeling (PM) methods actively involve affected interests and stakeholders to ground the field of inquiry in a specific social-ecological context. Furthermore, PM processes act to reconcile the diverse understandings of the empirical world that stem from divergent discipline and community viewpoints. In this perspective article, we argue that PM can support systems thinking in practice and is essential for IAH implementation. Accordingly we invite PH, OH, and EH practitioners to systematically incorporate specialists in systems science and social engagement and facilitation. This will enable the appropriate contextualization of research practice and interventions, and ensure a balanced representation of the roles and relationships of medical, biological, mathematical, and social disciplines. For completeness, funding schemes supporting IAH need to follow the same iterative, adaptive, and participative processes to accompany IAH projects throughout their implementation.

Keywords: One Health, EcoHealth, Planetary Health, systems theory, systems thinking, participatory modeling, resilience, sustainable development goals

INTRODUCTION

The emergence of One Health (OH) and EcoHealth (EH) approaches over the past decade, recently complemented by the Planetary Health (PH) movement (1), illustrates the consolidation of a consensus in the veterinary and public-health domains that there is a need for integrated, interdisciplinary and inter-sectoral approaches to better understand health issues, and to improve the sustainability and relevance of interventions targeting individual and population health in various social, cultural and environmental contexts. The recent publishing of the One Health theme issue in the Philosophical Transactions of the Royal Society B (2) and the present issue embody this consensus and highlight the need for a clarification of the principles underlying these integrated approaches to health (IAH) (3, 4), the key methods and tools they rely on to collect data, monitor processes and outcomes, and their effectiveness and relevance for coping with veterinary and public health issues.

The Ecosystem approach, underpinning Ecohealth (and in principle One Health) (Wilcox et al., under review in this Research Topic), has been developed over the last two decades (4–6) to address pressing social-ecological challenges. However, it remains sparsely used when it comes to public health related interventions (Wilcox et al., under review in this Research Topic). Building on the conceptual foundation of the ecosystem approach (6), we propose that IAH initiatives, whatever their dominant epistemological orientation (e.g., One Health and veterinary sciences, Ecohealth and disease ecology, etc.), should routinely take a comprehensive view of the complex interactions between human and natural systems at multiple scales and levels (7). This would require taking a participatory approach to more widely involve key stakeholders in:

1. definition and description of relevant social-ecological systems in terms of scale, extent, structure and functioning;
2. assessment of their state in terms of health, as defined by what is acceptable to society;
3. assessment of threats;
4. maintenance, mitigation, and rehabilitation, and;
5. using adaptive management strategies to ensure longer term systems resilience (8).

We also argue for more attention within these participatory approaches to the use of modeling techniques which encourage those involved to clarify what key variables affect the underlying system(s), the factors that will shape responses, uncertainties involved, and the likely outcomes of particular strategies (9).

Such integrated approaches (to health and other areas) recognize that animals, humans and the environment are interdependent, and the complex interactions between these components not only challenges simplistic views of ecosystem functioning (10), but should change the way we manage them, moving from the imposition of technocratic solutions targeted at subsets of the system; to working directly with stakeholders in the decision process, and acknowledging local social-ecological knowledge in practice (6, 11). This is, in effect, social learning as a participatory process of social change in which people learn from each other in ways that can benefit wider social-ecological systems (12), and in which modeling serves as a key tool, both for this learning to happen and for supporting decision-making processes (13, 14).

Zinsstag et al. (3) argue that individual and population health can be seen as emerging properties of a system's interacting social and ecological factors. It follows that any IAH attempting to sustainably improve public-health and population well-being needs to help key stakeholders understand and adaptively manage social-ecological dynamics. We note two major impediments to the success of IAH projects in this regard. Firstly, there is insufficient representation and integration of social sciences and disciplines related to ecological thinking and environmental management (15–18). Secondly, more participatory and integrated modeling is needed to help systematically capture and integrate our understanding of how changes in management, climate, demographics, and other factors affect selected indicators of system health (19). The fact that these fields are underrepresented in IAH reflects the human and veterinary health sector foci on disease when addressing health issues. Disease management is not the same as promoting health, which requires a more salutogenic orientation (20, 21) grounded in resilience theory and practice, medical sociology and anthropology and participatory action-research. This orientation more closely fits what arguably should be One Health's primary concern to maintain the integrity of the human-animal-environment complexes in face of stressors. This orientation is also better aligned with the United Nations Sustainable Development Goals, which involve a more diverse range of expertise as well as methodologies for their integration (Wilcox et al., under review in this Research Topic).

In this perspective article, we highlight the importance of underpinning IAH approaches with three key practice areas: (1) systems thinking—to help a wider range of stakeholders develop a shared agreement around problem structuring; (2) modeling—to help people understand trends and see processes unfold that are either too big or too little to appreciate with the naked eye; and (3) facilitation—to support the constructive participation of key stakeholders in the wider decision-making process. We also reinforce the importance of linking across these three practice areas. We begin by discussing the converging attributes and underlying characteristics of OH, EH, and PH (all designated by "IAH") [see also Lerner and Berg (22) for a complementary discussion] and briefly clarify system thinking origins and epistemology. Finally, we highlight a rationale for the design of more integrated and adaptive methodologies for effective implementation dealing with complexity in practice.

THE UNDERLYING CHARACTERISTICS OF IAH

Complexity

IAH recognizes that complexity is an inherent characteristic of natural systems (10, 11). Since the mid 1980s, starting with the pioneers of the Santa Fe Institute in the United States, complex systems became a field of investigation. Definitions of systems properties that are commonly associated with complexity, such

as chaos, scales, emergence, bifurcation, auto-organization, adaptation, and resilience can be found in the complex systems literature. Here, we focus on some features of this field that have direct implications for IAH.

While complexity and how to address it is still debated, the synthesis by Deffuant et al. (23) offers a good overview of the origins, uses and operational implications of complexity–based practices and offers a roadmap for more integrative implementation (**Table 1**). The authors distinguish three main epistemological views pointing to the importance of clearly understanding and explicitly acknowledging which view(s) are being considered, and perhaps integrated, when dealing with complexity on a project-basis. These viewpoints influence the kinds of questions we raise and the methods we develop to address them (**Table 1**).

The three views of complexity have different implications related to how the principles and methodological attributes are implemented in the context of IAH. View 1 acknowledges that the predictive power of models[1] is often intrinsically limited because of the sensitivity to initial conditions, that uncertainty and surprise must be taken into account, and that emerging properties should be identified—and so far as possible understood. From view 2, it is understood that heterogeneous available knowledge and data can be integrated into simulation models used to explore scenario-based projections. Complementarily, view 3 recommends the use of participatory processes to build iterative and adaptive management strategies in which resilience thinking and the active engagement of stakeholders to insure relevant representation of worldviews and perceptions, attributes that are inherently subjective, are essential ingredients.

Participation and Transdisciplinarity

When implementing IAH, the ultimate goal is to improve health of humans, animals and ecosystems conjointly. This statement is highly subjective, and the third vision of complexity tells us that to achieve such a goal, participation (active involvement and engagement of affected interests and stakeholders in framing the problem and the discovery of adaptive responses to meet IAH objectives) is key. Attention should be paid to the participation label. It hides a substantial diversity of inclusion criteria and practices (24, 25). In participatory research, the diversity in implementing and designing participatory processes relies on the necessity to adapt to local contexts and the classical questions regarding who to involve, how and where, and for whose benefit (26, 27). The point here is to acknowledge that representatives of civil society, and decision makers at all relevant levels, must be involved in IAH, including in research design and implementation. Accordingly, the mobilized knowledge is not only scientific and expert, but also practical and local (28, 29). Consequently, power relations (who knows, decides and acts) are decentralized, shared between heterogeneous actors, and made dynamic throughout the participatory process (24, 30). Winter [(31), p7] contends that "*policy* [substituted here as IAH] *brings to statement what is judged to be possible, desirable and meaningful… and is the nexus of facts, value and ultimate meaning in which scientific, ethical and theological-philosophical reflections meet.*" Embracing the complexity of a situation with its heterogeneous set of actors, accounting for the diversity of their perspectives, perceptions and values, creating knowledge oriented toward solutions and transferable to both scientific and societal practice, is fundamental to transdisciplinary research (32–36). IAH practice should also encourage researchers to actively include a process of reflection about the transdisciplinary process itself (25). Allen et al. (37) and Seidl (38) contend that the majority of researchers in the "hard" sciences are unfamiliar with such a reflexive approach and may consider it a challenge to existing power relationships, but it is essential to the progress of the field.

Transdisciplinary research bridges science and practice (39, 40) and fosters the emergence of social learning and collective intelligence via participation. Boulding (41) argues that effective applications of general systems theory (and by extension transdisciplinary research and participatory modeling) catalyzes and coheres a "Republic of Learning" comprised of all affected interests and disciplines.

The extent to which the historical, cultural, environmental, sociological, and economical contexts are integrated depends on the definition of the problem and the formation of an interdisciplinary, cross-sectoral team that will define it. Lerner and Berg (22) argue the definition of boundaries when adopting an integrated approach is an important step. The same can be said regarding the choices in the levels of organization, and the time and space scales, i.e., the characteristic physical dimensions of the phenomenon under consideration (7). Therefore, the set of disciplines, and more generally the set of knowledge, we have to mobilize to deal with a specific IAH problem cannot be entirely defined *a priori* by a particular integrative framework. Rather it should be negotiated and incrementally agreed. Doing otherwise would freeze the definition of the problem and the set of perspectives to be involved in addressing it, limiting the set of possible responses and decisions. Therefore, the participatory process must be iterative and adaptive, focusing on clear and contextualized objectives. The participatory process enhances co-learning, evolves, and should strive to manage any conflict and power strategies (24, 26, 30). As much as possible, we must aim to create "safe forums for articulating and debating issues where facts are uncertain, values in dispute, stakes high and decisions urgent" (41–43).

From these considerations, a practical methodology for IAH should consider the three views of complexity, and should be iterative, adaptive, and participative (6).

SYSTEMS THINKING AS A FOUNDATION

Systems Theory and Modeling

Systems theory has a long history. The word theory is misleading here since it is more a paradigm than a theory one can falsify. Von Bertalanffy (44) in *General system theory* discussed the tendency of wholeness in sciences (holism), the necessity of knowledge integration, open and closed systems, feedback loops and control and regulation, interactions between system components and

[1] A "model" is a representation of reality (e.g., diagram, map, mathematics, game).

TABLE 1 | Three views of complexity and their implications for IAH implementation—Elaborated from (23).

View	Main origins	Main characteristics	Consequences
1	• Mathematics • Physics • Computer sciences	• Sensitivity to initial conditions. • A complete/full description of system outcomes is not possible (while the rules may be simple). • For most systems, their global behavior cannot be directly inferred from the rules governing components and their interactions (holism).	• A small perturbation/event can have dramatic consequences. • Impossibility of predicting with certainty (uncertainty and errors in the predictions). • Existence of emergent properties.
2	• Data mining • Computer sciences	• Acknowledges vision 1. • Modeling and simulation to integrate heterogeneous expertise and massive data sources is the main strategy to build new knowledge. • The prediction of future states is an approximation and is confined within a certain time and space horizon.	• Decision making cannot be perfect. • We can narrow down the set of possibilities.
3	• Sociology • Cognitive sciences • Biology	• The subjectivity of individuals and societies is a difficult problem in modeling. • Ecosystems (including societies) self-regulate, adapt, evolve. • Heterogeneities in perceptions, values, regulations, and social structures.	• Importance of resilience. • Participation is required. Adaptive management is required.

emergence (41, 45, 46). At its origin, systems theory is closely related to cybernetics (47, 48). It was J. W. Forrester who initiated the modern vision of the field of system dynamics. Forrester was a pioneer in applying systems engineering and computer simulations to analyze social systems and predict their behavior (49). Since, systems theory has spread and developed in different fields, such as business, management (50, 51) and ecology (52). We invite the reader to search the literature, e.g., Luhmann's 2012 book *Introduction to systems theory* (53), to grasp the depth of the field and explore its foundational developments. Systems theory provides a common language to deal with reality, necessary for collaborators to understand each other in interdisciplinary research. Von Bertalanffy used mathematics derived from the field of dynamical systems to describe systems and predict their behavior. The field of dynamical systems inherits insights from a long tradition in mathematics and physics in its methods and principles, which still widely support current modeling and simulation in biology, ecology, and epidemiology. Dynamical systems applications provide a fundamental theoretical framework IAH can benefit from, including, for example, perspectives derived from chaos theory or resilience theory (54). Theory of modeling and simulation (55) can be viewed as a foundation for more recent model variants developed in ecology, epidemiology and coupled social and ecological modeling, such as agent- or individual-based models (56–58). This has important implications for IAH development, which can benefit from the conceptual and methodological advances in these mathematical fields. Although modeling has been highlighted recently for its potential to deal with IAH complexity (59, 60), its use in the context of IAH research and intervention remains minimal. We emphasize here that modeling is a process of applying systems theory.

Systems Thinking

The term "systems thinking" has developed as an approach to real-world problem solving through the Operational Research field (41, 61–63). P. M. Senge developed the concept in the field of organizational theory and management. He identified the problems brought by fragmented knowledge and the lack of holistic learning in organizations (50). Ross and Wade (64) presented systems thinking as a set of skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and planning change to produce desired effects. Systems thinking is a practice based on systems theory. It addresses concrete problems where the complexity of the system constrains understanding and explanation due to pre-conceptions and the limitations of cognitive processing. **Figure 1** gives a synoptic view of systems thinking.

Ross and Wade (64) summarize the following sequence of tasks when applying systems thinking:

- Identify and understand the system structures considering different scales and levels.
  - Definition of the system boundaries, its closeness or openness, the scales considered in time and space, the organization level (cells, individuals, societies, ecosystems, etc.), the set of components and the connectivity between them.
- Identify and understand the system dynamics at different scales.
  - Description of the flows of matter, energy and information between the components, the synergies and the context-dependent changes in system structure.
- Reliably infer the impact of change to the system.

To these points we add elements of social context when applying systems thinking:

- Incorporate multiple perspectives and worldviews.
- Consider the environmental, cultural, religious, economic, and political contexts.
- Consider power relationships.

While these tasks are often used to describe modeling and simulation activities, they are increasingly used as a framework for complex participatory problem solving. Modeling activities are defined broadly and include a wide range of tools and methodologies (66). These include mind maps, charts, diagrams,

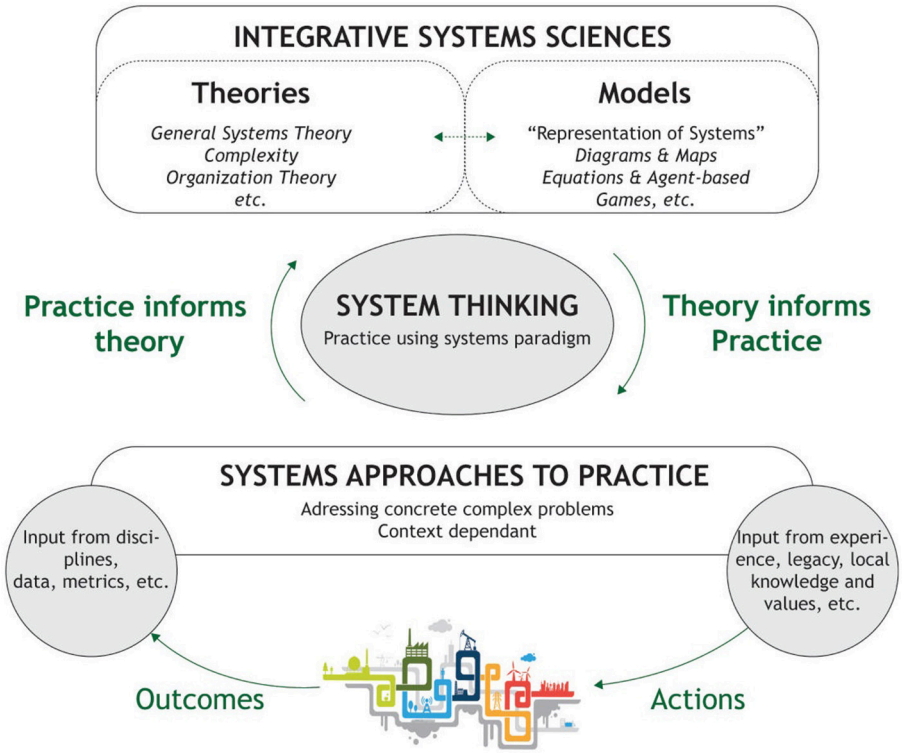

FIGURE 1 | Systems thinking—Adapted from (65).

or equations, while simulation ranges from computation using a computer to role playing games involving human actors. These existing tools support practitioners to apply modeling and simulation to implement systems thinking.

The knowledge we have about the context, the structure and the dynamics of a system constrains the decisions we make on its management, and consequently the potential for sustainable health development. When implementing IAH, knowledge is distributed and exchanged between different actors. Therefore, their participation and smooth communication is necessary if we want to integrate the contexts and the different perspectives into the iterative process of identifying problem and solutions (67). Modeling and simulation should therefore be participative and integrated research teams should also include social science expertise in engagement and facilitation for designing, managing and evaluating the participatory process (27, 68).

Participatory Modeling and Co-learning

From the above, we argue that IAH should be iterative, adaptive and participatory to deal with complexity. Participatory modeling demonstrates how these requirements can be met in practice. It mobilizes the implicit and explicit knowledge of different actors to build a shared representation of reality (67, 69–72). Participatory modeling is a transdisciplinary process that facilitates knowledge sharing and the generation of new knowledge to support negotiation and planning. As such, it supports decision-making and adaptive management (73). The model is not presented as a singular definitive solution or final product but an intermediary pedagogical device used to foster dialogue (74). Numerous participatory modeling methods exist, all derived from the field of collaborative learning which appeared in the late 1960s (75). Co-learning is an approach that promotes multiple forums where diverse participants can work together on concrete problems or to create a product (76, 77). Discussions are not just about technical solutions, but also center on issues of ethics and power (31, 68). When coupled with participatory simulation (scenario analysis), this approach generates collective innovations.

Group Model Building (GMB), initiated in the field of system dynamics in the 1980s (67, 78, 79), was the first participatory modeling methodology studying stakeholder involvement and its effects on model production and decision-making, and fostering ideas into concrete actions. GMB was first applied in the business field, and environmental modelers adopted it in more diverse, cross-sectoral and ill-defined contexts characterizing environmental challenges (75). Methodologies, such as Community-Based System Dynamics modeling (CBSD) developed in 2009 by P. Hovmand (80), and Mediated Modeling (MM) founded in the 2000s by M. van den Belt (81) are closely related to the GMB approach. MM involves a series of workshops proceeding through stages of problem definition, conceptual model of the system (in which scientists may help to quantify flows and gather data), then participants "test" the model through scenarios. A strength within the mediated modeling

approach developed by Thompson et al. (27) is that facilitators created a novel operating context for the modelers, using participatory techniques, such as historical and cultural timelines to elicit participant knowledge about changes in the complex system under study. Whereas CBSD focuses on advancing social innovation and capacity building, MM promotes more the creation of a shared understanding. These methodologies are mainly associated with systems thinking and facilitation, but fit very well with the development of system dynamics models.

Spatial group model building (28, 82) incorporates a spatial basis to participatory modeling, which can either be computer-assisted (28), or use manual methods, such as transparent map overlays (82) depending on the nature of the participants and availability of technology in the study context. Maps help participants visualize the context of the complex system, elicit more contextualized information (28), locate components of the complex system, and allow tracing of movements, such as supply chains (82).

Another participatory modeling approach that appeared in the 1990s, the Companion Modeling (ComMod) (72), shares many characteristics with the methodologies cited above. It uses multi-agents systems and role playing games to conduct participatory simulation sessions. ComMod systematically considers power relationships among stakeholders within a social context. It was characterized in a review paper by Seidl as a "genuine participatory approach" [(38), p. 575], ComMod is deeply adaptive; the model evolves as the problems change during the research and implementation period. Even the modeling tools can be different all along the process. Therefore, ComMod qualifies itself more as a research posture than a methodology attached to a particular set of tools.

On the basis of these different methodologies and others, a generic framework of participatory model development has been proposed (83). Binot et al. (59) and Duboz and Binot (84) contend that participatory modeling approaches are ideal to accompany adaptive management as well as to foster engagement and sharing of responsibilities. They should be used to implement IAH. However, Allen et al. (68) remind us that existing participatory initiatives in integrated science are better seen as islands of success, rather than evidence of a new sweeping paradigm.

In proposing participatory modeling as a potential pathway for improved systems approaches that can deal with the complexity of IAH we do not wish to understate the potential shift in ethos and practice required. Participatory modeling itself needs to reside within an overall systems problem-solving framework. This calls for greater appreciation of the social processes of building collective systems knowledge, understanding choices and designing and monitoring interventions for change. This correspondingly calls for a wider remit for social process specialists in IAH initiatives (27) and, we would argue, an acknowledgment of the limitations of modeling approaches without this partnership.

CONCLUSION

In this paper, we highlight systems thinking as a necessary foundation for IAH. We do so by discussing the origins and epistemology of systems thinking, revealing its strong mathematical roots and arguing that modeling informed by both dynamical system theory and social participatory innovations can help ground IAH theoretically and advance the tools necessary to deal with complexity in practice. Mathematical or computational models, for instance, within the first and second views of complexity (see **Table 1**) help identify and understand global system properties, such as feedback loops, controls, viability, resilience and emergence, elements of complexity that are usually ignored mostly because of the lack of tools to assess them. Combining mathematical models with innovative participatory approaches that encourage co-learning helps ensure that modeling is context-sensitive (i.e., culturally and socially relevant), iterative and adaptive. These approaches also enable a normative focus to ensure issues around ethics, equity, and power are included in the decision-making process. The idea of a negotiated complexity (85) for decision support systems similarly supports more inclusion of social sciences in embracing complexity. We argue that participatory modeling should be a key component of any IAH initiative, as it enables the practical operationalization of an otherwise elusive holistic effort.

To take a consistent and comprehensive approach, funding schemes supporting IAH would follow the same iterative and adaptive principles. It follows that funding agencies need to be included in the design and development of IAH research and adaptive management strategies. Furthermore, and despite the critical role played by participatory innovations that are inherently grounded in social sciences theory and practice, many key social science disciplines remain under-represented in most current IAH. Including social research expertise to manage appropriate participation, social engagement and facilitation is essential to address the ethical dimensions of systems, identify power relations, equity and gender issues, and therefore are keys to adapt the modeling process to the social and cultural context.

Accordingly, we argue that systems thinking and its attributes should be part of veterinary health and public health curricula (it is already well-accepted in ecology, the other dimension in One Health and EcoHealth). To achieve this, theory and methods taught in systems engineering and ecology can be adapted to the particular issues addressed by these domains. This instruction also needs to go further and provide students some expertise and familiarity in working comfortably in inter- and trans-disciplinary teams that also include system thinking specialists that can bring complementary skills in system dynamics modeling and in facilitation and problem structuring.

AUTHOR CONTRIBUTIONS

RD and PE are the main contributors. The manuscript is the result of a workshop where all the authors collectively decided the argument and content. All authors contributed ideas, passages

and edits to the manuscript and actively reviewed and provided comments to the manuscript prior to submission.

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Operationalizing One Health Employing Social-Ecological Systems Theory: Lessons From the Greater Mekong Sub-region

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The idea of the interdependency of the health of humans, animals, and ecosystems emerged from the interplay of theory and concepts from medicine, public health and ecology among leading thinkers in these fields during the last century. The rationale for One Health and its focus on the "human, animal, and environmental interface" stems from this legacy and points to transdisciplinary, ecological and complex systems approaches as central to One Health practice. Demonstration of One Health's efficacy, its wider adoption and continual improvement require explicit operational criteria and evaluation metrics on this basis. Social-Ecological Systems Theory with its unique conception of resilience (SESR) currently offers the most well-developed framework for understanding these approaches and development of performance standards. This paper describes operational criteria for One Health developed accordingly, including a protocol currently being tested for vector borne disease interventions. Wider adoption of One Health is most likely to occur as One Health practitioners gain an increasing familiarity with ecological and complex systems concepts in practice employing a transdisciplinary process. Two areas in which this inevitably will be required for significant further progress, and where the beginnings of a foundation for building upon exist, include: (1) Emerging and re-emerging zoonotic diseases, and (2) successful implementation of the United Nations (UN) Sustainable Development Goals (SDGs). The former includes the challenge of stemming the threat of new microbial pathogens, anti-microbial resistant variants of existing pathogens, as well as resurgence of malaria and other recalcitrant diseases. The applicability of SESR in this regard is illustrated with two case examples from the Greater Mekong Subregion, Avian Influenza (H5N1) and Liver Fluke (*Opisthorchis viverrini*). Each is shown to represent a science and policy challenge suggestive of an avoidable social-ecological system pathology that similarly has challenged sustainable development. Thus, SESR framing arguably is highly applicable to the SDGs, which, to a large extent, require consideration of human-animal-environmental health linkages. Further elaboration of these One Health operational criteria and metrics could contribute to the achievement of many of the SDGs.

Keywords: adaptive health management, complexity, One Health, sustainable development goals, transdisciplinarity, system thinking, ecology, adaptive cycle

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INTRODUCTION

The interdependence of the health of humans, animals, and of ecosystems, along with the biological diversity they represent, is commonly described as the underlying tenet of One Health (1–4). As a research aim, understanding this interdependence is closely aligned with that articulated for sustainability science. Both are argued to require an integrated framework that includes concepts, principles and methods spanning multiple disciplines. This goes beyond the biomedical and ecological sciences to include social sciences and local knowledge (5). More generally, and especially in traditional ecological and health knowledge contexts, the broader concept of "local science" is arguably more appropriate (6).

This implies disciplinary integration, including, in particular, integration of elements of the biomedical and ecological sciences, as well as social sciences. Those typically trained as scientists and/or practitioners in biomedicine, public health or allied fields, including One Health proponents and workers, are not necessarily accustomed to cross-disciplinary integration. Few are simultaneously familiar with concepts and disciplinary jargons spanning human and veterinary medicine, environmental science, and ecology, let alone the social sciences. Yet, One Health, as a transdisciplinary, ecological and systems thinking endeavor (4, 7–9), additionally requires a working understanding of these concepts and associated methods. While notable progress recently has been made in this regard (4, 10–12), realizing One Health's full potential through its wider adoption, demonstration of its efficacy, and continual improvement demands explicit criteria and associated evaluation metrics (9, 13, 14).

Social-Ecological Systems Theory with its unique conception of resilience (SESR) as a complex adaptive system property, provides a framework that currently best meets this need for operationalizing One Health. Originally developed on the basis of studies of ecosystem dynamics, SESR has grown into a robust integrative, transdisciplinary approach that uniquely combines natural and social sciences perspectives. As a central postulate and heuristic tool SESR's adaptive cycle has proven widely applicable for understanding adaptation and sustainability across many types of systems (15). The fact that it is based on principles emerging from studies of ecosystem functioning applied to environmental management, including pest control, and sustainable resources management and development, makes it particularly applicable to One Health's focus on problems at the human-animal-environment interface, especially emerging zoonoses (16, 17).

In this paper, we review the key elements of SESR applicable to One Health and elaborate on recently developed explicit operational criteria including a protocol for One Health projects. We then illustrate with two examples where this has provided new insights into two high profile One Health problem areas related to the now endemic avian influenza (H5N1) and long endemic liver fluke (*Opisthorchis* spp.) transmission in the Greater Mekong Sub-region (GMS). Finally, we consider how these insights and the transdisciplinary frame offered by SESR render these and One Health challenges in general operationally inseparable from the region's sustainable development. These insights suggest how biomedicine, public health and ecology, while often in conflict, actually represent complementary perspectives and synergistic opportunities. Finally, we show how this approach could contribute to the achievement of many of the SDGs.

SOCIAL-ECOLOGICAL SYSTEM AND RESILIENCE THEORY

In a previous paper (18), we traced the history of how the cross-fertilization of ideas associated with ecology, health and sustainability led to the present interest in their linkages. The highlights of this scholarly and practical evolution include the development of SESR. Its application, the core elements of which are the novel conceptions, "resilience" and "adaptive management," emerged from a re-conceptualization of ecosystems (conventionally defined as distinct from human systems) viewed as coupled human-natural systems as described in a series of landmark books (19–23).

"'Resilience," as represented in this body of work, is understood as an emergent property of these systems (i.e., managed forests, fisheries, rangelands, and natural ecosystems) (21–26), described as "complex adaptive systems" (CAS) (24, 25). This is distinct from the linear, equilibrium view of all living systems that remains relatively dominant in science. By contrast, CAS are far-from-equilibrium systems that exhibit non-linear dynamics and emergent properties (e.g., disease emergence). They are predictably unpredictable, despite human intentions. Moreover, our intervention programs become part of the system, a factor in its dynamics that further adds to their complexity and potential unpredictability. As human—animal—environment CAS are always changing (always have and always will), they are effectively moving targets from a management standpoint (26).

Along with the adaptive cycle as metaphor of these system's dynamics, the complex systems-based conception of resilience arguably provided the linchpin, which explains the science underlying sustainable development (27). This tying together of humans and nature, and subsequently the economics and ecology of biodiversity (28), represented critical break-throughs in our understanding of ecosystems as coupled human-natural systems and their transformations based on a synthesis of social and ecological system change theories (22). The term social-ecological systems subsequently was adopted as this body of theories and concepts serving as an integrative framework (23).

SESR represents a revolution of practical insights about how coupled human-natural systems learn, thus adapt to continuously changing internal and external conditions, based on extensive quantitative and qualitative model development and testing with real world cases (29). This includes models of knowledge-system integration, counting the critical roles of visioning and scenario building, leadership, agents and actors, social networks, and institutional change, all of which underlie adaptive capacity. SESR's applicability to zoonotic disease emergence was first pointed out over a decade ago (16, 17).

A social-ecological system can be envisioned as shown in **Figure 1**. The more commonly held conception of the human-nature relationship, at least previously in the environmental and ecological sciences, is that of humans impacting nature or vice versa, but generally not an ongoing co-adaptive (or maladaptive on the part of society) dynamic. SESR views the ecological and social subsystems as reciprocally linked by numerous interacting components as indicated by the two large arrows. For example, parasites and pathogens are an integral though largely invisible component of social-ecological systems and their dynamics, which nearly everywhere on the planet are undergoing dramatic, human-induced changes. How these alterations—most visible in terms of landscape change (e.g., deforestation, construction of dams and irrigation infrastructure, and cropland, and pastureland expansion) and less visibly through pesticides and other chemicals—affect parasite and pathogen diversity, abundance, and dynamics has been the subject of extensive research in, for example, the relatively new field of disease ecology (31).

The arrow in **Figure 1** pointing from the social sub-system to the ecological sub-system represents this influence of human-related activities on natural systems. This arrow also represents the policy and management responses to the unintended "side-effects" of development, thus completing one feedback cycle. Such interventions typically are top-down and aimed at the control of ecosystem elements (e.g., vectors or parasites). While proving beneficial in the short-term they erode resilience in the long term. As widely documented in environmental and natural resources fields, such control attempts, including of pest populations, often result in a social-ecological system "pathology" (21, 22, 26). This involves a loss of resilience and sustainability with unintended consequences, which can include a return of the problem an agency originally sought to solve. Given its validation on the basis of extensive research and real world application, including continual refinement of understanding how to avoid these pathologies (15), SESR warrants serious consideration as the primary framing system for operationalizing One Health.

THE ONE HEALTH FRAMING PROBLEM AND SESR

It is widely accepted that One Health requires systems thinking (4, 32), and specific One Health issues often are best addressed "on the ground" employing ecosystem approaches (1, 33). As alluded to above, SESR developed as an elaboration of thinking that originated with research on natural ecosystem behavior (34). The idea of adaptive management evolved from initial attempts to apply this thinking in the context of environmental assessment (19) and subsequently to natural resources management problems (20)—spanning issues such as the failed forest and crop pest control efforts and collapse of "scientifically managed" fisheries. Adaptive management became a core principle (and procedural component) of Ecosystem Management now widely adopted by natural resource management agencies worldwide. SESR subsequently emerged from the same school of thought, though Ecosystem Management can be seen as a special application (35). Thus, Ecosystem Management is SESR applied to areas of publicly and associated privately held lands with mapped legal and associated ecological boundaries (e.g., national parks and protected area complexes, eco-regions, or river basins).

The idea of the human-animal-environment nexus of One Health implies a similarly describable spatial context, whether a geographic or geopolitical region, and/or a place. Ideally, a target or "study" area's boundaries can be at least approximately delineated corresponding to an ecologically functional whole such as a watershed, or river basin. Or, this could be a contiguous habitat area supporting a particular set of ecological processes and interacting species spanning protected area's or state's boundaries (e.g., Serengeti ecosystem).

SESR application may not require a similar focus or depth of analysis of natural resources as typically conducted in Ecosystem Management. Instead, particularly in the context of zoonotic diseases it stresses coupled human-natural system's hierarchical organization (more accurately the embedded structure) and importance of considering cross-scale interactions in planning and management. This should include identification of key social (institutional), as well as relevant natural system components (e.g., vectors and their habitats), ecological interactions, and possible outcomes (e.g., the response of host-pathogen-environment complexes to interventions and vice versa).

While this of course requires the assemblage of appropriate kinds of disciplinary expertise (vector and host reservoir ecology in the above example), in our experience this is not a limiting factor in the uptake by One Health of SESR, and especially its intellectually challenging conception of resilience. Rather, the main difficulty seems to be that transdisciplinary research and integrative, holistic thinking challenge the conventional reductionist thinking and practice to which most of us are accustomed. Biomedical academic training and practice in clinical, laboratory, and even farm settings, tends to engrain a linear, reductionist way of thinking. This even holds for fieldwork including epidemiological studies and trials, which are purposely designed to "control" for real world complexity.

This default frame is often more than adequate, even powerful, including providing elegant mathematical explanations and associated interventions for infectious disease dynamics (e.g., the eradication of small pox and rinderpest and control of numerous infections that had previously plagued humans and livestock). However, the present global emerging zoonotic disease crisis demonstrates the reductionist biomedical frame is inadequate by itself for understanding and managing problems of host-pathogen-environment complexes (16, 36, 37).

THE ADAPTIVE CYCLE AND RESILIENCE

SESR's adaptive cycle metaphor (**Figure 2**) is central to understanding and navigating social-ecological systems as CAS's (24). The adaptive cycle explicates resilience and vice versa, while is also arguably key to understanding notions of health and

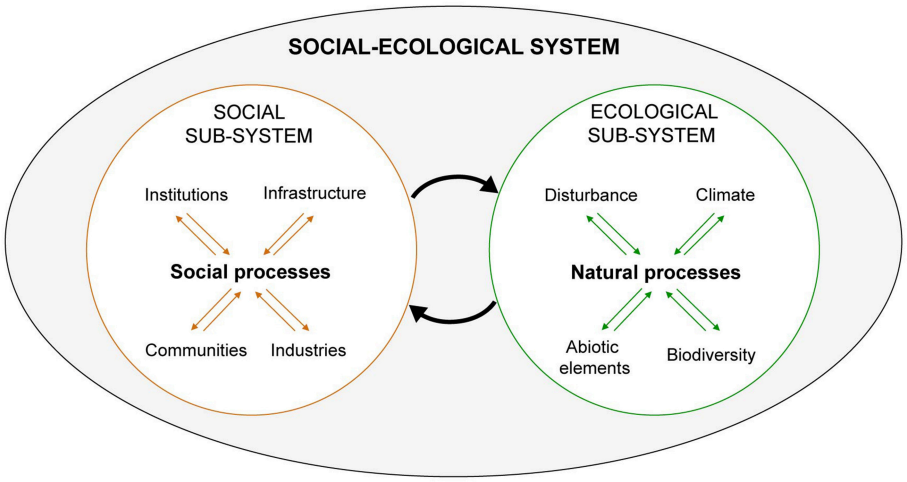

FIGURE 1 | Graphical representation of a social-ecological system. The large oval represents an entire social-ecological system including its component social and ecological subsystems. The two large arrows in the middle represent interactions between them. For example, the arrow targeting the ecological sub-system represents human influences on nature. These are the outcome of processes influenced and/or driven by citizens, commercial interests, institutions (rules, regulations, customs), and the human-built infrastructure. They impact the ecological sub-system in numerous and often invisible ways mediated through ecosystem processes and functions, as a result of myriad abiotic and biotic interactions. The arrow targeting the social sub-system represents the outcome of all these factors. Adapted from Chapin et al. (30).

sustainability in One Health. Although SESR originated with the study of natural ecosystems, viewing humans as outside agents, it was born from the realization that humans—acting as controllers of the natural system—can be thought of as both part of the system, and the problem (25). Even in the absence of human interference, ecosystems exhibit natural rhythms of change, the amplitude and frequency of which are determined by internal processes (e.g., ecological processes such as interspecific interactions) in response to past events. The discovery that these rhythms alternate periods of increasing organization and stasis with periods of reorganization and renewal was a significant break-through in the field of systems ecology, hence determining ecosystem productivity and resilience across scales (34).

The adaptive cycle (**Figure 2A**) is a metaphorical representation of the temporal and spatial patterning of these rhythms, which originated as a means of describing how conventional environmental management efforts involving ecosystems often fail over the long term (22). The adaptive cycles' four distinct stages are: (i) growth or exploitation *r*, (ii) conservation (*K*), (iii) collapse or release (Ω), and (iv) reorganization (α). It exhibits two major phases (or transitions). The first (fore loop), from *r* to *K*, is the slow, incremental phase of growth and accumulation. The second (the back loop) from Ω to α, is the rapid phase of reorganization leading to the system's renewal, or possibly a "flip" to a new stability domain. This also is referred to as a regime shift, which generally means a tipping point or threshold has been reached following which a social-ecological system "collapses" (38, 39).

These collapses can be triggered by politics, invasions, market shifts, or global climate change external to a system whose resilience at a particular scale has contracted due to states and dynamics at scales above and below (38). These collapses, described as panarchy (**Figure 2C**), were first discovered in studies of rangeland management systems. The adaptive cycle metaphor, including regime shift can be applied to relatively abrupt, irreversible agro-ecosystem transitions impacting livelihoods and human well-being (39). The adaptive cycle or the notion of social-ecological system pathologies in reference to landscape transitions has not yet been considered in the One Health literature to our knowledge. However, the applicability to One Health challenges is apparent as we describe here, using as an example the dramatic agro-ecosystem transformation underway in the Greater Mekong Sub-region (GMS). This mainly involves the widespread industrial intensification of agricultural production and food supply chain, with considerable but as yet not systematically investigated emerging zoonotic disease risks (40). This transformation, involving changing land use and land cover, increased chemical inputs including pesticides and anti-microbials, represents attempts to control a range of key variables including increased food and reduced pests and pathogen.

The initial phase of the adaptive cycle is driven by the "quest for increased economic growth." This is the *Exploitation* phase during which the initial successes in each of these elements in terms of increased economic output reinforce the belief in the intensification approaches. Thus, increased investment and improvement (administrative, operational, organizational, technical, etc.), grows. The success breeds confidence and continues even when effectiveness of, for example, pesticides and antimicrobials begins to wane due to emergence of resistant strains.

The *Conservation* phase is illustrated here by the tendency to "double down" on the ongoing approach even as it becomes less

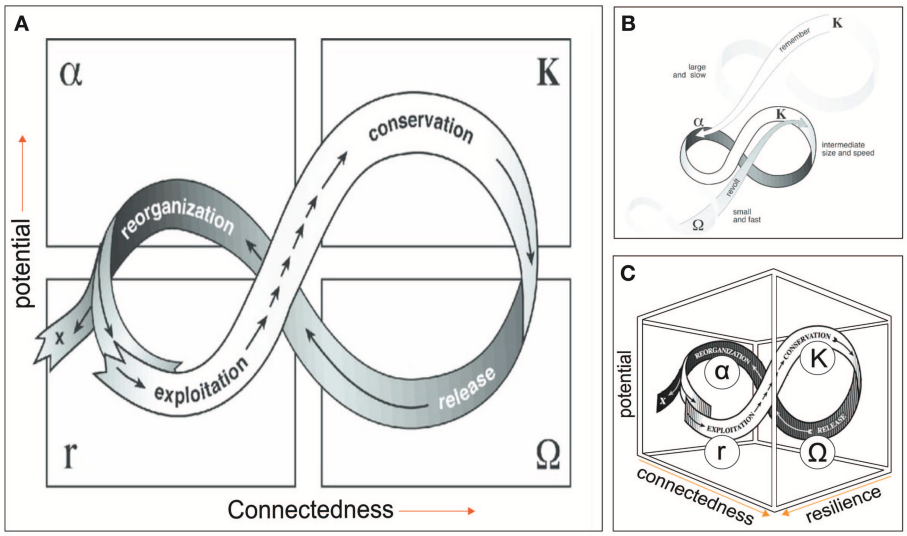

FIGURE 2 | (A) Adaptive cycle. **(B)** Panarchy. Cross-scale linkages among adaptive cycles in a social-ecological system, in which successively smaller, faster cycles are embedded in larger, slower ones. **(C)** Three dimensional representation of the adaptive cycle. ***Potential*** represents resources in the form of stored capital available to effect change, which may include knowledge and financial, social, and natural capital; ***Connectedness*** refers to the flexibility or rigidity of controlling variables or processes in response to external variation; ***Resilience*** is the capacity of the system to absorb or withstand perturbations and other stressors such that it maintains its structure and functions [i.e., does not undergo regime change. Adapted from Gunderson and Holling (22)].

effective, due to the system having become entrenched both in its thinking and mode of operation—reflecting a loss of flexibility, over-connectedness, and resulting fragility.

During the *Release* phase, a crisis stage is reached—i.e., the system clearly becomes unprofitable, as events such as major disease outbreaks, become increasingly costly for the controlling institutions. Prompted by revolutionaries within or outside of them pushing for change, the system enters the creative destruction phase. Assuming the system resilience remains sufficient, that is, sufficient adaptive capacity remains, and the system has not collapsed to a different state, irrevocably, the opportunity to reconfigure may exist. Thus, the system enters the reorganization phase and, hopefully, the result leads to desirable outcome.

A regional agroecosystem consists of many agroecosystem subtypes on the landscape scale, for instance, spanning small-scale traditional and small-holder systems to intensive large scale corporate industrialized systems. It can be envisioned how each has its own adaptive cycle whose dynamics operate on different time and space scales, including smaller, faster cycles being embedded in larger, slower ones (**Figure 2B**). The larger, slower cycles can constrain smaller, faster cycles, which the latter can disrupt and even cause a regime shift in which the social-ecological system is fundamentally altered.

As seen in the three-dimensional graph of the adaptive cycle (**Figure 2C**), resilience represents a third dimension that expands and shrinks through the cycle as slow variables change. It shrinks as the cycle moves toward K, and the system becomes more fragile, and expands abruptly when a cycle shifts into a "back loop" to reorganize for the initiation of a new cycle. "X" represents a regime shift whereby the system "collapses," becoming a new system, functionally and structurally. The back loop, Ω phase, is a period in which novelty and experimentation is needed and possible, given a decline in connectedness (e.g., as institutional rigidity or inflexibility diminish) and increase in resilience. It constitutes an opportunity for "revolt," a cross-scale phenomenon precipitated by fast, small variables.

As recently pointed out (15), a resilient system may successfully navigate itself through each of the phases and into new regime that satisfies societal goals. In general, however, successful navigation (an indication of resilience) suggests the capacity to recognize barriers, critical thresholds and principles associated with this front loop that can trap a system—resulting in a pathology. System features, allowing escape from these traps, have been provisionally described (15)—representing adaptive management.

CASE EXAMPLES FROM THE GREATER MEKONG SUBREGION

This paper offers two case studies on One Health efforts employing SESR based on our work in the Greater Mekong Subregion (GMS) (**Figure 3**). The first is related to food production intensification found to represent a substantial range of health threats realized most dramatically with the emergence of the H5N1 strain of highly pathogenic avian influenza (HPAI) (40). An interdisciplinary research effort supported by the US National Science Foundation Coupled-Human Natural Systems Program sought to apply an SESR frame to better understand the causes of HPAI emergence (41).

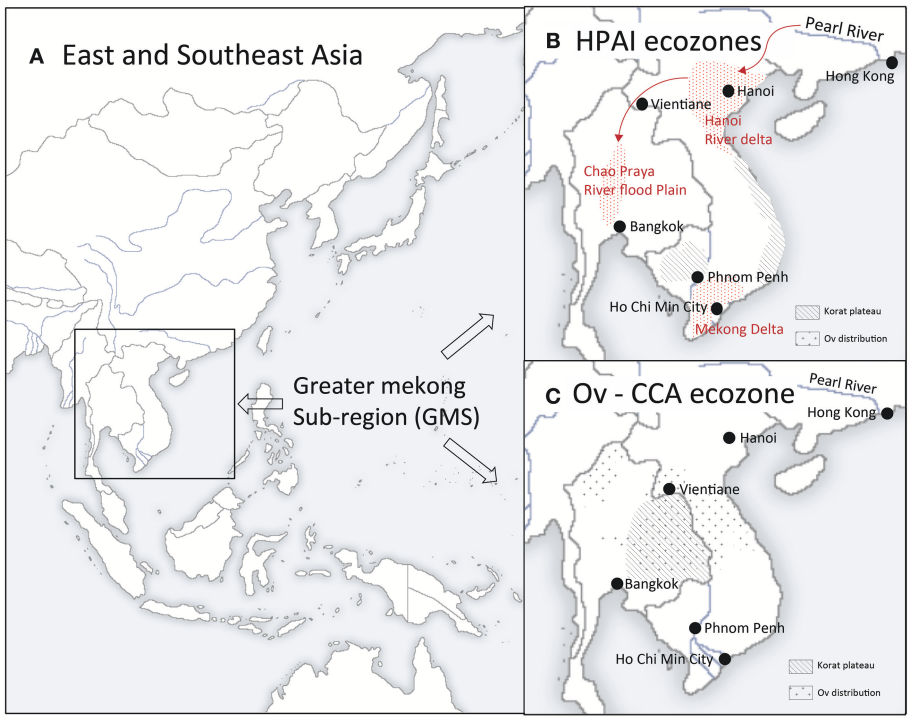

FIGURE 3 | Greater Mekong Subregion and ecozones of the case examples. **(A)** East and Southeast Asia. The Greater Mekong Subregion includes six nations (Cambodia, China, Laos, Myanmar, Thailand, and Vietnam) whose national boundaires overlap the hydrographic boundaries of the Mekong River Basin. **(B)** HPAI ecozones. Red stippled areas indicate the distribution of Highly Pathogen Avian Influenza (H5N1) cases during the 2003-4 emergence/pandemic. These three perennial flood zones of Thailand (Chao Praya River flood plain) and Vietnam (Red River and Mekong Deltas) are centers of concentration of domestic poultry production as well of wild water birds including the primary natural host reservoirs for avian influenza viruses, dabbling ducks. Chickens and domesticated duck production, trade networks, and wet markets grew explosively beginning in the 1980's in response to increased export market demand. This represented a social-ecological system transformation and ultimately a regime shift from once the first H5N1 virus variant invaded Vietnam's Red River Delta from the Pearl River Basin or elsewhere in China. The Red River Delta may have provide the key stepping stone to southern Vietnam's Mekong Delta and Thailand's Chao Prya River Basin. Following these first epidemic waves outbreaks were brought under control in the Chao Prya, but not in Vietnam where HPAI outbreaks continue to occur. **(C)** Liver fluke-Liver Cancer ecozones. *Opisthorchis viverrini* infection in humans is wide-spread throughout its geographic distribution. Yet its epidemiological characteristics in the Korat Plateau are distinct, reflecting its unique culture and environment. The Plateau historically had been sparsely populated (by human's and likely the liver fluke as well) but grew exponentially since WWII while dams and irrigation systems transformed the Plateau's social-ecology including expanding favorable aquatic habitat for *Bythnia* snails, *O. viverrini*'s first intermediate host. The Plateau's population (~ 25 million people today) of predominantly Lao dialect-speaking, a rice-fish culture for the second intermediate host, is a staple food. As is observed when they relocate today within Thailand, along with this food cultural practice, they would have carried the fluke with them from their area of origin in Southern China as they migrated southward during the last millenium.

The principal findings of this effort (42) are summarized as follows. The initial outbreak in Hong Kong, when H5N1 was first isolated, was optimistical but mistakenly thought to have been successfully eliminated by massive poultry culling in 1998 (43). However, experts and government authorities either ignored or otherwise were oblivious to the change (large, slow variable in SESR parlance) taking place regionally. This consisted of growth of industrial scale poultry operations in Guangdong, China, and particularly the transformation of the poultry production landscape taking place in geographically adjacent Vietnam. This included dramatic changes in breed composition and flock size, and the expansion of this intensification across Vietnam (linking the north with the south of the country), as well as into Cambodia, Laos, and Thailand via the Mekong corridor in the south (**Figure 3B**).

These changes were pushed by global forces, driven by the economic opportunity presented by the growing export market. This historically unprecedented production intensification was not accompanied by similarly intensified biosecurity measures. The operations in China, which included breeding facilities with up to a million birds, constituted a crucible of genetic innovation (a small, fast variable). Among the untold new microbial variants generated, H5N1 variants sporadically and unpredictably spilled south over the China-Vietnam border via local trade networks and migrating ducks (another small, fast variable).

This might have been of limited consequence, as it was geographically speaking with the Hong Kong outbreak, where this agro-ecosystem's insularity helped prevent H5N1's escape to the south and ultimately globally. But it was the ongoing transformation, which is retrospectively even observable via satellite and on the ground (41, 42). This represented "an accident waiting to happen," which did as evidenced by the explosive epidemic waves of 2003-4 initiated in Vietnam with H5N1 spreading to 60 countries. This fits the classic case of

"surprise" in SESR jargon defined as a cognitive disagreement with expectations based on the responsible social institution's failure to recognize signs indicating the system's increasing fragility (22).

HPAI is now endemic throughout the Mekong Region (as well as in parts of insular Southeast Asia and Egypt), as part of a new social-ecological regime. This new regime effectively represents a regional agro-ecosystem distinct from that previously, structurally and functionally, including a number of less desirable social, economic, political, environmental, conservation and public health features. This includes most prominently a far less diversified poultry production sector now dominated by large agribusinesses, increased dependence on agrichemicals, drugs, and vaccines. In addition, outbreaks threatening wildlife including in protected areas have been recurring (Dr. Paisin Lekchareon, personal comm). Transboundary movements involving product supply chains for multi-country operations may play an important role in AI virus transmission ecology along with human movement.

The emergence of HPAI (H1N1) demonstrates SESR's value applied as a retrospective method of analysis in the elucidation of the previously unexplained details of its pandemic emergence. It also offers numerous insights related to the HPAI and newly emerging avian influenza strains in the GMS as a One Health problem area that is intertwined with the multitude of issues related to the intersection of environment, conservation, development, and public health—thus, inevitably sustainable development. It remains to be seen whether the integrative perspective and problem-solving approach SESR offers will be considered by regional and/or national bodies in the GMS.

Our second case example has prompted actions among GMS countries toward implementing changes in interventions based on SESR. In this case, we (BW and PE) were recruited to assist with applying an ecosystem approach to the problem of Liver Fluke (*Opisthorchis viverrini*) infection as a putative cause of the relatively high incidence of liver cancer (cholangiocarcinoma) in Northeastern Thailand, "Isaan" encompassing the Korat Plateau of the Lower Mekong basin (**Figure 3C**). This work included designing and conducting research aimed at filling gaps in understanding environmental and ecological aspects of the parasite's transmission. More generally this resulted in broadening the understanding of the social and ecological dimensions of liver fluke transmission and its role in disease (44, 45).

In addition to resulting in a rethinking of the Ov-CCA problem (46–50), this effort drew attention to a deficiency in the larger program with which this research was affiliated: the absence of explicit criteria and procedures for applying "ecosystem approach to health" (51). Among the outcomes prompted by this is the recognition of complex systems thinking including transdisciplinary methods required by the ecosystem approach (52).

Despite a diversity of perspectives on the Ov-CCA problem—held by stakeholders with very different perceptions, values, objectives and even social standing (e.g., university professors, public health practitioners, social anthropologists, government representatives and villagers)—a biomedical research frame (consistent with the biomedical model) as the basis of the design of public health interventions had been accepted by default to the exclusion of any others. This included that held by "risk groups" themselves, mainly villagers and farmers, who do not perceive eating fermented fish as a particularly high-risk behavior. Rather, they view it not only as normal behavior, but as an integral part of their daily life. The beliefs and practices related to preparing, sharing and eating fermented fish dishes, along with rice cultivation and consumption are inseparable from their cultural identity, their local natural capital, and social capital as evidenced by fish dish sharing networks in villages (49). An exclusively biomedical model-driven research and intervention agenda prevailed for decades despite evidence of its limited capacity to effect a decrease in infection prevalence or CCA incidence. Added to this is this agenda's potential dangers with regard to other health and well-being dimensions that are inadvertently affected by targeted liver fluke-CCA interventions (45, 47).

In fact, evidence from existing data or studies, as well as that from new results from the recently added social and ecological components, suggests villagers perceptions, or the "lay model," is apparently no less valid than the biomedical model. At least four different models of *Ov* and health connection are recognizable (47), none of which, including the biomedical model, are completely wrong, but just incomplete. In the final analysis it can be seen how the *Ov*-CAA problem is a "moving target" and the targeted attempt to control, top down, a social-ecological variable, prevalence of infection through consumption of traditional fish dishes, represents a "disease control pathology" in the classical SESR sense (16). The Isaan-Lao cultural and natural ecology (livelihoods, environmental exposures, and human and land health profiles, i.e., social-ecological system) of the Korat Plateau effectively have been undergoing a regime shift. The multitude of interacting factors likely responsible for the region's relatively high CCA incidence as recently demonstrated (46), almost certainly also have been shifting as well. The appreciation of this offered by SESR has stimulated the beginning of a "revolt" akin to the panarchy (**Figure 2B**).

TRANSDISCIPLINARY PROCESS FOR BUILDING ADAPTIVE CAPACITY

Perhaps the most important lesson learned from these case examples is how defaulting on one perspective, or model, resulted in an only partial understanding of the problem—thus only partial or temporary solutions. This invokes transdisciplinarity in which a ongoing process of "problem orientation"—that is, sharing of different understandings, reflecting and even negotiating around a definition of "the problem"—is requisite from the very beginning. As illustrated in **Figure 4A**, this drives, at least initially, integration, and ultimately adaptation, although as a transdisciplinary process develops each feeds back on the others. **Figure 4B** decomposes this simplified description of these three interrelated processes into a suggested stepwise protocol, based on an analysis of criteria along a continuum of increasing

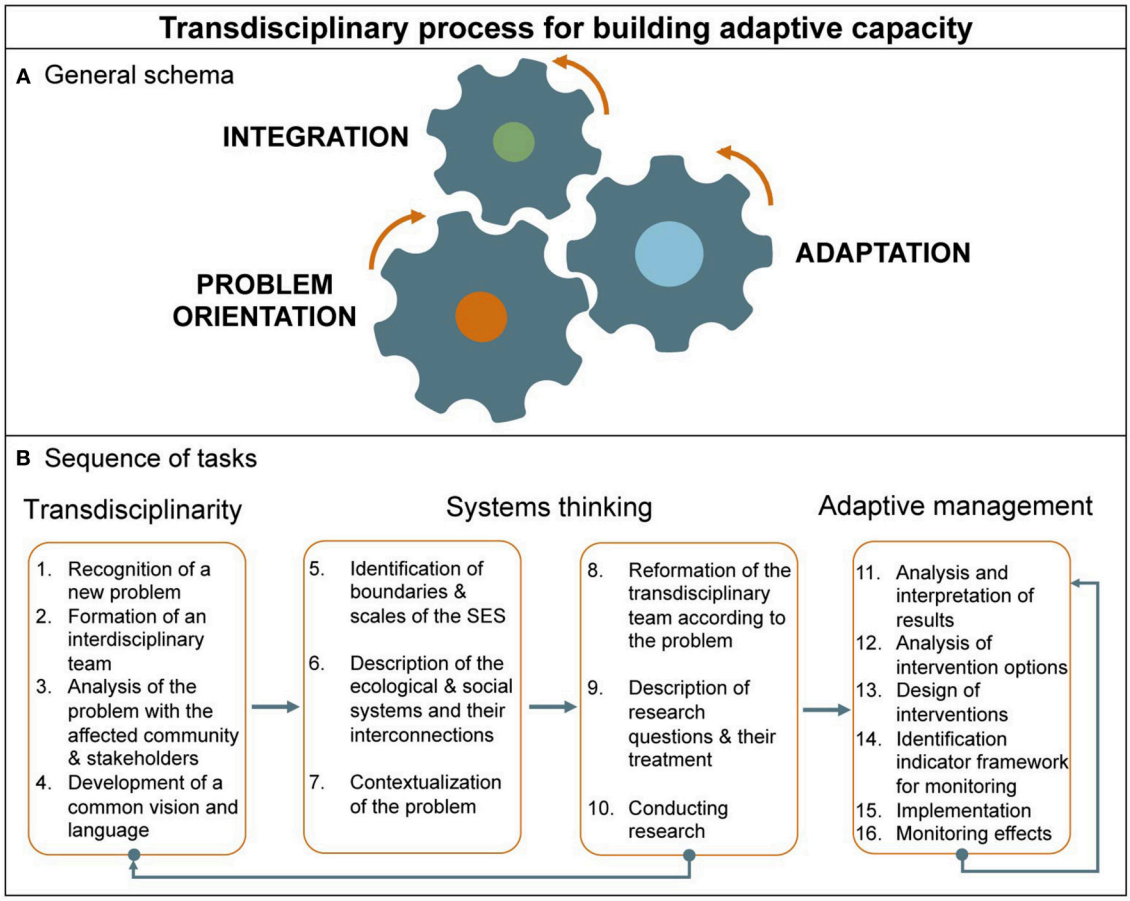

FIGURE 4 | Transdisciplinary process for building adaptive capacity. **(A)** Transdisciplinarity can be envisioned as a process involving three mutually reinforcing, and overlapping activities: problem orientation, integration and adaptation (as defined in the text). **(B)** This process can be further broken down into a sequence of specific actions representing a protocol against progress including conformance to One Health as a transdisciplinary, ecosystem approach could be measured, when combined with the criteria described in **Table 1** [adapted from Richter et al. (53)].

TABLE 1 | Dimension of resilience containing sequential criteria of progressing comprehensiveness.

Resilience	Weakest	Weak	Intermediate	Strong	Strongest
Transdisciplinarity	Integration	Composition	Differentiation	Collaboration	Value creation
Community participation	Representation	Involvement	Partnership	Empowerment	Autonomy
System thinking	Scoping	System description	Problem analysis	Mitigation	Adaptiveness

Resilience at multi-stakeholder group level is expected to be strongest when common values and understandings, as well as aims, are emerging from iterative negotiations. Adding onto that, when community stakeholders are intended beneficiaries, community members need to be co-designers at the onset of a research and development project while being provided with the tools and forums for inclusion and expression. A strengthening element leading to innovation and adaptive capacity is system thinking and the capacity to identify relevant entities and influences accoss scales. Adapted from (53).

comprehensiveness (from weak to strong transdisciplinarity, (54) and increasing resilience as further described in **Table 1**.

The transdisciplinary system's purpose is the cooperative generation of knowledge to solve, mitigate, or prevent a complex societal problem—such as involving diseases and environmental degradation—as distinct from academically defined problems solvable though conventional disciplinary research. In "real life," academics and social actors often disagree on problem's causes, consequences, and problem-solving strategies. Transdisciplinarity involves grasping complexity, accounting for the diversity of perceptions, linking abstract and case-specific knowledge, and development of knowledge and practices for the common good. The manner and the extent to which different parts of "a whole" interact need to be agreed upon and reevaluated throughout as a means of encompassing the problem. In this regard, it is useful to designate a phase devoted

to the task of drawing on systems thinking (4). Typically, this involves identifying (literally drawing a schemata, mental maps, or actual geographic maps) the system's boundaries and the social and ecological components and their interconnections.

The adaptive cycle metaphor not only describes social-ecological system pathologies and how they lead to management failures, but also successes, employing adaptive management, described by cyclic phases consisting of learning, describing, predicting, and doing [**Figure 2**; (55)]. These tasks are a prerequisite for a program of adaptive management that includes consideration of intervention options accounting for feasibility, development of a system of metrics for monitoring interventions' impacts, reconsideration and redesign of interventions, evaluation, and so on, as a cycle (**Figure 4B**).

As has been cogently explained by its originators (21), adaptive management is an inductive approach, relying on comparative studies, ecological theories and observations, and the design of planned interventions in nature with an understanding of how, in turn, humans are likely to respond. Its aim is to identify uncertainties, test hypotheses about them, thereby employing interventions (management) as a tool to change the system. In the process, it is learned how to match the human and natural dynamics across scales, thus insure greater resilience: That is, the "enhanced capacity to deal with change and surprise, including avoiding shifts to undesirable stability domains, while providing flexibility and opportunity in a rapidly changing and human dominated planet" (22).

Finally, a major challenge for One Health, only briefly touched on above, but also apparent from SESR, is the role of the political economy, as well as systems ecology. One Health approaches arguably should include consideration, if not investigation, of the links between "macro-structural" contexts affecting local agro-ecosystem/agro-economic circumstances. For example, this includes those ultimately responsible for the evolution and emergence of highly pathogenic avian influenza H5N1 (56), which became and remains an ongoing human-domestic animal-wildlife problem globally. This is consistent with ecosystem thinking and SESR in particular, which points to the importance of considering social-ecological systems' hierarchical organization and associated cross-scale institutional, as well as ecological dynamics involved in zoonotic disease emergence (57). Ultimately "adaptive health governance," involving coordination among disciplinary, sectorial and public domains, is required (58).

ONE HEALTH: INFORMING THE IMPLEMENTATION OF THE UN SUSTAINABLE DEVELOPMENT GOALS

The lessons from the past several decades since the idea of sustainable development was introduced together with more recent science-based global policy frameworks, such as the Millennium Development Goals (MDG), suggest the need for a more in-depth understanding of human-nature systems, as offered by SESR. Shortcomings of the Millennium Ecosystem Assessment, a key component underlying the MDG strategy, reflected a failure to account for how both ecosystems and health systems are complex adaptive systems (18, 59). One Health's transdisciplinary, ecosystem approach imperative, along with SESR's operational relevance to sustainable development, presents a current and unique opportunity for bridging science-policy gaps. This would allow an improved synergy between practitioners, and environmental-health policies.

The health-sustainable development linkage has a strained policy history. Health was addressed only very obliquely by the World Commission on Environment and Development (WCED) in the lead up to the historic 1992 UN Earth Summit in Rio de Janeiro, Brazil. In the historic and widely read report titled "Our Common Future," also known as the Brundtland Report, WCED codified and was the first to explicitly define sustainable development. This framed the 1992 Rio Earth Summit and its key outcomes, international treaties on climate, biodiversity and desertification, as well as non-binding Agenda 21, which was dominated by environmental and conservation perspectives of health. For example, the "control of communicable diseases" was mentioned without further elaboration (60). The World Health Organization (WHO), the UN's chief health agency, was largely left out of the policy formulations.

In the years following, WHO's administrators, being keenly aware of having played "back seat" role at best, developed a number of programs aimed at remedying this by focusing on environmental health. Yet, many countries did not officially affirm the linkages between public health and the health of the environment (60). This changed somewhat at the 2002 Summit on Sustainable Development and more recently with the UN Sustainable Development Goals (SDGs), although major gaps remained. This slow progress in recognizing the synergies between health and the environment continues to be a reflection of the epistemological gaps separating the health sciences from the fields of environmental science, economics, and international development.

The SDGs, seen as a response to the limitations of the Millennium Development Goals (MDGs), are an opportunity to further integrate health, environment and development. Several UN agencies have noted the need and opportunity the promulgation of SDGs offers to One Health, from the standpoint of the synergistic possibilities among sectors. Although only three of the SDGs explicitly mention health, most (if not all 17) indirectly can be linked to the "principles" supporting the One Health approach and having a direct or indirect impact on the main cornerstones of sustainable development as they relate to zoonotic and vector-borne diseases and extend to salutary factors (**Table 2**). The authors point out the SGDs' requirement of an integrated response is similar to what recent programs addressing neglected tropical diseases (NTDs) have defined (61). The vast majority of NTDs are zoonoses. Thus, their assessment is applicable to the One Health tenets.

TABLE 2 | United Nations Sustainable Development Goals (SGDs) from a One Health Perspective as they relate to zoonotic and vectorborne diseases.

SDG	Brief description	Application to one health example
1	End poverty in all its forms everywhere	Addressing challenges at the interface of human, animal and ecosystem health are inextricably and reciprocally linked to poverty. Zoonotic infections exacerbate poverty and vice versa.
2	End hunger, achieve food security, improve nutrition and promote sustainable agriculture	Chronic parasitic infections often exacerbate caloric and nutritional deficits in people and animals, not only affecting the productivity of infected farmers but livestock production as well.
3	Ensure healthy lives and promote well-being for all	One health interventions are particularly relevant in terms of reaching people with limited access to health systems in rural areas, as well as other development-related goals addressed by Agenda 2030.
4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	Zoonotic diseases can stigmatize affected students, reduce attendance and school performance. Also, school based health education programs including targeting control of specific diseases (e.g., arbovirus vector community-based control) can be highly effective.
5	Achieve gender equality and empower all women and girls	Women are disproportionately affected by poverty, illiteracy, lack of education, land ownership and political voice, and access to health care. They also have greater exposure to a number of diseases through their domestic and other work roles.
6	Ensure access to water and sanitation for all	Water, sanitation, and hygiene activities associated with prevention and control of zoonoses require integration with a range of cross-sectoral activities aimed at interrupting transmission cycles of many zoonotic and vector borne diseases.
7	Ensure access to affordable, reliable, sustainable and modern energy for all	Construction of hydroelectric dams often alter local ecological conditions favoring vectors, while vector control and organic waste management as a sanitary measure via biogas systems for example align with sustainable energy development.
8	Promote inclusive and sustainable economic growth, employment and decent work for all	Zoonotic infections represent a large burden to health care systems and negatively impact economic productivity, which can be significantly mitigated by zoonotic disease prevention and control.
9	Build resilient infrastructure, promote sustainable industrialization, and foster innovation	Interventions targeting neglected populations require development of transport and storage infrastructure as well as clinics for the provision of health services including distribution of donated medicines.
10	Reduce inequality within and among countries	Interventions targeting the most disadvantaged and marginalized populations whose disease prevalence typically is highest will contribute to reducing socio-economic disparity.
11	Make cities inclusive, safe, resilient, and sustainable	Mosquito and other disease vectors adapted to urban habitats continue to proliferate with urbanization. Integrated, community based vector control interventions will make cities more livable and resilient.
12	Ensure sustainable consumption and production patterns	Waste management aimed at sustainable use, reuse, and recycling simultaneously can address control of nuisance or disease vector mosquitos and other threats including from pesticide exposures.
13	Take urgent action to combat climate change and its impacts	Though currently largely unpredictable, changes in temperature, rainfall and relative humidity associated with global environmental change affect the dynamics and spread of disease vector populations. One Health oriented research on these linkages will contribute to reducing these potential risks.
14	Conserve and sustainably use the oceans, seas and marine resources	Coastal populations throughout tropical developing regions, where Aedes mosquitoes are ubiquitous, are thus even vulnerable to the negative socioeconomic consequences of marine resource degradation, as impoverishment reduces prospects for vector control and avoiding more severe disease outcomes upon infection of high zoonotic disease prevalence. Thus improved sustainable management of marine ecosystems will positively impact zoonotic disease control.
15	Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss	Zoonotic disease emergence is known to be facilitated by deforestation, the disturbance and degradation of natural and semi-natural habitats, and in particular biodiversity loss. This includes that of natural ecosystems as well as agroecosystems (agrobiodiversity) including plants and animals cultivated and domesticated by farmers over millennia.
16	Promote just, peaceful and inclusive societies	Zoonotic disease epidemics frequently are associated with political and armed conflict. Interventions aimed at affected civilian populations at times and places can be a tool to promote peace.
17	Revitalize the global partnership for sustainable development	Integration of all the above requires new as well as the strengthening of existing partnerships among a wide breadth of interests spanning private and public organizations and agencies in the spirit of transdisciplinarity.

CONCLUSIONS

In order to operationalize One Health, there is a need for: a "proof of concept" incorporating environmental and ecosystem factors (13); integration and systems thinking (4, 12); standardized evaluation metrics (14); and a framework incorporating the broad social, as well as biological aspects.

Unprecedented human impacts and transformation of Earth's ecosystems have become the most pressing global threat to human health and well-being. Knowledge integration and working collaboration among scientists on the one hand and among multiple sectors, NGOs, local communities, and policy makers on the other is imperative. Thus, rethinking how we approach health in relation to our environment, drawing on a One Health approach understood as a transdisciplinary and ecosystem-based endeavor, particularly in light of new insights offered by SESR, is timely.

The United Nations 2030 Agenda for Sustainable Development, signed in 2015, is perhaps the most significant effort yet undertaken to address the above threat. The nations of our planet and their leaders have universally agreed to this new and more comprehensive development road map. This requires integration of markedly different perspectives, perceptions, values and normative conventions representative of the fields spanning the 17 goals. It is certain that all 17 SDGs can only effectively be implemented if public policies reflect a truly integrated global policy agenda. This can only be achieved through an understanding of health as seen through a transdisciplinary, ecosystem-oriented lens.

AUTHOR CONTRIBUTIONS

BW and PE developed the rationale and the overall orientation of the ideas. AAA, BW, ND, BS, and PE wrote the manuscript. All the authors read and approved the final manuscript.

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The One Health Concept: 10 Years Old and a Long Road Ahead

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Over the past decade, a significant increase in the circulation of infectious agents was observed. With the spread and emergence of epizootics, zoonoses, and epidemics, the risks of pandemics became more and more critical. Human and animal health has also been threatened by antimicrobial resistance, environmental pollution, and the development of multifactorial and chronic diseases. This highlighted the increasing globalization of health risks and the importance of the human–animal–ecosystem interface in the evolution and emergence of pathogens. A better knowledge of causes and consequences of certain human activities, lifestyles, and behaviors in ecosystems is crucial for a rigorous interpretation of disease dynamics and to drive public policies. As a global good, health security must be understood on a global scale and from a global and crosscutting perspective, integrating human health, animal health, plant health, ecosystems health, and biodiversity. In this study, we discuss how crucial it is to consider ecological, evolutionary, and environmental sciences in understanding the emergence and re-emergence of infectious diseases and in facing the challenges of antimicrobial resistance. We also discuss the application of the "One Health" concept to non-communicable chronic diseases linked to exposure to multiple stresses, including toxic stress, and new lifestyles. Finally, we draw up a list of barriers that need removing and the ambitions that we must nurture for the effective application of the "One Health" concept. We conclude that the success of this One Health concept now requires breaking down the interdisciplinary

barriers that still separate human and veterinary medicine from ecological, evolutionary, and environmental sciences. The development of integrative approaches should be promoted by linking the study of factors underlying stress responses to their consequences on ecosystem functioning and evolution. This knowledge is required for the development of novel control strategies inspired by environmental mechanisms leading to desired equilibrium and dynamics in healthy ecosystems and must provide in the near future a framework for more integrated operational initiatives.

Keywords: One health, EcoHealth, infectious disease, non-communicable disease, multifactorial disease, ecotoxicology, interdisciplinary research, public health

INTRODUCTION

Human population increase, industrialization, and geopolitical problems accelerate global changes causing significant damage to biodiversity, extensive deterioration of ecosystems, and considerable migratory movement of both mankind and species in general. These rapid environmental changes are linked to the emergence and re-emergence of infectious and non-infectious diseases (**Figure 1**). Over recent years, certain zoonoses, such as bird flu or the Ebola and Zika viral epidemics, have illustrated this fact to the whole world demonstrating the interdependence of human health, animal health, and ecosystem health. Coming from the "One Medicine" concept (1) that advocates a combination of human medicine and veterinary medicine in response to zoonoses (2), the "One World - One Health" concept[1] was created in 2004. The novelty was the incorporation of the ecosystem health, including that of wild fauna. The "One Health" initiative[2] therefore constitutes a global strategy highlighting the need for an approach that is holistic and transdisciplinary and incorporates multisector expertise in dealing with the health of mankind, animals, and ecosystems (3) (**Figure 2**).

[1]www.oneworldonehealth.org.

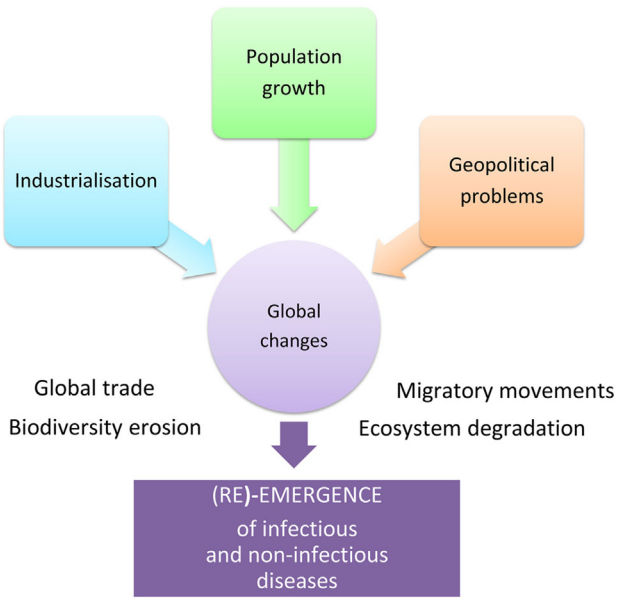

FIGURE 1 | Global changes favor the (re)-emergence of infectious and non-infectious diseases.

When one considers the multiple factors at play and the complexity of public health issues, it is clear that the "One Health" holistic approach (4) cannot be disassociated from the notion of ecological health (EcoHealth). The underlying premise is that the health and well-being of the human population will be more and more difficult to maintain on a polluted planet suffering from social or political instability and ever-diminishing resources. Supporting that view, the European ministers responsible for health and the environment as well as the World Health Organization (WHO) regional director for Europe met on June 15, 2017 in Ostrava, Czech Republic for the sixth ministerial conference on Environment and Health. They recognized that "environmental factors that could be avoided and/or eliminated cause 1.4 million deaths per year" in the WHO European Region. They declared that "public authority shares the common responsibility for safeguarding the global environment and for promoting and protecting human health for all environmental hazards across generation and in all policies." Paving the way for ambitious integrative initiatives in the One Heath framework, researchers in "Ecohealth" and its practitioners implement systemic and integrated practices to promote sustainable ecosystemic services linked to the concept of health (human, animal, and ecosystem) and to social stability. Thus, the One Health concept provides a way of looking at complex systems and approaching processes leading to undesirable effects such as disease emergence, etc. It thus encourages and promotes the interdependence, coexistence, and evolution of living beings and their environment, which is itself in a state of constant transformation (5).

However, after just over 10 years in existence, the "One Health" concept, which predicted the integration of the interface with ecosystems in the "One Medicine" concept, has not quite completed its transformation (6). The documents and publications on the "One Health" approach, and the strategic framework developed around it, have largely focused on the battle against emerging zoonoses originating in domestic (7) or wildlife (8) and/or their interactions (9), without really considering the role of inclusive ecosystems (10). Thus, a quick review of scientific investigations claiming to adhere to the "One Health" concept clearly reveals

[2]www.onehealthinitiative.com.

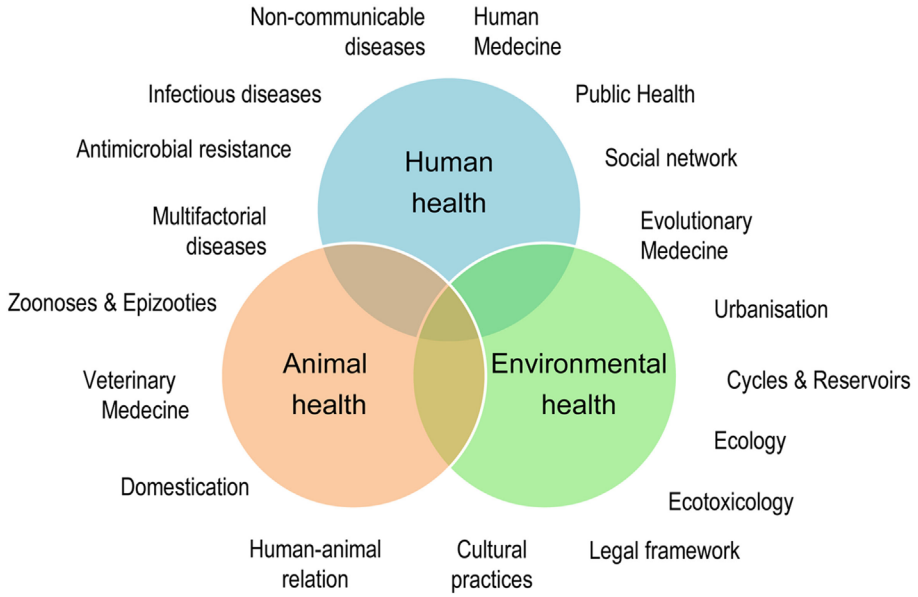

FIGURE 2 | The One Health concept: a holistic, transdisciplinary, and multisectoral approach of Health.

that they only mention the environment and its biotic and abiotic components as the scene of transmission, often reduced to global planetary changes or the Anthropocene. Very few studies deal effectively with the ecology of transmission and the ecology of health meaning developing an ecological and progressive epidemiology linked to components of biodiversity, ranging from physiological stresses on populations to changes in habitat, or linked to ecosystem processes (11, 12, 13).

One of the major challenges in the successful integration of the environment alongside human and animal health in the "One Health" triptych is the capability to define the state of health of our ecosystems. Ecology researchers face a growing demand from administrators for detailed, relevant information on the health and desired equilibrium or dynamics of multifunction ecosystems to guide decision-making on sustainable development, species conservation, and human, animal, and plant health (14). This calls for the definition of shared indicators for ecosystem health (biodiversity, ecosystem services, desired "equilibrium", and "evolutions" on relevant space–time scales, etc.).

When the "One Health" concept was conceived, initial collaboration between human medicine and veterinary medicine resulted in an inevitable research bias toward zoonotic diseases (15), temporarily ignoring the important question of chronic non-infectious diseases, which are the leading cause of global human mortality. Nowadays, the "One Health" concept hopes to extend to other fields, such as antimicrobial resistance, ecotoxicology, or health in urban environments.

In this review article, we discuss the need of incorporating ecological, evolutionary, and environmental sciences into One Health approaches for an innovative and effective control of both infectious and multifactorial non-communicable diseases. We next provide examples in which the integration of the ecosystemic component of the One Health concept enabled deciphering the processes underlying disease emergence and re-emergence. Finally, we discuss operational brakes that still limit the application of the concept, its ambitions, and future challenges.

INFECTIOUS DISEASES

Ecosystem Dynamics and Imbalances

The emergence and re-emergence of infectious diseases are closely linked to the biology and ecology of infectious agents, their hosts, and their vectors (16). Therefore, a comprehensive understanding of ecosystem dynamics that informs on the processes leading to the occurrence or the recurrence of infectious agents, and their dissemination and extinction in natural habitats, is essential in assessing the risk of infection. The genomes of parasitic organisms, in the widest sense of the term (virus, prokaryotes, and eukaryotes), evolve in their natural environment through mutation, recombination, horizontal transfer, and hybridization. These "genetic entities" respond differently to selective environmental filters, and some genotypes are selected. These genotypes may express new phenotypes and colonize new hosts. They can also cause damage to the hosts they colonize, thereby becoming pathogens. Above and beyond the need for a comprehensive understanding of the life cycles of pathogens, transmission pathways, and transgression of species barriers, further research is required to (i) explore pathogen dynamics in natural habitats and (ii) develop models of infection close to natural systems. Developments that have been achieved for certain models, such as pathogenic vibrios in mollusks (17, 18) or pathogenic *Leptospira* in many vertebrates (19, 20), open up the possibility of a better understanding of pathogen dynamics in microbiota, interacting with a host species or a community of hosts.

Understanding ecosystem dynamics allows us to assess the degree to which the alterations caused by anthropogenic

forcing lead to the development of large-scale infectious events. Historically, the domestication of animals has indirectly mediated the transfer of infectious agents between wildlife and humans (7). The majority of emerging infectious diseases considered to be significant in terms of public health also have a zoonotic origin (21), and almost three-quarters originate in wild animals (22). The study of ecological factors affecting the transmission of infectious agents in wildlife is therefore essential in understanding the mechanisms involved in transgression of species barrier (also referred to as host-switching, host-jumping, or host-shifting) and emergence in human populations. For example, the density and diversity of hosts, migration, environmental persistence, and interaction within communities of infectious agents have been identified as determining factors in the emergence of direct and vector-borne transmission agents (23, 24). Assessing the risk of the emergence of zoonoses in human populations therefore requires the analysis of interaction networks between infectious agents, their hosts, and the environment in which they evolve [for an instance of transmission of malaria between macaques and humans, see Huffman et al. (25)].

Habitat destruction and fragmentation, environmental pollution, and climate change have a confirmed catalyst effect on the occurrence and geographic distribution of infectious agents (26, 27, 28). Recent examples of epizootics, particularly destructive epidemics or zoonoses (bird flu, coronavirus, Ebola, chikungunya, dengue, and Zika) indicate that this spread was in many cases assisted by global changes. Thus, by altering the repartition of pathogens, their vectors and their reservoirs, global warming is responsible for the appearance of new diseases at northern latitudes that have previously never been affected (29–31). Particularly, noteworthy examples are the cases of schistosomiasis (32) and chikungunya emergence (33) in the European continent. The recent Ebola epidemic in Western Africa recalls that epidemics are not only limited to the circulation of viruses or knowledge of contamination principles but also strongly influenced by history, political contexts, economic inequalities, and cultural phenomena (34, 35).

In the same vein, the globalization of trade and exchange and the industrialization of agriculture, aquaculture, and agribusiness have occurred in a very short period of time when viewed on an evolutionary scale (36, 37). These trends are responsible for increased movement of humans, plants, and animals with their accompanying infectious agents, who have been able to colonize new territories. Industrialization, which has fostered intensive breeding and farming practices, has also generated stress in organisms, which in turn has created an environment that is conducive to the spread of infectious agents.

The industrialization of agriculture and farming is also responsible for the widespread and often abusive use of pesticides, fertilizers, and antibiotics, which have selected on the one hand resistance to insecticides in mosquitoes that transmit pathogens (etiological agents of malaria, arboviruses, filarioses, etc.) (38–40) and on the other hand resistance to antibiotics in bacteria (41). The selection of antibiotic-resistant strains has occurred in the same way, through abusive and poorly considered use of antibiotics in human health care. This issue now represents one of the most serious threats to global health, food security, and development for the WHO. Antimicrobial resistance is a global health crisis with multiple dimensions. Using a "One Health" approach connecting medicine with some of the well-established key concepts in eco-evolutionary dynamics is urgently needed for developing novel approaches to bacterial infection therapy for which resistance is less quick to evolve (42). Beyond research, the examples of resistance to antimicrobials and pesticides are indicative of the need to develop a policy framework that is common to public health, agriculture, and farming (43).

Resilience, Restoration, and Eco-Inspired Control

The concept of resilience emerged in the ecological literature in 1960s and 1970s to describe the response of ecosystems to disturbances (44). In socioecology, resilience is defined as the capacity of a socio-ecosystem to absorb disturbance and to maintain particular properties such as function, structure, identity, and feedback (45). Resilience should be viewed in a dynamic way, as it allows an ecosystem to shift between different steady states, each of them possessing different sets of processes allowing functions to be maintained. On one hand, it has been advocated that an integrated One Health approach addressing the potential health effects at the human/animal/environment interface will enhance the resilience of local communities (46) through better disease prevention (47). On the other hand, the concept of resilience plaids for system-based thinking and holistic approaches, which for the "One Health" concept means to take into account the importance of diversity (from genes to species), redundancy, and adaptability of the socio-ecosystem to better face, for example, health sanitary crises.

Thus, the spread of infectious agents can be controlled by biological diversity, with predation, competition, and host–symbiont interactions, all playing a role in holobiont fitness and their dynamics, i.e., hosts and their associated microbiota. However, processes by which biodiversity can dilute or amplify disease transmission are still poorly known and are both scale- and context-dependent (48). "Demoresilience" associated with progresses in prevention and simple hygiene has not eliminated old scourges, such as plague, tuberculosis, etc., which are still infecting people and communities, but has led to a continuous decrease in epidemics, this far before vaccines and antibiotics were made available (49).

Nature can help provide viable solutions that use and deploy the properties of natural ecosystems and the services they provide. Thus, eco-inspired innovative strategies have been developed to control infectious diseases. Phages are natural predators of bacteria, controlling bacterial behavior and dynamics in the environment (50). Similarly, antimicrobial peptides, effectors of innate immunity in metazoans, and competition in prokaryotes can also influence pathogen dynamics (51, 52), vector-borne transmission (53), and may allow alternative routes of transmission in the natural environment (54). These natural control mechanisms are real sources of inspiration for the development of new anti-infectious strategies. New methods of fighting vector-borne transmission based on microbial symbiosis represent an area of research that

is being promoted and encouraged on a global level by the WHO [Bourtzis et al. (55)[3]]. Likewise, just as the specter of the post-antibiotic era appears before us (56), research into alternative anti-infectives has become an international priority, once again backed by the WHO, who recommends a global action plan based on "One Health" principles (57).

We now need to evaluate the capacity of these alternatives to induce resistance and define its molecular basis in order to assess the risk. Indeed, the challenge over future years will be to identify new anti-infectious strategies likely to generate less resistance and having reduced impact on non-target organisms and the environment (58). Studies in this particular field are already underway and indicate a definite advantage to using phage cocktails (59) or antimicrobial peptides from metazoans (60) as an alternative to antibiotics. There are also promising leads opening up with the development of immunomodulatory peptides derived from antimicrobial peptides (61), whose risk of inducing resistance is extremely low.

If research is called upon to find innovative and ambitious solutions to control infectious diseases, then society, for its part, must not forget that for many extremely destructive infectious diseases, hygiene and prevention are far more effective control solutions than the use of anti-infectives or vaccines, if they exist. This also applies to various vector-borne diseases, for which education and information are the key to avoiding exposure to vectors and the pathogens they transmit.

MULTIFACTORIAL AND NON-COMMUNICABLE CHRONIC DISEASES

Toxic Risk

Complexity and Ambitions of Ecotoxicology

The toxic risk is implicated on many levels in the issues surrounding the "One Health" concept because of direct harmful effects of contaminants and their impact on the physiology, immune, and endocrine responses of organisms, biodiversity, and the transmission of pathogens. Contaminants and toxins can also impact host–pathogen interactions, by directly affecting the pathogens (62). However, toxins and pollutions are to a certain extent part of nature, and toxicity does not mean the same for all organisms. For example, Lake Natron (Kenya) is an unhospitable place for most species, but some have adapted to this environment (like flamingos, *Spirulina*, and invertebrates adapted to caustic waters they live on). As a consequence, the occurrence of toxicants *per se* might not be problem, and there is certainly a lot to learn from the adaptive mechanisms evolved by species living in such "toxic" environments.

Environmental pollution is *a worldwide concern*. The toxic risk is particularly high in environments where the human population is very dense, such as coastal areas, where species are subjected to multiple toxins and pollutants including natural toxins (e.g., paralytic shellfish poisoning toxins synthesized by certain harmful microalgae), emerging pollutants (e.g., micro- and nanoplastics) and diffuse pollution linked to multiple anthropogenic releases (63, 64). However, even remote areas without high anthropogenic activities such as polar areas are also contaminated, with a long list of legacy or emerging organic and inorganic compounds involved (65). The recent and global nature of environmental pollution is even reflected by marked differences in Holocene signatures in stratigraphic records showing unprecedented combinations of various anthropogenic substances (66). Wildlife and domestic animals are currently exposed to numerous contaminants at levels endangering their survival and health, their ability to reproduce and capability to cope with other stressors such as pathogens, and this represents a threat on biodiversity and ecosystem functioning which is now acknowledged (67–71).

The widescale development of *multifactorial diseases* affecting both invertebrates (bees, corals, and oysters) (72–75) and vertebrates (amphibians, cetaceans, and chiropterans) (76–79) is increasingly recognized thanks to the development of tools in genomic medicine and epidemiology that facilitate their study. As a consequence, diseases of complex etiologies are receiving increasing attention. Multifactorial diseases often emerge in organisms whose defense capacities have been reduced by changes in nutrition, temperature, salinity, pH, exposure to pollutants, toxins, radiations, etc. Through cumulative and long-term effects, toxins have significant impact on morbidity caused by both pathogens and other toxic substances (cocktails). Toxicants increase the risk of infectious diseases when the immune system is directly or indirectly affected (67, 71, 80–83). Immunotoxic effects do not only have a direct effect on human health and the viability of human and animal populations, but also affect the broader functioning of ecosystems and promote the transmission of zoonotic diseases by increasing the prevalence of pathogens in animal reservoirs or intermediary hosts. Therefore, the major threat posed by pollutants to biodiversity has currently undetermined consequences on biotic interactions (**Figure 3**). As a result of changes in species abundance and food web topology (extinction of "regulatory" predators, role of "super-predator," consumptive competition, effects on keystone species, biological invasion, increase in resistant disease reservoir species, density effects dependent on emergence of epizootics or zoonotic diseases, etc.), pollution further significantly increases the risk of disease.

The occurrence of some *chronic non-communicable diseases* is currently soaring in southern countries, highlighting the globalization of sanitary risks (84). Part of it is due to significant advances in combating infectious diseases, which have greatly reduced mortality and as a consequence modified the occurrence of non-infectious diseases. However, environmental changes, and particularly exposure to toxic substances, were shown to play an important role in the occurrence of serious chronic non-infectious diseases in humans (respiratory, cardiovascular, neurological, and metabolic diseases, obesity, diabetes, and cancer), the prevention of which is a major challenge for our society, both for the present and the future generations. Transgenerational effects of environmental stress (85) transmitted by epigenetic mechanisms (86) have been described in various species. There is no reason to think that humans should be exception to this rule, and indeed a comparable picture emerges for wildlife from

[3]http://www.eliminatedengue.com/program.

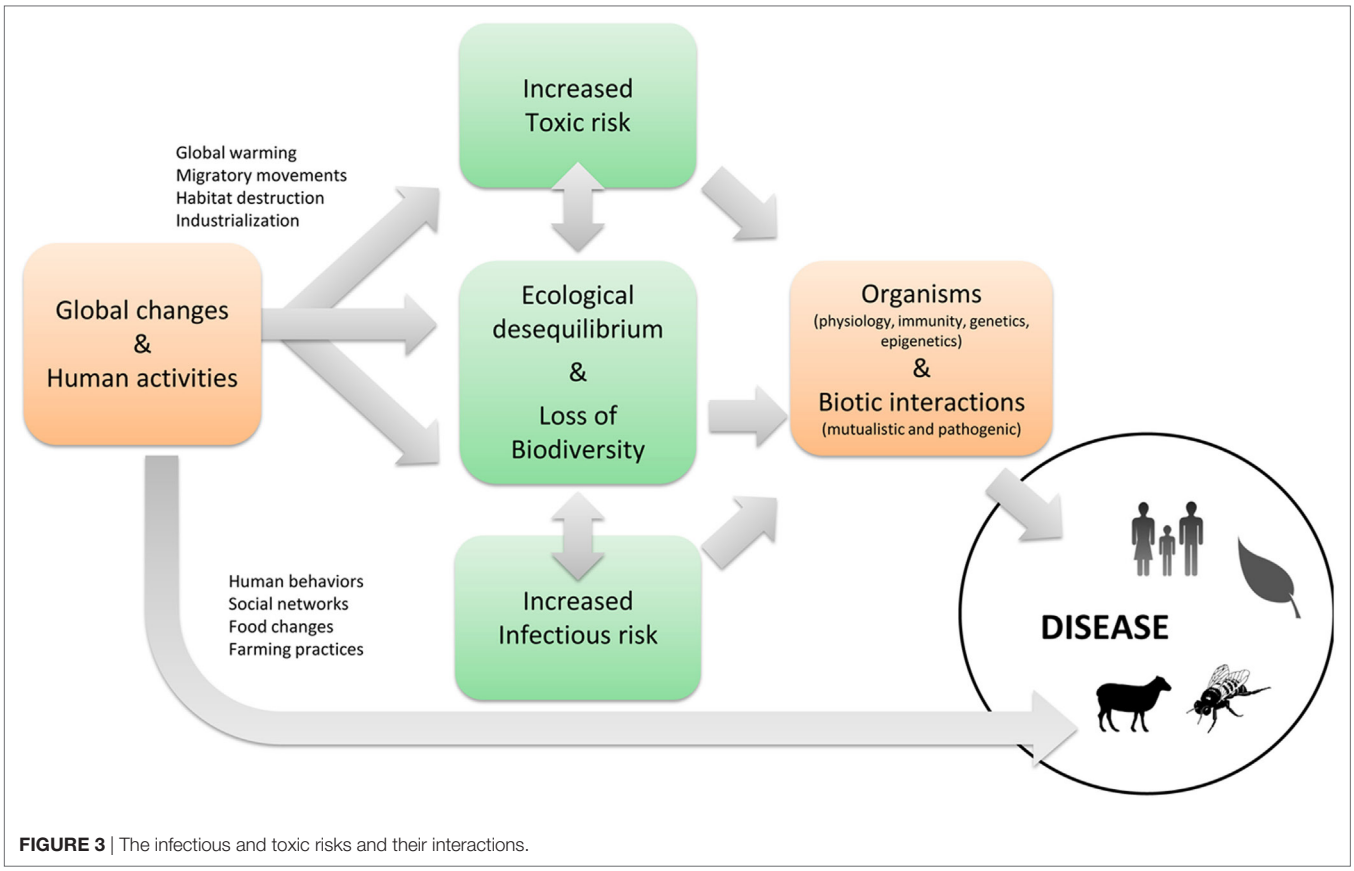

FIGURE 3 | The infectious and toxic risks and their interactions.

many case reports worldwide (70). This indicates the importance of the man–animal–ecosystem interface in determining the evolution and emergence of chronic diseases in humans, just as in other species. For this reason, human and veterinary medicine is often developing a reductionist and frequently reductive approach that needs reviewing in the context of the current situation. Prevention and control, which are increasingly accessible, have a great potential for tackling such complex disease dynamics.

Building a Harmonized Framework for Biological and Chemical Contaminants

Over the past two decades, a few articles called for a transdisciplinary harmonization of ecotoxicology as a component of "Ecosystem Health" and the encompassing "One Health" (81). Evidence, examples, and opportunities for cooperation have been detailed (26, 27, 81, 87–89). However, studies incorporating chemical contaminants and environmental quality in a "One Health" framework are still marginal (87). Addressing simultaneously the needs of "Ecosystem Health" and "One Health" with their inherent trade-offs is a required step forward that would undoubtedly help achieving the goal of better health for people, animals, and our environment.

Beyond integration of environmental pollution as one of the anthropogenic disturbances impairing environmental health, consideration of toxicants for their role in immunity and endocrine system would benefit from a unified framework merging the theoretical and applied contexts of eco-epidemiology, ecophysiology, and ecotoxicology (90). Pathogenic organisms and chemical pollutants have their own specificities. However, many common ecological, physiological, and biological processes rule the transmission of biological and chemical contaminants on the one hand and the exposure and responses of organisms and ecosystems on the other hand. System studies on both pathogens and toxicants not only require specialists but also joint expertise to assess impacts, manage risk, and apply therapeutic care. For instance, similar tools in mathematical modeling can be shared for trophically transmitted parasites and pollutants. This calls for more cooperation between human and veterinary medicine, functional and evolutionary ecology, institutional health-care and wildlife management, as well as socioeconomics and regulatory issues.

Furthermore, interactions between pathogenic organisms and chemical toxicants have a high interest in itself. Thus, evaluating the impacts of massive use of biocides and xenobiotics has become a priority to anticipate the consequences of such delivery on the whole ecosystem. Integrating ecotoxicological issues of biocidal substances in "One Health" should help refining the chemical control of pathogen vectors (e.g., mosquitoes) or parasites (anti-helminthic, acaricide, etc.). As a first step, the development of "adaptive monitoring" approaches dealing with co-exposure to pollutants and pathogens is absolutely crucial (91–93). The challenge is to assess exposure and organism response on both an individual level and at the population level through relevant and

appropriate approaches for both wildlife and human (91, 92). A further challenge consists in defining spatial and temporal scales, types of sample, biomarkers, and end points (92, 94).

Toward Integrated Multiscale Approaches

The ecotoxicological impact of diffuse pollution, phycotoxins, and contaminants of emerging concern, as well as their modulation by environmental factors, needs assessing today using an integrated approach that encompasses the different scales of organization of living beings (macroscopic, cellular, biochemical, and molecular) and includes studies in both controlled environments and *in situ*. The study of population response to multiple stress factors and the genetic and epigenetic bases of their capacity to adapt to these stress factors are currently priority fields of research in order to anticipate future sanitary crises that may influence the fate of species.

Urbanization and Health

Urbanization, associated with ground and air pollution, and its role in lifestyle changes (energy-dense diets with ready-made foods that are rich in lipids, reduced physical activity, more sedentary lifestyles, etc.) represents a major environmental change for man. Since 2010, towns and cities have been the living environment of more than half of humanity (95). Our increasingly urban lifestyle leads to exposure to multiple stress factors (exposome), the health impact of which we do not yet fully understand, especially among the more fragile members of society.

The way in which people are connected and our towns constructed has an enormous impact on health, and particularly its evolution with age. A person's social network will influence both his propensity to being infected by directly transmissible pathogens (without an intermediary host) (96) and to being affected by non-infectious diseases such as obesity (97) or blood cholesterol. However, we do not yet know exactly how urbanization, mobility, or social network nurture or hinder good health. This will require significant research. New portable detectors such as GPS or accelerometers make it possible to record extensive and precise data pertaining to people's mobility and activity (98). The combination of this type of approach with social network measurements opens up new ways of measuring and understanding epidemics and health inequalities (96, 99). The development of statistical methods, graph theory, and multiagent simulation would make it possible to (i) identify which urban environment or social network properties influence well-being and activity and (ii) provide concrete recommendations to improve urbanization plans and public health strategies.

The notion of ecological, epidemiological, sanitary, and demographic transition seems to be a particularly federative idea in the "One Health" approach, because it allows for both the implementation of concrete interdisciplinary research (ecologists, doctors, anthropologists, biologists, demographers, etc. can work together on the changes observed) and because it is also very closely associated with the environmental change represented by urbanization, making it possible to address the subject of the etiology and prevention of chronic non-communicable diseases and infectious disease in a new and innovative manner.

ONE HEALTH CONCEPT SUCCESSES IN THE INTEGRATION OF ITS ECOSYSTEMIC COMPONENT

Some key examples illustrate the degree to which the adoption of a "One Health" approach is both consensual and particularly effective in deciphering the processes underlying the emergence and re-emergence of diseases.

Optimizing Land Use to Control Pathogen Transmission

In 1960s, the European agriculture common policy encouraged French farmers to specialize in milk production. Farmlands from the Jura Mountains were then converted into permanent grasslands. With the destruction of hedges and increased productivity, this shifted the regional ecosystems toward large-scale small mammal pest surges with a cascade of direct and indirect consequences in agriculture, conservation, and public health, including exacerbating the transmission of *Echinococcus multilocularis*, a deadly parasite of public health concern (100). In China, similar effects came from deforestation and agriculture encroachments during 1980s (101). In such a context, research and disease regulation were necessarily considered together with the other issues. Researchers provided knowledge on ecological processes that helped stakeholders to discuss and select, in a system approach, the inherent trades off between seemingly divergent sectoral interests (102).

Deciphering the Emergence of Infectious Diseases through Holistic and Multiple Scale Approaches

In 2013 and 2015, two independent outbreaks of Schistosomiasis occurred in southern Europe (Corsica Island, France) with around 300 estimated cases (103, 104). The occurrence of this tropical disease in higher latitude was unanticipated and caught scientists and health authorities unprepared. At the beginning of the outbreak the locals were worried, the communication was not controlled, the local physicians were not trained to diagnose this tropical disease, and the ecologists were unprepared to consider this parasite in temperate zone. Moreover, the hybrid status of the parasite, a cross between a human and an animal schistosome, made the epidemiological situation much more complex. A collaborative effort between physicians, veterinaries, biologists, ecologists, and public health institutions was set up to identify the origin of the outbreak and control it (32). The biologists identified the intermediate host implicated, defined the hybrid status of the parasite and its Senegalese origin; veterinarians proved the absence of ruminant reservoir hosts; and physicians and health authorities improved diagnostic tools, addressed the clinical characteristic of the patients, and measured the extent of the outbreak.

Modeling Diseases in Social Networks

As the growing worldwide population becomes more mobile and urbanized the risk of epidemics is constantly increasing. Studying animal interactions and the coevolution between emerging social networks and pathogen transmission may help to predict outbreaks

and develop strategies avoiding epidemics and epizootics. Network studies, especially in non-human primates, suggest not only that the position of an individual in a group affects the risk of being infected and infecting conspecifics (105) but also that the shape of interaction networks independently from individuals affects pathogen transmission (106). Over the past few years, concepts such as efficiency, resilience, and nestedness (107, 108) have been used to understand the evolution of ecological and social networks facing to environmental changes. Modeling epidemic spread in social networks should help target animals as well as humans according to their social position in the network in order to vaccine them and better manage outcome of epidemic outbreaks. Integrating ecological pressures and intra- and interspecific relationships in these models could also bring new understanding about how these networks are robust to changes and could act as buffers between the environment and animals, including humans.

Those examples illustrate how the application of the "One Health" approach to infectious risk needs to be systematically reinforced with ecobiology expertise. Similarly, the toxic risk needs to be enriched with ecotoxicology expertise. Further understanding of the risk presupposes asking a certain number of questions which may be presented in the same way for both risks (see **Table 1**). This knowledge of ecosystem processes must generate the signposts to guide the sustained exchange effort required from ecologists, epidemiologists, evolutionists, and human and animal health-care specialists with other activity sectors.

OPERATIONAL BRAKES ON THE "ONE HEALTH" CHALLENGE AND RECOMMENDATIONS

Major barriers to the effective integration of "One Health" need to be removed (i) for the systematic implementation of a "One Health" strategy and (ii) for the development of operational solutions that both respect environmental health and its future and are realistic in the face of the urgency of medical care for patients.

A major barrier to the development of "One Health" approaches is very clearly the lack of communication between human and veterinary medicine, agronomy and ecological, environmental, and evolutionary science. Removing this major impediment implies the integration of sufficient understanding of other disciplines, multidisciplinary approaches, and the aims and conditions of their implementation. This can be formulated at different levels.

From a *training* point of view, it is essential to include ecology and evolution in any medical, veterinary, and agronomic training (109, 110). Although relatively recent, a number of these training courses are currently being developed around evolutionary medicine. This initiative should be supported and strengthened in the future.

From a *research* point of view, improved *scientific cooperation* requires the development of collaborative national and international research networks (including within Europe). The integration of southern countries, with their diverse intertropical ecosystems and biodiversity hot spots, is absolutely vital as they represent genuine natural laboratories for the implementation of the "One health" concept in the face of demographic and sanitary transition resulting from global changes. Networks must also include a maximum number of key players in research, representing various disciplines and specializing in different levels of organization of living beings, and spatial and temporal scales. They must work together toward the implementation of shared training programs, tools, and protocols with a shift from research generating basic and isolated knowledge to translational research leading to systems and implicational knowledge. This certainly needs a mentality change not only from researchers but also—and even more importantly—from research funding bodies. Scientific

TABLE 1 | Exploring the infectious and toxic risks through ecobiology and ecotoxicology expertise.

	Infectious risk		**Toxic risk**
	Case of pathogen emergence	**Case of antibiotic resistance**	**Case of emerging toxins and recurrent toxicants**
Ecosystem processes	How does a commensal infectious agent become a pathogen?	What is the ecological role of antibiotics and of their resistance genes?	What is the ecological role of toxins produced by microorganisms?
	How do infectious agents alter certain hosts?	How do antibiotics and their resistance genes operate?	How do toxins alter certain hosts?
	How do infectious agents proliferate within the microbiota of their hosts?	How do antibiotic production systems and their resistance genes proliferate?	How do organisms adapt to toxicants?
	How are infectious agents controlled in a natural environment?	How are antibiotic-producing or resistance gene-carrying populations controlled?	How are toxins controlled?
Anthropogenic alterations	How do global changes/anthropic activities impact on environments affect biodiversity and the emergence of pathogens?	How do global changes/anthropic activities impact on environments affect the emergence of antibiotic-resistant bacteria?	How do global changes/anthropic activities impact on environments affect toxic risk?
	How does the synergy between infectious and toxic factors multiply the effects and complexity of responses?		
Solutions	Which innovative control solutions are inspired by the ecobiology of infectious agents, their hosts, and their vectors?	How can we develop anti-infectives that generate less resistance?	Which control solutions are inspired by the ecology of emerging toxins?

This table summarizes questions to be addressed for understanding the risks and develop innovative solutions.

cooperation also needs better access to knowledge, which is currently partially blocked (intellectual property, patents), thereby depriving certain key players of diagnostic criteria or fundamental knowledge (81). *Observation tools and data management programs* should also be supported. Long-term monitoring of transmission or exposure systems must be organized and supported by appropriate means and measures, including outside peaks of visible emergence, taking into consideration the different spatial and temporal scales relevant to the organisms in question (e.g., multiannual demographic variations of organisms, landscape changes, practice changes, rearrangement of communities in response to these factors, etc.). This requires the implementation of policies to collect, capitalize, secure, and make available the data derived from ambitious research (database management, observatories, etc.). In addition, promoting *multidisciplinary integrative approaches* is needed for the development of a progressive health (human and animal) ecology, which is based on acquired expertise and methodology in immunoecology and endocrine-epidemiology (111) and links the study of proximal factors (mechanisms) to their ongoing evolutionary consequences (112, 113). It is also necessary to support work into the *definition of ecosystem services* for the regulation of infectious or toxic risk (contributing to the requests of the, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services).

From a *political* point of view, it would appear necessary to implement a gradual *reinforcement of biosecurity* including production, transport, and transformation of biological resources. It is additionally absolutely essential to *break down the sectoral partitioning* that exists between public health, agronomy policy, and other sectors of activity (27). Indeed, current sectoral partitioning trends foster infectious risk. For instance, to date the agriculture/public health interface does not come under the competences of farmers nor vector control services, which increases the development of insect vectors resistant to agricultural insecticides. The synergy of a partnership between scientists, farmers, and the vector control services would initiate pluridisciplinary research programs whose goal would be to protect the crops while reducing the populations of vectors as much as possible. Similarly, sectoral partitioning increases the emergence and the spread of microorganisms that are antibiotic-resistant as a result of spreading slurry from farms using antibiotics or by the increase in size of host populations of pathogenic agents. It is therefore clear that a comprehensive review of industrial agriculture and farming practices is vitally urgent. Overall, significant efficacy gains can be achieved through intersectoral cooperation in a "One Health" approach. This should include a control at source, which is often more cost-effective than fighting a disease. This supposes (i) cooperation in terms of monitoring and diagnosis for a quicker and more precise diagnosis; (ii) cooperation in terms of preventative measures, such as vaccination, to increase coverage; and (iii) a detailed and immediate communication to reduce the number of cases (114).

Remarkably, a purely *economic* view also calls for a global approach of Health that relies on both "prevention at source" for animals and "control" for humans (115). It has been estimated that this two-sided approach would cost between 1.9 and 3.4 billion dollars per year to implement and optimize this approach, a sum which is far below the annual average of 6.7 billion dollars of economic losses historically suffered as a result of epidemics (114). These methods will require the consolidation of regional, national, and international approaches to biosecurity for the control of human, animal, and plant diseases and the implementation of an integrated, interdisciplinary, intersectoral approach to the monitoring of and investigation into diseases common to man and animal. A first necessary step is the development of a database that includes a corpus of essential statistics on demography, the sanitary situation, health determinants (human, animal, and ecosystem), and risk factors. These multi- and intersectoral collaborations, nourished by the results of relevant research, are also essential in identifying the bio-economically, socially, and ecologically acceptable compromises between (sometimes) contradictory management objectives (food production, health, biodiversity preservation, etc.).

In addition to prevention, ecology today must be able to offer the authorities *innovative solutions* to vector control (antivector fight) and pathogenic infectious agents (remediation) that are more ambitious and less destructive to biodiversity and ecosystems than those currently deployed. With regard to antibiotic resistance, research programs working on the identification of new anti-infectives must henceforth consider the risk of resistance emergence from the moment that new therapeutic agents are developed.

CHALLENGES AND AMBITIONS FOR THE "ONE HEALTH" CONCEPT

The insufficient consideration of certain key components in the implementation of the "One Health" concept can be highlighted. Particularly, the wildlife component and numerous related ecological issues (community ecology and evolutionary ecophysiology) are still neglected (116), as are certain environmental science components (soil and climate) (117). Additionally, social, legal, and economic sciences are similarly marginalized (118).

However, social sciences play a major role in the construction of the problems facing "One Health" research. The understanding of infectious or toxic risks cannot simply be reduced to its biological or chemical components. It is also essential to take into consideration the vulnerability, variability, and susceptibility of human societies as well as the different ways they interact with animals and ecosystems. The "One Health" concept, which promotes an interdisciplinary and intersectoral approach, must therefore engage at different levels of health governance, from a global level right down to a local level, by encouraging participative approaches that bring together communities, scientific experts, administrations, and other key players (NGOs, industry, legal experts, etc.). Infectious and toxic risks must also be addressed through their perceptions and impacts to contribute to the improvement of surveillance and prevention systems and the resilience of societies in the face of sanitary crises.

The issue of plant health as a full component of "One Health" concept is a challenge to be urgently resolved (119). In fact, human health and animal health are directly or indirectly dependent on plant health, as the latter is essential as food

resources, phytomedecine, land management, etc. In terms of basic knowledge, investigations in plant ecology and epidemiology have provided useful data for understanding the mechanisms of virulence and adaptation of pathogens in humans and animals. A renowned example is the discovery by botanists of interfering RNA as a key component in gene regulation, including host–pathogen interactions (120). While some plant pathogens may pass the species barrier and cause nosocomial diseases, such as the *Burkholderia* complex bacteria responsible for human cystic fibrosis (121), others belonging to enteric bacteria (*Salmonella, Escherichia coli*, *Shigella*, etc.) are plant inhabitants that can cause food contaminants that are harmful to human (122). Thus, raising the concept of "One Health" to a realization requires also access to a good plant health through a productive (yield, quality, nutritional value, and biosafety) and sustainable (reducing pesticides and chemical fertilizers, encouraging culture rotation practice, biofertilization, etc.) agriculture.

The question of ethics should also be more widely integrated into the "One Health" concept. If ethics are referred to essentially through bioethics and the ethics of animal health, other components are often neglected. This is the case for environmental and biodiversity ethics, social science ethics, and the ethics of various legal concepts, such as human rights, the rights of indigenous people, environmental justice, and animal rights. The Nagoya Protocol to the Convention on Biological Diversity is one of the ethical and legal frameworks which are legally binding on scientific research, generating new consequences on the access to and sharing of microorganisms, human, animal and plant samples, data, and traditional and local knowledge and skills. Far from being a new constraint, it is an opportunity to reflect on the role of scientific research in our societies (123).

CONCLUSION

This review illustrates how crucial it is to consider ecological, evolutionary, and environmental sciences in (i) understanding the emergence and re-emergence of infectious and non-communicable chronic diseases and (ii) in creating innovative control strategies. However, the actual organization of research and the sectoral allocation of resources in our societies still limit the development of transdisciplinary approaches and integrated operational actions. Removing the interdisciplinary barriers that still separate ecological, environmental, and evolutionary sciences from human and animal medicine is a major challenge to the implementation of the "One Health" concept, which moves beyond science and impacts politics (health, agriculture, aquaculture, land management, urbanism, and biological conservation), law, and ethics. There is a need to provide evidence on the added value of "One Health" approach for governments, researchers, funding bodies, and stakeholders (124). Finally, promoting the integrative benefits expected of the "One Health" concept requires a new interface with human, social, and legal sciences that remains to be built.

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All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Member Perceptions of the One Health Initiative at a Zoological Institution

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Zoological institutions play an important role in promoting the goals of the One Health movement. We launched the Institute for Conservation Medicine (ICM) at the Saint Louis Zoo in 2011 to advance the goals of One Health. In 2016, we distributed a survey to Zoo members to evaluate member awareness and understanding of One Health and to provide direction for future communication and actions from the ICM. We hypothesized that Zoo members would be aware of One Health and care about infectious disease issues. Survey results showed Zoo members primarily cared about chronic, non-infectious diseases and their associated economic costs, with participants ranking their top three health issues of concern for humans as nutrition/obesity/diet (49%), costs of health care (48%), and cancer (37%). Zoo members were interested in the roles of zoos in One Health and found them important, but were less aware of the Saint Louis Zoo's actions that did not directly relate to animal welfare. Only 6% of members had awareness of the term "One Health" and 16% were aware of the term "Conservation Medicine." These results suggest that zoos may do better to tailor One Health messaging to align with member interests. Messaging and programming from the Saint Louis Zoo will now include the direct benefits to human health that zoos offer, in addition to the ICM's more ecologically focused activities. This study offered valuable insight into how Zoo members view One Health and may serve as a template to help zoological institutions develop and promote One Health.

Keywords: conservation medicine, emerging diseases, human health, Saint Louis Zoo, public health, transdisciplinary

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INTRODUCTION

Worldwide, there has been a shift in disease research and interests from infectious, communicable diseases to non-communicable, chronic, human-induced diseases (e.g., obesity, diabetes, heart disease), as these non-infectious diseases increasingly threaten human health and overall public health (1). This shift, termed the "epidemiologic transition," describes the changes in patterns of population age distributions, mortality, fertility, life expectancy, and causes of death (1, 2). The epidemiologic transition is associated with industrialization and urbanization, with impacts on the environment and all living things within it. As such, chronic, non-communicable diseases are at the forefront of health care for humans, and these diseases result in increasing health-care costs and are strongly associated with obesity. Depression, for example, is the second leading cause of disability adjusted life years worldwide (3).

During this time of shifting human health challenges, conservation challenges have also increased. Since the 1970s, average global population sizes of wildlife have decreased by more than 50%, leading

to the development of the field of conservation medicine in the 1990s (4–7). This is a holistic approach that evolved at a time when infectious and non-infectious diseases increasingly threatened the conservation of wildlife, wild lands, and the humans dependent on both (4). While conservation medicine provides a broad approach to the ecological context of health, a newer movement has emerged in response to the increase in emerging infectious diseases and their often zoonotic origins (8, 9). This initiative, most recently named One Health, has been defined as "a transdisciplinary approach to sustainable management of complex health problems arising from the interaction of animals, humans, and their environment" (10). The One Health initiative may best be considered from its two core components: translational, focusing on comparative medicine, and ecological.

One Health initiatives from zoos have primarily focused on research and messaging about zoonotic diseases and the human–wildlife interface (8, 11–13). Communicating to people about these threats to both human and wildlife health is an important part of One Health (11). One goal of these communications has been to generate public support for healthy wildlife populations with the assumption that if disease risks are well communicated, then public attitudes toward zoonotic disease management should be impacted (11, 14). As the field of One Health grows and public awareness increases, broader communications about the role of One Health are necessary, and zoological institutions should be at the forefront of the One Health movement, because of the transdisciplinary nature of their work and their strong focus on recreation, education, research, and conservation (8, 12, 15). Recreation is of increasing importance in the context of One Health because of the health benefits for zoo visitors in a largely urbanized and sedentary world. On average, Americans spend 87% of their time indoors, and 6% of their time in enclosed vehicles, which has drastic impacts on human health (16). Zoos connect people with nature and encourage healthy human habits through physical movement across zoo campuses and interactions with exhibits and animals (17, 18).

Zoos have a unique position within One Health, for which we have identified seven important tenets. These include (1) providing health care for zoo wildlife to help sustain biodiversity; (2) studies on diseases of conservation concern; (3) understanding diseases in zoo wildlife as sentinels for emerging diseases of humans and other animals; (4) surveillance of disease in wild animals at the interface of wildlife, domestic animals, and humans; (5) contributing to the field of comparative medicine and the discovery of all life forms; (6) exploration of the diversity of life at both micro and macro levels; and (7) human health benefits from nature (5, 8, 18). These roles inform the actions that zoos take in regards to One Health messaging and encourage zoos to invest resources into promoting One Health to visitors, members, and communities.

In linking the roles of zoos in One Health and current public health issues, it has been demonstrated that exposure to nature for at least 5 h a month has lasting restorative effects, such as elevating mood and decreasing risk of depression (10). Studies have indicated that public health strategies should address these concerns *via* an upstream approach that provides opportunities for people to connect with nature, such as spending time in greenspaces, including zoos (19–21). Nature can promote health through many different pathways, but most broadly does so through environmental conditions, physiological and psychological states, and behaviors (17). We also know that children with attention-deficit disorders exhibit diminished symptoms following activities in green settings, such as zoos (22). Finally, it has been shown that zoos may improve both psychological and physiological well-being through decreasing stress and increasing physical activity (18, 23).

In response to the growing conservation and public health challenges, the Saint Louis Zoo launched the Institute for Conservation Medicine (ICM) in 2011 to advance the goals of One Health. The ICM's mission statement reads as follows, "The Saint Louis Zoo Institute for Conservation Medicine takes a holistic approach to research on wildlife, public health and sustainable ecosystems to ensure healthy animals and healthy people." The 50,000 ± Saint Louis Zoo member households, which equates to more than one-third of total annual Zoo visitation, often receive One Health messaging. This includes a quarterly magazine, often with a feature on the ICM's activities, and weeks prior to the Zoo's annual One Health Fair a promotional email is distributed to all Zoo members (24). Zoo members also consistently report being significantly more aware of the Zoo's conservation work in Missouri and around the world than those Zoo visitors who are not members [Niedbalski, unpublished data]. Additionally, the Zoo's social media accounts, which have nearly half a million followers, provide occasional updates on One Health activities and the ICM.

While the ICM was founded over 5 years ago, it had yet to be evaluated whether the presence of ICM in our newsletters, social media and other layperson friendly publications, and zoo-sponsored activities was having an impact on Zoo goers' understanding of One Health. The primary objective of this study was to evaluate Zoo member understanding of the concept of One Health 5 years after the establishment of the ICM to provide department evaluation and direction for the coming 5 years. Additionally, we wished to determine what health concerns/issues were at the forefront of Zoo members' thinking.

Our hypotheses were that Zoo members would have a high level of awareness regarding One Health and that they would be aware of and care about infectious disease issues, since the survey was administered during significant media coverage of the spread of the Zika virus in North America. Therefore, we asked respondents' awareness of types of One Health projects in which the Zoo is involved, rating of concern of zoonotic disease transmission (with an open-ended follow-up response), and awareness and explanation of the terms One Health and Conservation Medicine. Finally, we asked ratings of awareness, interest, and importance of five of the various roles of the Zoo's involvement in One Health areas.

MATERIALS AND METHODS

We distributed an online survey *via* email to 2,983 Zoo members selected from the member database in June 2016 (**Table 1**). Zoo members were defined as individuals or households who purchased an annual membership through the Saint Louis Zoo. The

TABLE 1 | Items on the One Health questionnaire answered by survey participants in the 2016 One Health membership survey at the Saint Louis Zoo.

Survey questions

1. What do you think are currently the most important health issues facing humans? Please select your top THREE choices.
   - ❑ Nutrition/obesity/diet
   - ❑ Substance abuse (tobacco, opioids, alcohol, etc.)
   - ❑ Access to health care, environmental quality (water, soil, etc.)
   - ❑ Mental health
   - ❑ Wildlife-related diseases (Zika, Rabies, etc.)
   - ❑ HIV/AIDS
   - ❑ Cancer
   - ❑ Heart disease
   - ❑ Diabetes
   - ❑ Costs of health care/insurance
   - ❑ Climate change (extreme weather, etc.)
   - ❑ Population growth
   - ❑ None of these
   - ❑ Other (please specify)

2. Which ONE of these issues are you most concerned about in the future?
   - ❑ Nutrition/obesity/diet
   - ❑ Substance abuse (tobacco, opioids, alcohol, etc.)
   - ❑ Access to health care, environmental quality (water, soil, etc.)
   - ❑ Mental health
   - ❑ Wildlife-related diseases (Zika, Rabies, etc.)
   - ❑ HIV/AIDS
   - ❑ Cancer
   - ❑ Heart disease
   - ❑ Diabetes
   - ❑ Costs of health care/insurance
   - ❑ Climate change (extreme weather, etc.)
   - ❑ Population growth
   - ❑ None of these
   - ❑ (Insert text from other)

3. Why? (Referencing question 2)

4. Are you aware that the Saint Louis Zoo conducts projects (science, outreach, etc.) involving the following areas?

	Yes	No
Animal health	❒	❒
Human health	❒	❒
Environmental health	❒	❒

5. Please describe any of the projects with which you may be familiar.

6. How concerned are you about the following groups contracting diseases from wildlife?

	Not at all concerned	Not too concerned	Neutral	Somewhat concerned	Very concerned
Humans	❒	❒	❒	❒	❒
Domestic animals	❒	❒	❒	❒	❒

7. Why or why not?

8. Have you ever heard either of the following terms?

	Yes	No
One Health	❒	❒
Conservation medicine	❒	❒

9. What do/does the term(s) mean to you?

10. Please review the following five roles that the Saint Louis Zoo has in this area. Please rate your AWARENESS that the Zoo is involved in each role, your INTEREST that the Zoo is involved in each role, and the IMPORTANCE you place on the Zoo's involvement in each role.

1 = not at all, 5 = completely

Providing health care to zoo animals					
Awareness	1	2	3	4	5
Interest	1	2	3	4	5
Importance	1	2	3	4	5
Research on how disease can threaten species with extinction					
Awareness	1	2	3	4	5
Interest	1	2	3	4	5
Importance	1	2	3	4	5

(*Continued*)

TABLE 1 | Continued

Survey questions					
Studying disease in animals in zoo care					
Awareness	1	2	3	4	5
Interest	1	2	3	4	5
Importance	1	2	3	4	5
Studying how diseases in wild animals have an impact on domestic animals and humans					
Awareness	1	2	3	4	5
Interest	1	2	3	4	5
Importance	1	2	3	4	5
Research comparing diseases between different species, including humans					
Awareness	1	2	3	4	5
Interest	1	2	3	4	5
Importance	1	2	3	4	5
11. With which gender do you most closely identify? Male ❒ Female ❒					
12. Which of the following categories includes your age? 18–24 years ❒ 25–34 years ❒ 35–44 years ❒ 45–54 years ❒ 55–64 years ❒ 65+ years ❒					
13. What is your five digit ZIP code?					
14. Do you have any additional comments for the Zoo?					

Saint Louis Zoo maintains a database of approximately 50,000 member households, with just over 30,000 providing permission to utilize their email addresses for receiving communication from the Zoo. The Audience Research department of the Saint Louis Zoo provides data-driven evidence for informed decision-making that contributes to the achievement of the Saint Louis Zoo's mission-oriented goals. Audience Research staff at the Zoo sends approximately 10 member surveys per year, with no member household receiving more than one survey in a 365-day period. Therefore, email addresses are subset into 10 smaller samples (of approximately 3,000 email addresses), and each subset is representative of the total member population based on membership level. This study involved an online survey of members and was exempt from Institutional Review Board approval. Completion of the survey indicated consent.

We used IBM SPSS Version 24 to analyze the data and run descriptive statistics. We obtained data on median household income from https://www.incomebyzipcode.com and matched it to each respondent's zip code. These data were dichotomized into higher or lower than the median household income in the United States, which the census reported as $56,516 (25). For the open-ended questions, two individuals (HP and ET) sorted and independently coded the qualitative data into different categories, and then a third individual (AN) assessed and made the final decision on the coding when there were discrepancies between the original two coders. Survey answers were stratified by age, gender, and income category and then analyzed in a crosstab analysis. We collapsed age categories into three categories for the crosstab analysis: 18–34, 35–54, and 55+.

RESULTS

Sample

There were 439 survey respondents. We excluded 154 responses, as they were incomplete, leaving 285 completed surveys, for a response rate of 9.6%. Eighty percent (228) of respondents identified as females and 20% (57) identified as males. Sixty-two percent of those surveyed live in zip codes above the United States median household income. The majority of respondents were over the age of 35, with the largest age groups representing those between the ages of 35 and 44 (28%) and over the age of 65 (22%) (**Table 2**).

TABLE 2 | Demographic characteristics of the four populations of Saint Louis Zoo patrons: those surveyed during the 2016 One Health Study at the Saint Louis Zoo, Saint Louis Zoo members, Saint Louis Zoo visitors, and people who live in the Zoo Museum District[a].

Demographics	Study group (%)	Zoo members (%)	Zoo visitors (%)	Zoo-museum district[a] (%)
Gender				
Male	20	30	30	52
Female	80	70	70	48
Age				
18–24	1	0	19	12
25–34	14	14	33	18
35–44	28	29	22	15
45–54	15	13	14	17
55–64	20	20	9	18
65+	22	24	3	20
Income				
Less than $25,000	1	1	12	24
$25,000–49,999	18	9	27	23
$50,000–$74,999	54	19	20	17
$75,000–$149,999	25	49	33	25
$150,000 or more	2	22	8	11

[a]*Zoo Museum District is the tax district from which the Saint Louis Zoo receives taxpayer support.*

Survey Results

We asked participants to select and rank the top three health issues facing humans from an extensive predefined list of choices, which

included an "other" option, allowing respondents to provide an answer that was not already in the list. Participants identified the top three important health issues facing humans as (1) nutrition/obesity/diet (49%), (2) costs of health care (48%), and (3) cancer (37%). These responses held true for future concerns, in which participants identified the one issue about which they were most concerned for the future, with costs of health care, nutrition/obesity/diet, and cancer in the top three, at 2, 16, and 11%, respectively. Only 1% of respondents were very concerned about wildlife-related diseases being a future health threat. These responses only differed significantly for the answer choice "mental health," with 24 females identifying mental health as an important health issue compared to 0 males. Results did not vary significantly by age category or income level. When respondents were asked why they selected the one issue they identified as being the most important for the future, most responses referenced the cost of health care, Earth's limited resources, and the broad scope of the one issue they chose (**Table 3**).

Eighty-six percent of respondents were aware that the Saint Louis Zoo conducts projects involving animal health, but only 22% were aware of the Zoo's involvement with projects for human health, and 61% were aware of projects regarding environmental health. However, the majority of those who claimed to be aware were not able to name a specific project or program when asked to describe them. Fifty percent of participants were concerned about humans contracting diseases from wildlife, 34% were not concerned, and the remaining 16% were neutral about the issue. We asked participants to provide why they were, or were not, concerned about humans contracting diseases from wildlife. Among those who were not concerned, 40% "just don't think about it" and 21% have no or minimal interaction with wildlife (**Table 3**). Participants also answered questions about their concern for domestic animals contracting diseases from wildlife. Forty-eight percent were concerned about domestic animals contracting diseases from wildlife, 33% were not concerned, and 19% were neutral about animals contracting disease from wildlife. Of those who were not concerned, 36% "just don't think about it," while 23% indicated minimal interactions with wildlife (**Table 3**). Only 6% of survey participants had heard of the term "One Health," whereas 16% had heard the term "conservation medicine." Participants also provided their interpretation of the term(s) "One Health" and "conservation medicine," and these responses focused on how "the health of everything on earth is interconnected" (**Table 3**).

We asked participants to rank their awareness of the Saint Louis Zoo's role in five different areas of One Health, their interest that the Zoo participates in these areas, and the importance of the Zoo's participation (**Figure 1**). The five different areas referenced in the survey were: (1) providing health care to animals in zoo care, (2) research on how diseases can threaten species with extinction, (3) studying diseases in animals in zoo care, (4) studying how diseases in wild animals have an impact on domestic animals, and (5) research comparing diseases between different species, including humans (**Figure 1**). Eighty-six percent of respondents were aware of the Zoo's role in providing health care to animals in zoo care, 80% were interested, and 95% thought it was important. Fifty-five percent of respondents were aware of the Zoo's role in research on how diseases can threaten species with extinction, 67% were aware of the Zoo's role in studying diseases in animals in zoo care, but only 27% were aware of the Zoo's role in studying how diseases in wild animals have an impact on domestic animals and humans, and only 23% were aware of the Zoo's role in research comparing diseases between different species, including humans. For each of the five areas, except for the category of "providing health care to zoo animals in zoo care," participants were consistently less aware of the Zoo's role in each specific area than their interest and perceived importance of the Zoo's work in that role. Individuals over the age of 55 were significantly more interested in the Zoo's participation in these areas compared to the other age categories.

TABLE 3 | A sample of representative quotes from responses to a One Health membership survey distributed in 2016 at the Saint Louis Zoo.

Quotes
3. What do you think are currently the most important health issues facing humans? Which one of these issues are you most concerned about in the future? Why?
"If we cannot sustain a livable environment, none of this matters."
"Environmental factors contribute to many of the other issues we face, from cancer to health risks, we don't even know about."
"With the changes in our health-care system recently, I am finding that even as a middle class American, health care is expensive. […] Cost should not be the driving factor in our health care."
7. How concerned are you about humans contracting diseases from wildlife? How concerned are you about domestic animals contracting diseases from wildlife? Why?
"Although humans do contract diseases from animals (ebola, strains of influenza, and even originally HIV), there are many other health concerns that lead to more human diseases and deaths that are purely human caused. Plus, our human population is still increasing dramatically."
"In most cases, humans don't have much actual contact with wildlife except for insects—the zeka (sp) virus is still an unknown. In spite of certain special interest groups, I do not see a threat to domestic animals (except for the occasional dog vs skunk—or, more seriously, snake)"
"Not in the news so assuming it's not a huge issue"
9. What do the term(s) One Health and/or Conservation medicine mean to you?
"Working with the environment. The health of everything on earth is interconnected"
"Simultaneously addressing the combined health concerns of humans and wildlife."
"One Health means nothing to me. Conservation medicine means (to me) ways to keep animals healthy so they can survive and reproduce, particularly for endangered species."

In this table, all the questions refer to survey questions from **Table 1**.

DISCUSSION

The findings from the survey revealed that Zoo members primarily cared about chronic, non-communicable diseases, and their associated costs. These results were initially surprising, because at the time of the survey, Zika outbreaks were receiving heavy media attention. However, when examined in the context of population surveyed and the political climate at the time, these results were more understandable. The United States has

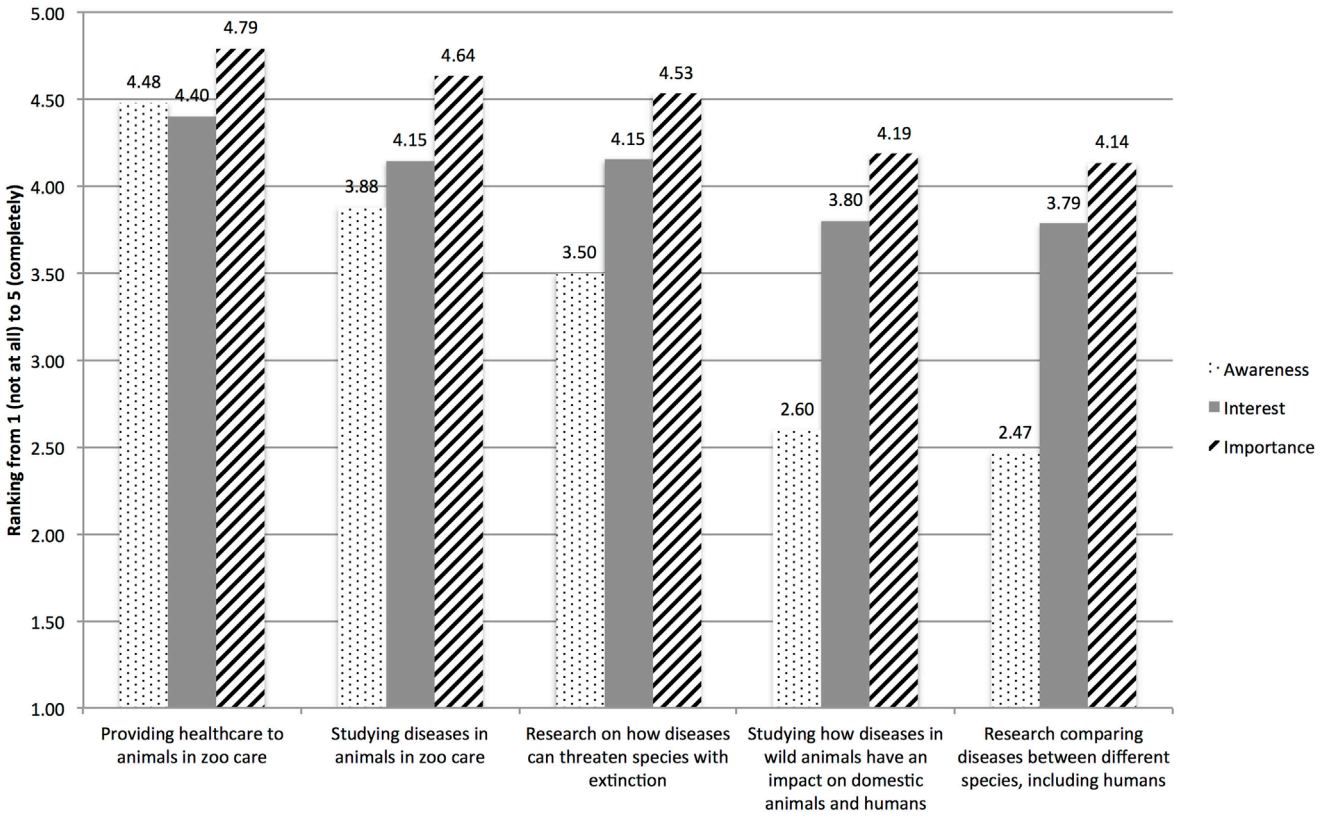

FIGURE 1 | Saint Louis Zoo member responses from the One Health membership survey on the five key tenets that zoological institutions have in regards to One Health. Awareness, interest, and importance of these actions at the Saint Louis Zoo were measured for each tenet.

already undergone an epidemiologic transition and thus, more people are afflicted with chronic, non-communicable diseases that are associated with increased health-care costs. Leading up to the 2016 United States Presidential election, there was growing unrest in the general American population around the recent implementation of the Affordable Care Act, mostly aimed at the lack of affordability of health care. While the survey results indicated Zoo members focused on health-care costs, these results may not be representative of the larger American population. Possibly related to the physical geography of the United States and the varying population densities, there may be a higher perceived threat from zoonotic diseases in people residing in coastal areas compared to the Midwest. Although One Health initiatives by zoos and other conservation organizations have primarily focused on messaging about infectious, zoonotic diseases (11, 13) to more effectively promote One Health programs at zoos, it may be beneficial for zoos to address the health concerns more specific to their zoo-going population. The results of this study may serve as a template to help guide zoos in their development of One Health messaging.

Along with learning about human health benefits, Zoo members were overwhelmingly interested in learning about the Zoo's activities in One Health and believed these to be an important role for the Zoo. People were more familiar with the term "Conservation Medicine" (16%) than "One Health" (6%), but their general lack of awareness of the terms themselves indicates that we should do more to effectively disseminate information about the ICM and the role of the Saint Louis Zoo in One Health.

The survey indicated that there is interest in One Health in the St. Louis community of Zoo members and to promote it messaging should include One Health in the context of chronic, non-communicable diseases, in addition to our other more ecological research-focused programming. This messaging should also be aimed at individuals over the age of 55, who were consistently interested in the Zoo's activities, but less aware. People were generally aware of One Health activities, but then were unable to put a term to these activities. The messaging from the ICM about One Health, *via* newsletters, magazines, talks, and social media outlets did appear to have some impact on the member community. The ICM continues to pave the way for further more effective messaging to the Zoo's membership and visitors regarding One Health.

This study provided a brief, but valuable insight into Zoo members' understanding of One Health, which may help inform not only our future work at the ICM, but also at other zoos as they develop programs to promote and disseminate information regarding the One Health initiative. While the results obtained are valuable, it is important to note the limitations of the study itself. The surveyed population was Zoo members, who primarily

reside in St. Louis and the surrounding areas. As the Saint Louis Zoo does not have an admission fee for visitors, its members may be distinct socioeconomically from the general population of Zoo visitors. Even with this distinction, the study population still represented a varied socioeconomic demographic, with 40% of study respondents being from zip codes below the median household income in the United States. The study is also subject to volunteer bias, as we sent the survey to over 3,000 individuals, but only 285 provided complete answers. In regards to how the respondents answered questions, the survey was distributed when there was heavy media attention on the Zika outbreak, which may have influenced responses to health concerns: however, our data do not support this line of thinking. Additionally, survey respondents primarily lived in urban/suburban areas, and thus the results are not generalizable to rural settings. Overall, this survey offered a valuable initial look into the minds of Zoo visitors/members, with results that may help assist other zoos in One Health program development and/or implementation.

On the survey, individuals identified poor diet/obesity/lack of nutrition as one of their top three concerns. This concern may be easily addressed by One Health messaging since zoos help tackle this challenge by efforts to protect pollinators, like bees and bats, thus increasing food security and enabling a higher quality diet. Zoos provide communities with access to greenspace, and it has been shown that increased time in nature may mitigate the negative health impacts of urbanization (17, 19, 20, 22, 26, 27). Zoos promote healthy lifestyles by providing access to exercise and requiring movement by visitors, thus potentially having an impact on obesity, and health-care costs (18). Zoos also play an important role in conservation, which has long-term health impacts for individuals, reduces health-care costs, and increases healthy behaviors (5, 27).

While individuals' concerns over health-care costs and chronic diseases need to be addressed by One Health practitioners, infectious diseases should not be neglected in communication between zoos and the public. As climate change progresses and human habitats expand, there will be an increase in human–wildlife interactions, leading to an increase in zoonotic disease transmission (21, 28–30). Zoos have both the resources and capabilities to promote One Health, and they may provide messaging about it by sharing information on the positive health impacts zoos offer to their human visitors, while continuing to work to promote healthy habitats for humans and animals.

ETHICS STATEMENT

This study involved an online survey of members and was exempt from Institutional Review Board (IRB) approval. Completion of the survey indicated consent.

AUTHOR CONTRIBUTIONS

Conception or design of the work and acquisition, analysis or interpretation of data for the work; drafting the work or revising it critically for important intellectual content; final approval of the version to be published: and agreement to be accountable for all aspects of the work: HP, AN, ET, and SD.

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Urban Livestock Keeping in the City of Nairobi: Diversity of Production Systems, Supply Chains, and Their Disease Management and Risks

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Urban livestock keeping in developing cities have an important role in food security and livelihoods but can also pose a significant threat to the environment and health of urban dwellers. The aim of this study was to identify the different livestock systems in Nairobi, their supply chains, and their management and food safety risks. Seven focus group discussions with livestock production officers in charge of each major Nairobi sub-county were conducted. Data were collected on the type of systems existing for each livestock species and their supply chains, disease management, food safety risks, and general husbandry and gender factors. Supply chain flow diagrams and thematic analysis of the data was done. Results of the study show a large variability of livestock keeping in Nairobi. The majority were small scale with: <5 dairy cows, 1–6 dairy goats, <10 small ruminants, <20 pigs, 200–500 broilers, 300–500 layers, <10 indigenous chickens, or <20 rabbits. Beef keeping was mainly described as a "by the way" system or done by traders to fatten animals for 3 month. Supply chain analysis indicated that most dairy farmers sold milk directly to consumers due to "lack of trust" of these in traders. Broiler and pig farmers sold mainly to traders but are dependent on few large dominating companies for their replacement or distribution of products. Selling directly to retailers or consumers (including own consumption), with backyard slaughtering, were important chains for small-scale pig, sheep and goat, and indigenous chicken keepers. Important disease risk practices identified were associated with consumption of dead and sick animals, with underground network of brokers operating for ruminant products. Qualified trained health managers were used mainly by dairy farmers, and large commercial poultry and pig farmers, while use of unqualified health managers or no treatment were common in small-scale farming. Control of urban livestock keepers was reported difficult due to their "feeling of being outlaws," "lack of trust" in government, "inaccessibility" in informal settlements, "lack of government funding," or "understaffing." Findings are useful for designing policies to help to control urban livestock production and minimize its associated health and environment risks.

Keywords: urban livestock, supply chain, disease management, food safety, Nairobi, gender, risk practices

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INTRODUCTION

Urban agriculture is a dynamic concept that comprises a variety of livelihood systems ranging from subsistence production and processing at the household level to more commercialized agriculture. However, many urban farmers around the world operate without formal recognition of their main livelihood activity and lack the structural support of proper municipal policies and legislation (1). The attention given to urban agriculture has grown quickly over the past decades with the formation of an urban agriculture advisory committee by the United Nations Development Program in 1991. Mireri (2) classified urban farmers into three categories: (1) urban inhabitants who rely on farming as an important source of food; (2) commercial urban farmers who are formally employed and engaged in farming to supplement their hitherto low wages; and (3) those doing farming as their employment due to a weak economic base or lack of appropriate skills to participate in the modern sector. In addition, some people in urban areas keep animals for traditional purposes or as hobby. All these urban livestock keepers can play an important role in food security, but can also represent an important risk of pathogens transmission (zoonotic and non-zoonotic) and environmental contamination (1, 3, 4).

Nairobi, with 3.4 million inhabitants, is one of the fastest-growing cities in Africa with increasing demand for land and animal source products (5). The conversion and encroachment of potential agricultural lands into urban and peri-urban residential uses is leading to rapid transformations of the agricultural production (6). Today, regardless of farming being prohibited within city boundaries, there is a significant population of livestock (7). According to the 2013 report produced by the Kenyan Ministry of Livestock and Development (MoLD), the livestock population in the city was around 1.3 million (8). Crude biomass estimations indicate that there was 0.22 kg of livestock biomass per 1 kg of human biomass (0.11 kg of pigs, 0.09 kg of dairy cattle, 0.2 kg of beef, sheep and goats, 0.01 kg of poultry).[1] Poultry (with over 880,000 birds, half of them broilers) and pigs represented, however, the largest number of livestock in the city. In the period 2009–2012, the population of broilers in Nairobi has doubled, the population of layer birds has increased by 34% and the population of pigs has increased by 56% (8). Urban dairy cattle produced almost 4.5 million kilogram of milk per year, with a 4 and 14% increase in production in 2012 and 2011, respectively. Dairy, broiler, and egg production represented the priority commercial enterprise among livestock keepers in most parts of the city. Rabbit and dairy goat are emerging urban productions, while the sheep population rose 15% in 2012. Despite the overall increase in urban livestock population in Nairobi, there is a lack of comprehensive studies describing the type of livestock systems in the city, the value chains used, their role and their animal health and food safety management. For this, thematic qualitative research methods are useful as they allow exploring and identifying the diversity of systems and factors, and avoid restricting findings to predetermined knowledge. Furthermore, given the large size of the city and the wide range of livestock species raised, focus group discussions (FGDs) with key informants represent the most efficient approach to capture an overview of urban livestock keeping that can then be used for more detailed and focused research studies. For this, the livestock production officers (LPOs) represent a potential group of key informants. These are public administrators within the Ministry of Livestock Development whose jurisdiction is to supervise, give advice, and provide extension services on husbandry and farm practices to livestock keepers. These officers are, therefore, routinely exposed to the different types of livestock keepers in the city, giving them an important field experience and overall understanding of these urban systems, as shown in their 2013 report on livestock production in Nairobi (8).

The present study aims, through focus groups with Nairobi LPOs, to (1) identify and quantify the type of livestock keepers in Nairobi, (2) map their supply chains, (3) describe their main husbandry and gender patterns, and (4) assess their principal animal health management and food safety risk practices.

MATERIALS AND METHODS

The Approach and Selection of Participants

A cross-sectional study was conducted in Nairobi County, Kenya, in 2013 and 2014. Six FGDs were conducted with LPOs from six Nairobi sub-counties (one separate FGDs per sub-county): Dagoretti (three participants), Lang'ata (four participants), Kasarani, Embakasi (both with five participants), and Njiru and Makadara (both with three participants). In addition, one FGD was conducted with a neighboring sub-county (Thika west—three participants) (**Figure 1**). These sub-counties represented the former district divisions. Kamukunji and Starehe sub-counties were not included in the study because they are located in the Nairobi's business center and have minimal livestock production. Westlands district was not visited; Dagoretti was used as a proxy for this district. Overall, 23 participants (10 women and 13 men) LPOs participated in the FGDs. These belonged to a range of ethnic groups coexisting in Kenya (Kikuyu, Kamba, Luo, Kalenjin, Luhya, among others).

Research study ethical approval was obtained from the ethical committees from the International Livestock Research Institute (ILRI-IREC2014-04/1) and the Royal Veterinary College (URN 2013 0084H). Permission to do the study was granted by the Kenyan Ministry of Agriculture and Livestock Development. The FGDs were organized with the help of the chief LPOs of each sub-county, who facilitated assistance of the officers.

Data Collection

The FGDs followed a semi-structured interview guide. The purpose of the study was explained prior to the FGDs to participants; these were requested to provide written consent. Subsequently, the officers were asked to enumerate and explain their roles and

[1]Crude biomass estimations based on data from the Ministry of Livestock and Development report 2013 (8) and using corresponding average adult live weights and half of this weight for young people and livestock. The estimation also assumes that 75% of humans are adults; 75% of dairy cattle, dairy goats, and layers birds are adults; and 50% of other livestock are adults.

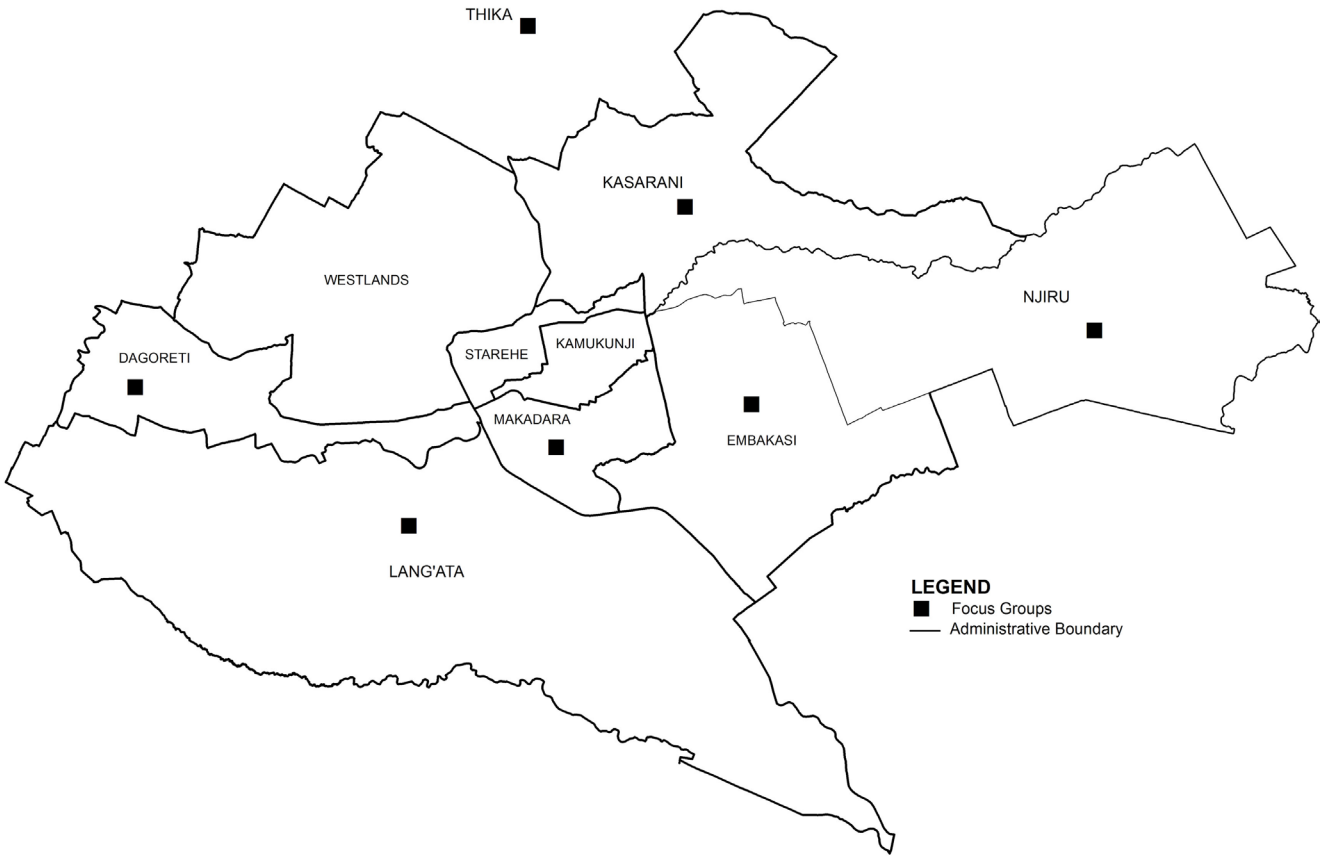

FIGURE 1 | Division of former sub-counties in Nairobi, and indication of sub-counties where focus group discussions with livestock production officers were conducted.

responsibilities as LPOs and the main challenges they faced as part of their everyday work. After this, the FGD activity was divided into seven parts; each of these focused on a specific livestock species (i.e., broilers, layers, indigenous chicken, pigs, beef cattle, dairy cattle, and small ruminants). Other livestock species were then also discussed if found relevant by participants in the area (e.g., dairy goats and rabbits).

For each livestock species, the following aspects were covered with the participants:

1. Identification of different production systems in their respective sub-counties: LPOs were given the freedom to categorize farms as they felt appropriate, but were also asked to categorize livestock keepers according to the size of production systems. Once the different systems were identified, LPOs were asked to estimate the proportion of livestock keepers falling under each type of production system. The classification was then drawn in a flipchart and was used as a basis for subsequent questions.
2. Mapping of existing supply chains: the main input sources (replacement stock, feed, and water) and output sources (animals and animal-derived products) used by the different systems were mapped. The proportion of livestock/product flowing through each supply chain for each livestock system was then estimated based on feedback provided by participants.
3. Identification and description of the relevant formal and informal animal health providers in each production system.
4. Description of the management practices of dead animals and the perception and experiences shared by participants concerning the most important food safety risks associated with each livestock production system.
5. Description of the main gender's roles and responsibilities for each livestock production system.

The interview guide allow for flexibility and probing of the questions depending on the issues raised by participants (e.g., follow-up questions were possible if a food safety risk was mentioned by participants when discussing other sections, such as supply chain structure). The finalized interview guide used for the FGD can be accessed in the Supplementary Material Annex A. Quantitative data were obtained through achieving consensus on the adequate proportions and ranks given to each system, supply chain, or other factor. For this, participants were asked to agree or to provide a different estimate on the proportion obtained. When discrepancies emerged, the facilitator encouraged the discussion

among participants to agree on final estimate. All seven FGDs were voice recorded and six of these were also video recorded after permission was given by participants. Each FGD lasted between 3 and 4.5 h.

Data Analysis

Data collation and qualitative thematic analysis: all data were collated into templates using a customized Microsoft Word document. These templates presented the following coding structure, repeated accordingly for each livestock species (except the first two codes):

(1) LPO responsibilities,
(2) LPO challenges,
(3) Value chain functionality:
    a. Type of livestock systems,
    b. Source of replacement animals,
    c. Source of feed and water,
    d. Distribution of livestock and animal-derived products,
    e. Challenges in the supply chains,
    f. Livestock keepers associations or groups (formal or informal).
(4) Animal husbandry issues
(5) Gender issues,
(6) Use of different animal health providers,
(7) Management of dead animals,
(8) Food safety risks,
(9) Other factors.

Triangulation was followed for the purpose of this project, through an iterative process of careful analysis of the content of the memos produced by researchers during the FDGs with the respective audio/video recordings of these sessions. Relevant data were then collated and placed within each of the coding sections. Thematic analysis (9) of the data was then conducted to identify salient themes that provide an understanding of the factors associated with the codes described above. A theme may represent a perception reported by the participants about a given code (e.g., a perception on a given food safety risk) or could be a factor emerging from the discussions between the participants that the authors identified as relevant within a specific code (e.g., "Adult pigs are slaughtered in backyard areas without any inspection" reported during discussion of supply chain functionality and classified as a theme within food safety risks). This analysis was performed separately for each sub-county (or each FGD), in order to maintain association of salient themes with the relevant geographical area. Themes from all the areas were then compared to produce a narrative for each of the codes. In addition, salient themes related to animal health managers were plotted in diagrams to better visualize dissimilarities on the roles of these stakeholders across the different types of livestock production systems. The same team of researchers that conducted the FGDs also performed all transcriptions of relevant information from audiovisual records for consistency purposes. The thematic analysis was mainly performed by the first author. The emerging themes were reviewed by two co-authors who participated in the FGDs for validation purposes.

Supply chain mapping analysis: a mapping diagram that represented the overall urban farming supply chains in Nairobi was produced for each livestock species. For this purpose, the diagrams obtained in the focus groups (in the flipcharts) in combination with the salient themes related to chain mapping information collated through the transcription of the audiovisual recordings were combined. Mapping diagrams were drawn using SmartDraw version 4.1 (SmartDraw software Incorporated, San Diego, CA, USA). The use of FGDs to mapping food value chain systems was based on previous studies conducted by Alarcon et al. (10).

RESULTS

Category of Livestock Farms in Nairobi

Classification of livestock keepers according to size of production is shown in **Table 1**.

Dairy Cattle Keeping

Categories of Dairy Cattle Keepers

According to the participants, small-scale farmers with 1–3 animals represented the majority (50–80%) in the city, and were the only type of dairy system reported in informal settlements. Slums were estimated to harbor about 5% of dairy animals in a sub-county. Medium and large farms in the city had between 4 and 20 dairy cattle. Small-scale farmers had an estimated average production of 9–10 l per cow per day, while medium- and large-scale farmers had an estimated average production of 20 and 25 l per day per cow, respectively.

Mapping of Nairobi Dairy Cattle Keepers Supply Chain

The map of the supply chain used by Nairobi dairy farmers, as described by LPOs, is shown in **Figure 2**. Almost all milk produced was reported to be consumed locally and was believed to represent between 10 and 25% of milk consumption in the city (5% of consumption in informal settlements). Participants perceived that dairy farmers prefer selling their milk directly to consumers (60–95%) because it is "more profitable," while consumers prefer buying from farmers because of "trust in quality," "cheaper prices," and its "easy access." Furthermore, hawkers (street mobile vendors) were mentioned not to buy milk from local farms because of "high farm-gate prices compared to farms outside Nairobi." However, in some informal settlements local farmers selling to hawkers were reported to be the prominent route of supply. The general pattern described was: small-scale farmers mostly selling directly to consumers; medium-scale farmers selling to processors, hawkers, hotels, and traders; and large-scale farms selling almost exclusively to processors. Several farmers in Nairobi also were reported to make fermented milk ("mala") from the excess of milk, which was consumed in the family or to sell it to limited number of local consumers.

General Dairy Cattle Farm Management and Gender Characteristics and Challenges

A zero-grazing system was reported to be the most frequent, where farmers cut the grasses alongside the roads and collect

TABLE 1 | Number of livestock kept per livestock keeper category identified for each species in Nairobi (in brackets the proportion of livestock keepers with each species in each area).

Species	Farm type	Dagoretti	Njiru	Kasarani	Langa'ta	Makadara	Embakasi	Thika west
Dairy cow	Total animals	3,884	1,157	7,744	11,345	535	1,900	
	V. small	–	–	–	–	1 (40%)	–	–
	Small	1–2 (majority)	1–3 (30%)	2–5 (50%)	1–2 (70%)	2–3 (40%)	1–3 (65%)	1–5 (80%)
	Medium	3–20	4–10 (60%)	6–19 (25%)	3–5 (29%)	4–9 (20%)	4–10 (20%)	6–10 (18%)
	Large	–	11–50 (10%)	>20 (20%)	11–15 (1%)	10	11–20 (15%)	10–20 (1.5%)
	V. large	–	–	300 (5%)	–	–	–	>20 (0.5%)
Sheep and goats	Total animals	7,922	5,425	9,820	22,390	2,048	5,370	
	V. small		<5	–	–	–	–	–
	Small	2–3 (80%)	6–10 (20%)	2–3 (70%)	1–6 (80%)	5–10 (70%)	1–3 (30%)	1–3
	Medium	10–20 (20%)	11–20 (60%)	10–15 (10%)	7–12 (18%)	11–50 (30%)	4–10 (20%)	4–10
	Large		21–50 (10%)	20–30	–	–	11–100 (35%)	10–15
	V. large		50–500 (5%)	>100	200	–	100–500 (15%)	
Pigs	Total animals	4,911	3,334	16,136	?	1,269	3,660	
	Small	–	1–5 (35%)	2–10 (80%)	2–8	1–2	1–5 (25%)	1–10 (80%)
	Medium	–	6–50 (15%)	11–15 (30%)	9–15	3–5	6–20 (60%)	11–20 (15%)
	Large	5–49	>50 (15%)	50	16–40	6–10	21–50 (15%)	30–50 (5%)
	V. large	50–100	–	–	–	>20	100–500 sows	–
Rabbits	Total animals	3,087	3,361	9,352	6,380	5,666	2,350	
	Small	1–5 (majority)	1–5 (40%)	–	5–10 (28%)	1–5 (60%)	1–20 (60%)	–
	Medium	–	6–20 (50%)	–	11–30 (70%)	6–10 (20%)	21–100 (35%)	–
	Large	–	21–100 (10%)	–	50–100 (2%)	11–20 (10%)	101–200 (5%)	–
	V. large	–	–	–	–	20–60 (10%) – one farm 500	–	–
Broiler chicken	Total animals	252,273	16,435	39,950	274,062	17,600	22,000	
	Household	–	Ap. 20 (2%)	–	–	–	–	–
	V. small	–	–	–	–	10 (5%)	–	150–200 (10%)
	Small	–	100–250 (30%)	100 (20%)	100–200 (40%)	50–100 (15%)	50–100 (30%)	300–800 (80%)
	Medium	–	251–800 (60%)	200–250 (65%)	201–500 (40%)	100–200 (30%)	101–500 (70%)	500–3,000 (8%)
	Large	–	801–3,000 (8%)	6,000 (15%)	501–2,000 (20%)	200–500 (30%)	501–1,000	5,000–10,000 (2%)
	V. large	–	–	6,000–10,000	–	–	–	–
Layer birds	Total animals	13,016	13,789	59,605	23,006	15,000	30,500	
	Small	<300	200–500 (20%)	100–200	50–100 (50%)	<100 (30%)	20–100 (30%)	300–500 (80%)
	Medium	300–500 (majority)	501–1,000 (70%)	250–500	101–200 (30%)	100–200 (50%)	101–300 (70%)	500–1,000 (15%)
	Large	–	1,001–2,500 (10%)	100–600	201–500 (20%)	200–500 (20%)	–	>5,000 (5%)
	V. large	10,000 (1 farm)	–	–	–	–	–	–
Indigenous birds	Total animals	41,177	34,669	86,656	20,071	14,500	35,500	
	Household	5 (100%)	1–5 (20%)	1–10 (80%)	1–10 (70%)	2–10	3–10 (100%)	1–10
	V. small	–	–	–	–	–	–	–
	Small	–	6–20 (40%)	–	11–50 (25%)	10–20	–	20–100
	Medium	–	21–50 (30%)	20–50 (20%)	51–100 (5%)	–	–	–
	Large	–	51–200 (10%)		>100 (1 farm)	200 (1 farm)	–	–
	V. large	–	–	–	–	–	–	–

vegetable leftovers, such as kales, cabbages, and maize stoves, from vegetable markets to feed the animals. Some farmers were described to purchase commercial feed from agrovet shops, while few farmers were able to make their own feed formulation. Medium-scale farmers in some areas were reported to buy hay and by-products from brewery companies and about 40% to have their own silage. Several dairy keepers were said to have contract with crop farmers to purchase Napier grass, or exchange it with manure. Large-scale farms were believed to have their own agricultural land outside Nairobi to feed their animals. It was reported that rarely dairy farmers kept a bull for reproduction purposes because of their high cost.

In small-scale farms, dairy animals were said to generally belong to the husband, who makes the major decisions such as buying or selling them. The women were described to be involved in managing the animals and selling the milk, and the money obtained to be shared with the husband. However, for medium- and large-scale farms, men were reported to dominate management activities with increased physical work, such as carrying feeds, while women were mainly involved in milking. In large-scale farms, all the activities were explained to be mostly done by men.

The LPOs perceived that one of the important challenges faced by dairy farmers was the "lack of land" to construct the

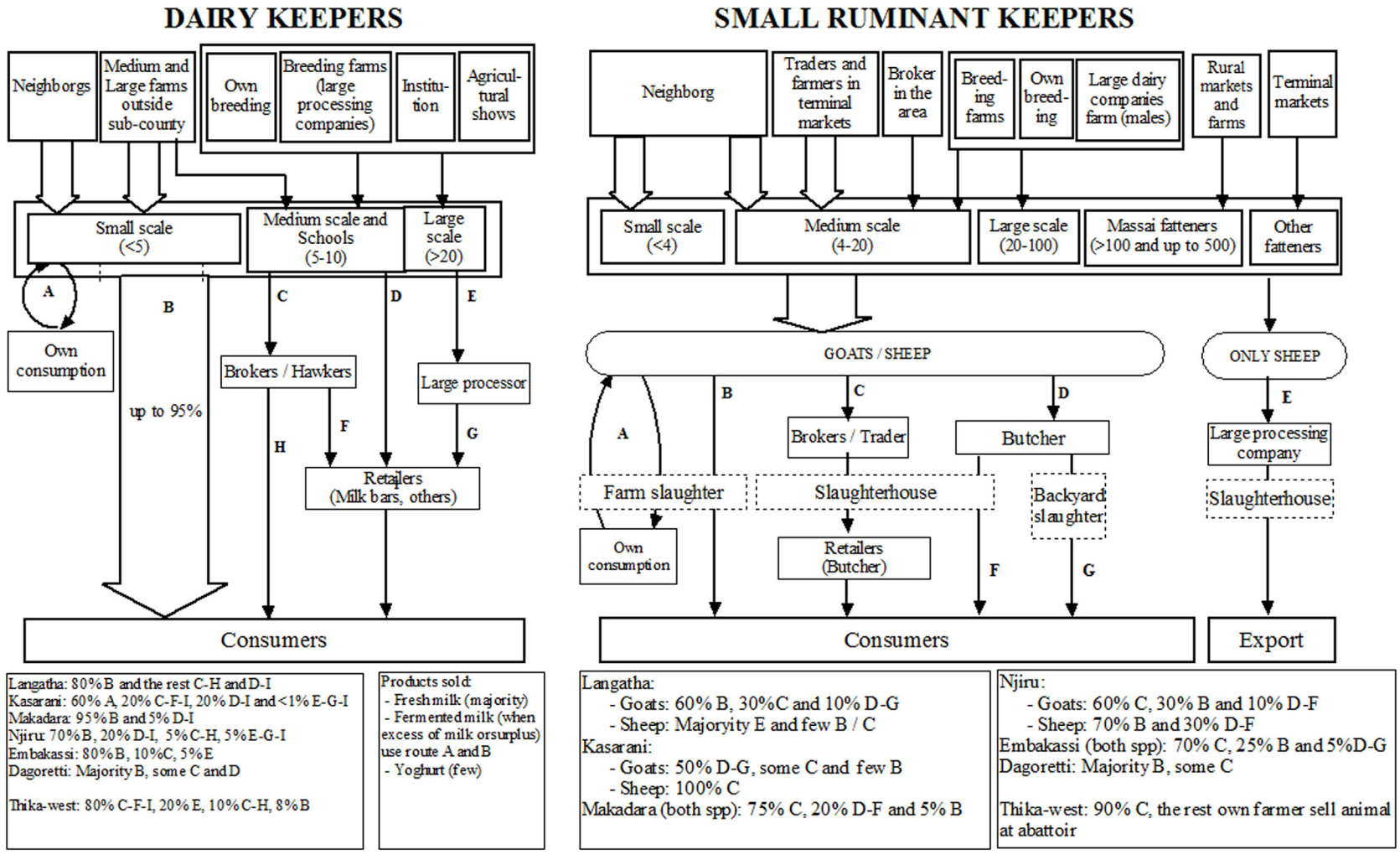

FIGURE 2 | Supply chain mapping for the dairy urban keepers (left) and small ruminant urban keepers (right) in Nairobi. The box at the bottom of the figure shows the percentage of the overall flow of products (dairy) or animals (small ruminants) within each of the distribution chains identified in each sub-county.

recommended animal houses and to graze the animals. Many dairy farmers were described to have "poor and dirty structures" to keep their animals. In informal settlements, many dairy keepers were said to share the same house with their cattle, keeping these in the living rooms or in the bedrooms. "Insecurity" was another challenge identified by participants, with animals being stolen and sold to slaughterhouses. LPOs explained that farmers prefer building animal houses close to residential houses to protect animals from thieves. The "high price of feeds" was believed to be the main challenge faced by medium and large-scale farms.

Beef Keeping

Category of Beef Keepers

It was estimated that most beef animals reared are Boranas or zebu. Beef farming in Nairobi was described as a "by the way production," meaning that it normally happens as an aside to dairy or other activities. Six types of beef keepers were identified in Nairobi:

(1) *Maasai beef fatteners*: these were described as Maasai communities who keep large numbers of beef cattle (and also sheep and goats) in Manyattas (temporary traditional structures) mainly for fattening purposes (~3 month). They were reported to keep from 10 to 200 animals.
(2) *Other temporary beef fatteners*: these were described as traders who buy beef cattle from rural areas and fatten them for 1 month in areas near the slaughterhouses in Nairobi.
(3) *Animal transit keepers*: they were described as mainly pastoralists (mostly Maasai) who graze their animals along the roads and to come from neighbor counties outside Nairobi, such as Kajiado. They were said to come in search for pastures, especially during the dry seasons.
(4) *Keepers that come to slaughter*: these were identified by LPOs as people who bring their animals for slaughter or sale in the city terminal markets. However, in several cases, these animals were believed to end up staying for long periods in the area and some even to reproduce.
(5) *Beef farms*: in one sub-county, two beef farms with normal breeding activity were identified. Few institutions, such as schools, also were reported to rear beef cows.
(6) *Bull calves producers*: these were described as traders who buy small male calves at weaning from the dairy farmers and rear them. Also, some dairy farmers were said to keep few male calves and rear them for sale at one and half years old. It was estimated that these producers correspond to the majority of beef keepers in one sub-county (60%).

Supply Chain Analysis of Nairobi Beef Keepers

Participants reported that most animals from beef farms in Nairobi are sold to traders or brokers who slaughter the animals in the terminal markets that are close to their settlement. Some were said to be sold directly to butchers and retailers. In this case, animals were described to be also slaughtered in the terminal markets. In many settlements, such as the Maasai fatteners, the milk and mala (fermented milk) from beef cows was believed to be produced and consumed by them. Some beef producers in the city were mentioned to sell beef calves to finishing farms outside the sub-county.

General Beef Farm Management and Gender Characteristics

Most animals kept by Massai beef fatteners were reported to graze in informally organized pasture areas within the sub-county, along roads and river sides. In Embakasi, up to 1,000 beef cattle were estimated to be found in grazing areas near the abattoirs. LPOs believed that these keepers do not own the land, but that this normally belongs to the government. The bull calves were described to be mainly zero grazed (80%) or to be tethered outside to graze (20%). The zero-grazed animals were reported to be normally fed on "high-quality feed" from agrovet shops and/or with grass or hay cut along the road. Some beef keepers were said to have small gardens that they use to cut grass.

Participants perceived that men dominate all beef rearing and selling activities in the city, with the exception of beef calves born on dairy farms. In these farms, women were reported to mainly rear the animals, but the men to maintain the ownership and to sell them.

Sheep and Goats Keeping

Category of Small Ruminant Keepers

The majority of small ruminant keepers were classified as small-scale (1–5 goats) and medium-scale farms (4–20 small ruminants), except in one sub-county where 50% of animals were reported to be clustered in large and very-large farms, with up to 500 sheep and goats per farm. Large farms with over 100 animals were described as Maasai temporary farms, but who could raise animals for up to 6 years. Transit keepers were also reported, corresponding to those that bring the animals to the terminal market or for grazing only. Fatteners, who are traders that buy animals in terminal market and fatten them for 2 month, were also identified. The ratio of goat to sheep varied depending on the size of the farms, with small farms keeping mostly goats and larger farms having an equal share of both species. In informal settlements, only small sheep and goat keepers were reported to exist. Most of these small-scale farmers were believed to keep small ruminant as a source for emergency funds.

The main breed of sheep in Nairobi farms were reported to be the Red Maasai and the Dorper. More purebreeds were said to be found in large farms, and a mixture of breeds in the medium- and small-scale farms. The main breeds of goats were the East African goat and the Galla goat.

Mapping of Nairobi Small Ruminant Keepers Supply Chain

Figure 2 also shows the supply chain associated with Nairobi small ruminant keepers, as perceived by LPOs. Several LPO focus groups had difficulties separating the food chains of goats and sheep. The reason reported was that many stakeholders sell sheep products, but label them as goat products. This was believed to be done because (1) "goats have higher demand than sheep in the market," and therefore a higher value, (2) "consumers cannot differentiate between sheep and goat meat," (3) "some consumers believe that goats carry fewer diseases," and (4) "for some families sheep meat is a taboo." Consequently, butchers were recommended to leave part of the goat tail in the carcass to facilitate

identification. Sheep supply chains were reported to be directed to high income consumers or type of families with culture of eating these animals.

Backyard slaughter on the farm or homestead was reported as a frequent practice and associated with festive seasons and celebrations or ceremonies. For this, many consumers were believed by LPOs to prefer buying directly from Maasai keepers because their goats are perceived to have "better taste" as they are grazed in the forest. The main reasons provided for consumers to buy from local farms directly and do backyard slaughtering were (1) the "high prices in festive seasons" (it is cheaper to buy a live goat) and (2) the fact that this "helps them to have fun, learn how to slaughter and to teach their children."

General Farm Management and Gender Characteristics and Challenges

Small farms were described to mainly feed their animals through scavenging, but also using vegetable markets waste and restaurant food leftovers. In two sub-counties, over 50% of small farms were estimated to raise their sheep and goats with zero-grazing practices. Most medium-scale keepers were reported to operate using a zero-grazing feeding regime. Large farms and fatteners were said to graze their animals in pastoral areas in the city. As with beef, Maasai keepers were described to raise and graze their animals in land owned by other people or the government.

Livestock production officers perceived men to dominate small ruminant rearing and selling among the Maasai keepers in the city. In other tribes and for small-scale farms, women were reported to be involved in rearing the animals because "these are easy to manage," but men to be in charge of selling them. Participants believed that the main challenges faced by small ruminant keepers were the "lack of grazing area," with grazing areas near the river being fenced; "insecurity and thieves," especially in festive seasons with transit farmers more affected; and "animal diseases."

Pig Keeping

Categories of Pig Keepers

Small-scale farmers keeping 1–5 pigs (1–2 sows) were identified by LPOs as the most frequent system. These were reported to be mainly located in informal settlements (80% of pigs in Korogocho and almost all in Kibera). However, in Dandora dumping site, with 1,500 pigs, 65% of keepers were estimated to have between 6 and 50 pigs. Very-large farms composed of 100–500 sows were reported to exist in one sub-county. Around 70% of pig farmers in the city were described as farrow-to-finishing in the city, while the rest were finishing farms. Pigs were mentioned to be sold at a live weight of 70–90 kg and at 8 month of age for small and medium keepers, and at 5 month of age for large farms.

Mapping of Nairobi Pig Keepers Supply Chain

Figure 3 shows the supply chain associated with Nairobi pig keepers, as perceived by LPOs. Selling pigs to a large integrated company (Farmers' choice) was reported as the most frequent chain in two sub-counties (50–70%) and to be minimal in other areas. It was mentioned that this company requires large number of animals per shipment and, therefore, is only accessible to medium to very-large farms. "Better prices" and "proximity to the company slaughterhouse" were also important factors perceived by participants for farmers to sell to this company. Selling live pigs to pork butcheries through brokers was reported to be mostly done by small- and medium-scale farmers in some sub-counties. However, in other sub-counties brokers were said not to be used because of the low prices they offered for pigs. In these areas, brokers were reported to be used only to sell dead pigs or pigs on the verge of death. Backyard slaughtering was described as a frequent practice due to "lack of abattoirs" existing in most sub-counties and the main route for pigs in informal settlements. In addition, some farmers were mentioned to sell pigs directly to consumers when they have gilts injured during mating.

General Farm Management and Gender Characteristics and Challenges

Feeding of pigs was dependent on the size of the farm and the area (peri-urban, urban, or informal settlement). Small-scale farmers were reported to largely depend on swill and market waste (e.g., sukumawiki, avocadoes, and fruits peeling) and to rarely include any commercial feed because of "lack of capital." Free-range scavenging, with no commercial feed supplement, was described to be practiced by a large proportion of small-scale farmers (50–70%), especially in informal settlements. These farmers were mentioned to release their piglets at 7 weeks of age to scavenge with their mother. The medium-scale farmers were reported to use swill (from restaurants and schools) and commercial feed (mostly from agrovet shops).

Pig keeping in the city was perceived by LPOs a male dominated activity (mostly by youth), except in large farms where both genders were reported to be involved. The important physical activity required (e.g., pulling carts full of market waste) and the fact that pig keeping is done in a "dirty environment" were the main reasons identified by the participants for the lack of women operating in these systems. Women were said to be involved only on cleaning activities. Main challenges believed to be associated with pig keepers were: the "lack of pork abattoirs," "scavenging pigs discourage consumption of pork," "perception of being outlaws," and "monopoly of pork in Kenya by [a big integrated company]." For the latter, it was reported that in times when this company stops buying pigs for one reason or another, many farmers ended up keeping their animals unsold for long periods.

Poultry Keeping

Category of Poultry Keepers

Broilers Keepers

Medium-scale farmers keeping between 200 and 500 birds were perceived as the most common broiler system in Nairobi (60–70%). However, in informal settlements such as Kibera, about 80% were estimated to be small-scale farmers, with less than 100 birds. The "very large"-scale farms were reported to be owned by large processing companies. Farmers were also categorized as operating as "individuals" or in "commercial groups." It was reported that many of these commercial groups form medium-scale farms by keeping birds together while maintaining individual ownership. These groups were believed to have been

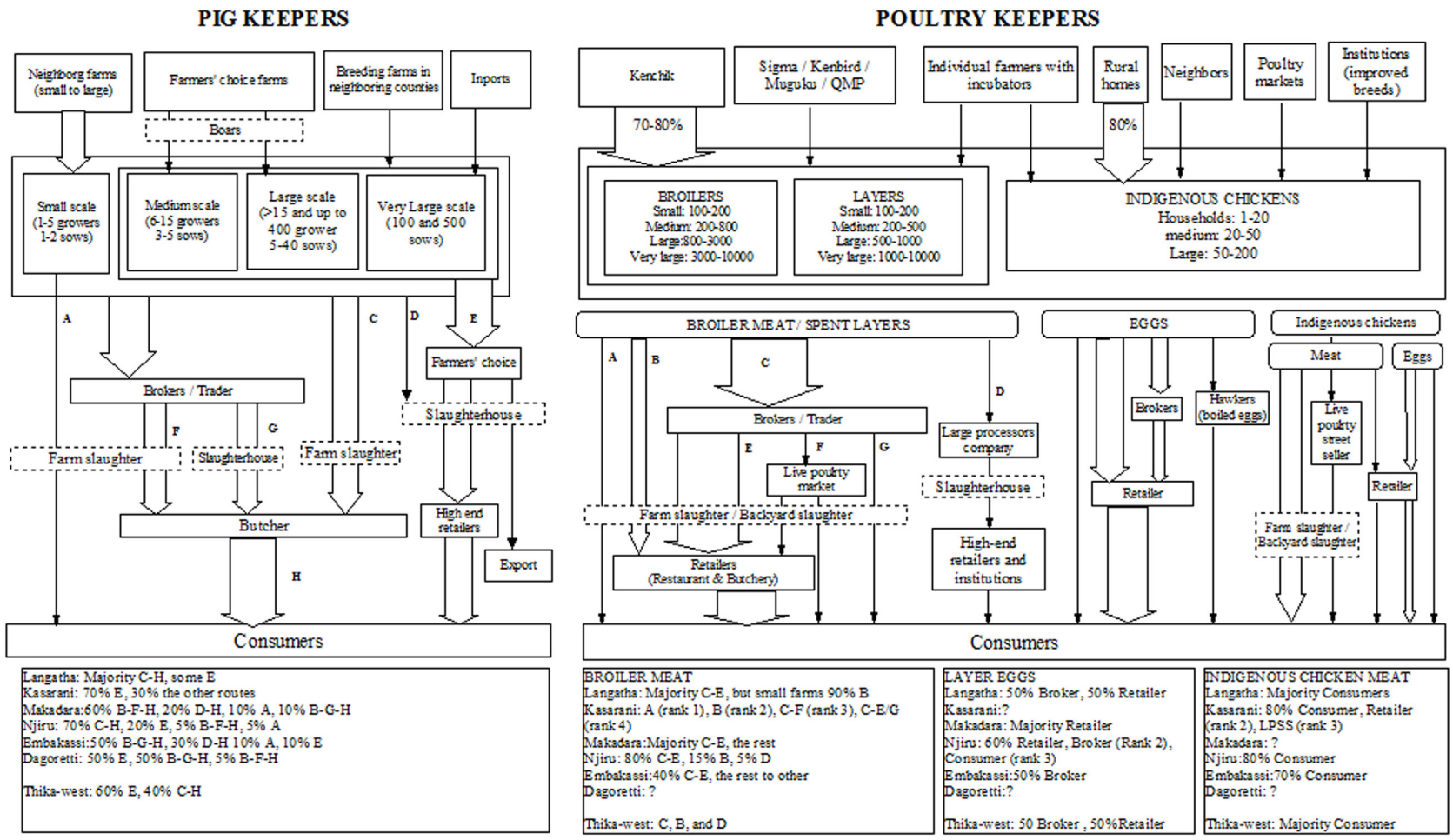

FIGURE 3 | Supply chain mapping for the pig urban keepers (left) and poultry urban keepers (right) in Nairobi. The box at the bottom of the figure shows the percentage of the overall flow of products or animals within each of the distribution chains identified in each sub-county.

created "to obtain funding from the government," "to get training services," and "to improve access to markets."

Layers Keepers

Majority of farms were estimated to keep between 100 and 300 layers. Medium and large farms were described to be run by individual farmers, women groups or institutions, such as secondary schools and churches.

Indigenous Chicken Keepers

Almost all indigenous chickens (65–100%) were reported to be owned by households, who have between 1 and 20 birds. Few large commercial farms with >50 to a maximum of 200 birds were mentioned to exist in several sub-counties.

Mapping of Nairobi Poultry Keepers Supply Chain

Figure 3 shows the supply chain associated with Nairobi poultry keepers, as perceived by LPOs.

Sourcing of poultry:

- *Broilers*: the large majority of broiler farmers in Nairobi (70–80%) were reported to source their day old chicks (DOCs) from one company. The "fast growth of birds" (5–6 weeks to mature compared to 6–7 weeks by other sources), "better feed conversion rates," "lower mortality rates," the company "good reputation," and the "extra services" provided were identified as the main reasons for farmers to prefer this company. Other sources were believed to be used by some farmers because of their geographical proximity. In one sub-county, some farmers were mentioned to have incubators and to sell day old chickens to small-scale farms.
- *Layers*: one large company was identified as the major source of birds for the medium- and large-scale farms in Nairobi (70–80%). Small-scale farmers were reported to source birds from fellow farmers, medium-scale farms, and nearby agrovet shops. In one sub-county, small-scale farmers were reported to buy birds at point of lay (pullets) from the medium-scale farmers, "to reduce feeding cost." In another sub-county, some farmers were said to have their own hatcheries that served both their farms and neighboring small- and medium-scale farms.
- *Indigenous chicken keepers*: most household (about 80%) were reported to source their indigenous chickens from rural areas. Many were explained to be obtained in form of gifts when visiting relatives. Neighbors' farmers and local markets were perceived as other important sources for indigenous chicken in the city. Some commercial farmers were reported to own hatching equipment, while some large-scale farms purchase improved breeds from recognized breeding farms.

Distribution of poultry/products:

- *Broiler*: the majority of farmers (up to 80%), especially medium-scale farms, were estimated to sell their broilers to brokers because "they have ready market," which farmers were said to lack. However, several small-scale farmers were reported to sell directly to retailers because of higher prices. Large-scale farmers were described to sell their birds to large processing companies, who then sell to large hotels and institutions. However, these companies were reported to only buy birds from contracted farms. The legs and heads were described to be mainly distributed through brokers or given to staff as payment for slaughter services.
- *Layers*: LPO explained that eggs from Nairobi farms are sold to retailers or to brokers, who then sell them to retailers. However, brokers were perceived as the least preferred option by farmers because "farmers know the market" and "eggs are easy to carry in trays." Hawkers, those informal mobile street vendors, were identified as the people who buy the crack eggs and boil them before selling to consumers. It was believed that production in some sub-counties cover about 20% of eggs consumption. For the spent layers, it was reported that Nairobi consumers do not differentiate broilers from spent layer meat, and these are then sold in a similar manner.
- *Indigenous chickens*: own consumption or selling of birds directly to consumers were the main chains reported. The "low production of indigenous chickens" and the "high demand" for their products were explained to create an "easy market access" for farmers and "little need to use brokers." Only few brokers were said to be involved with indigenous chicken or eggs. They were stated to purchase only from desperate farmers or in festive seasons when demand is higher. Some farmers were mentioned to sell their birds to people who resell these live birds in roadside sheds or at city market.

General Farm Management and Gender Characteristics and Challenges

Broiler and Layers Keepers

Five important companies supplying feed to broilers and layer farmers were believed to operate. LPOs reported that farmers purchase feed through stockist and agrovet shops. It was believed that the raising number of feed millers has led to "poor feed qualities in the market" which has affected the level of egg production and broiler growth at the farm level. Large companies were also reported to supply feeds to farmers buying their DOCs.

Small-scale farms were described to be mainly operated by women and young woman groups; however, birds were perceived to be owned by men. Medium-scale farmers were said to be run by both genders, while large and very-large broiler farms were operated mainly by men. However, in large-scale layer farms both genders were described to be involved. Participants perceived that the main challenges associated with these system were: "brokers buying broiler per head, while selling to consumers/retailer per kg.," "lack of price harmonization," "lack of knowledge on management practices," "lack of capital to get training," "aflatoxins in feeds," "lack of hygiene at slaughtering, with use of dirty environment and water," and "poor waste disposal by new farmers."

Indigenous Chicken Keepers

Scavenging was reported in all sub-counties, with birds released in the morning to scavenge and to return back in the evening. LPO described that household indigenous chicken keepers were mainly women, the medium-scale farmers were both youth and women, while large-scale farms were run by men. Youths were reported to engage in poultry farming because of "lack of other jobs." In one area, large-scale farming was reported to be practiced

by women groups. Main challenges reported by participants for indigenous chicken keepers were "massive disease outbreaks (e.g., Newcastle) due to lack of vaccination" and "thieves during festive seasons."

Other Livestock Keeping

Rabbit Keeping

Rabbit farming was reported to be gaining popularity in the city and was done by (1) Individual farmers, (2) Groups, or (3) Institutions, such as schools, colleges, and prisons. New Zealand white and California white breeds were identified as the most commonly kept by medium and large-scale farms, while Flamys breed were kept by small-scale farms because of their slow growth. The large-scale farmers were affiliated to "Rabbit Kenya," the only rabbit association in the country, and to be mostly owned by institutions.

Medium- and large-scale farmers were reported to buy bucks from organizations, such as the International Livestock Research Institute, Ngong breeding station-National veterinary farm, Limuru agricultural center, Rabbit republic, and Limuru agricultural center. However, farmers were said to use their own females for breeding and small-scale farmers to buy their replacement animals from fellow neighbor farmers.

Rabbit keepers were estimated to mostly sell their animals directly to consumers or for own consumption (about 50%). However, in one sub-county 90% of farmers were believed to sell rabbits to retailers, such as butcheries and restaurants, through a network of brokers. Institutions were described to mainly keep rabbits for own consumption. Large-scale farmers were reported to also supply big supermarket in the city.

The large- and medium-scale farms were mentioned to feed their rabbits on commercial feeds (pellets), while small-scale farmers feed them on green weeds, grasses harvested from the roadsides and/or gardens, market, and kitchen vegetables leftovers. Rabbit keeping was described as an activity mostly done by woman and children, but large farms were mostly owned by men.

Dairy Goats Keeping

The majority of dairy goat farmers were described as small-scale farmers keeping 1–6 goats, while medium-scale farmers have up to 20 goats. Some medium-scale keepers were identified as institutions, such as women prisons. No large dairy goat farm was reported in the city. In several sub-counties dairy goat keepers were reported to be organized in groups, where farmers help each other in issues of breeding, production and marketing of products.

Many farms were said to source their dairy goats from renowned breeding centers/farms outside Nairobi, several of which are owned by NGOs. A few were mentioned to buy from fellow farmers in the neighborhood. About 75% of the goat milk produced in some sub-counties was estimated to originate from small-scale farmers and to be sold directly to consumers, with the rest used for own consumption. Medium-scale farms were reported to sell their milk mainly to hospitals, and some to other institutions such as colleges and private consumers. The female goats (does) that are replaced were said to be either slaughtered for home consumption or sold to livestock traders, who take them to abattoirs. Most dairy goats were described as enclosed zero-grazed systems, with animals fed on commercial feeds and grass supplementation from roadside grasses and market waste. The dairy goat farming was seen as mostly managed by women, but who need to seek their husbands' permission to sell the animals.

Disease Management and Health Managers

Figures 4 and **5** shows the type of health managers used by each type of livestock keeper and the salient themes associated with each relationship. The health managers reported by LPOs were as follows:

- *Agrovets (Shops selling drugs and animal feeds)*: these were reported to be used by all type of livestock keepers for the supply of drugs, but also to obtain free advice on disease management. However, it was estimated that about 30% of staff working in these agrovet shops lack proper training and that in some cases "farmers are cheated" with wrong information/advice and by selling them drugs about to expire.
- *Unqualified health managers ("quacks")*: these were reported to be mostly used by livestock keepers in informal settlements. LPO explained that these people, however, "claimed to be trained on animal health management." When these "quacks" are faced to a disease situation that are not familiar with, they were said to "visit the LPOs for advice and by pretending to be farmers." Quacks were considered "responsible for high prevalence of animal diseases."
- *Herbalists*: were reported to be mainly used for beef and indigenous chicken keepers. For the latter, they were said to be used in non-vaccinated birds and to treat coccidiosis. Herbalists were considered to lack of any formal animal health training.
- *Animal Health Assistants or "veterinarian paraprofessionals"*: these were described as certificate holders with animal health training from an official institution. They were described also as private agents and to be used by the majority of commercial poultry producers and dairy keepers. It was estimated that they represent about 90% of trained people giving animal health care to farmers.
- *Livestock Production Officers*: these were reported to be used by poultry keepers in informal settlements and pig keepers for issues such as deworming and vaccination. The LPOs explained that they are also frequently used by rabbit keepers as the first call for disease issues.
- *Government veterinarians*: these were considered to be mainly used for inspection of animals slaughtered on farm, by dairy farmers in case of disease outbreaks, and by rabbit keepers when LPOs cannot handle the disease condition.
- *Private veterinarians*: they were reported to be rare and expensive, and mostly used by medium and large farms, and keepers in high income areas. They are considered to be used "when treatment fails on valuable animals" or "when there are large number of deaths." Medium-scale dairy farmers were said to use them also "in cases of dystocia and for vaccination." Some large companies were reported to employ them as farm managers. Dairy goat farmers were mentioned to use them frequently because of the high value of these animals.

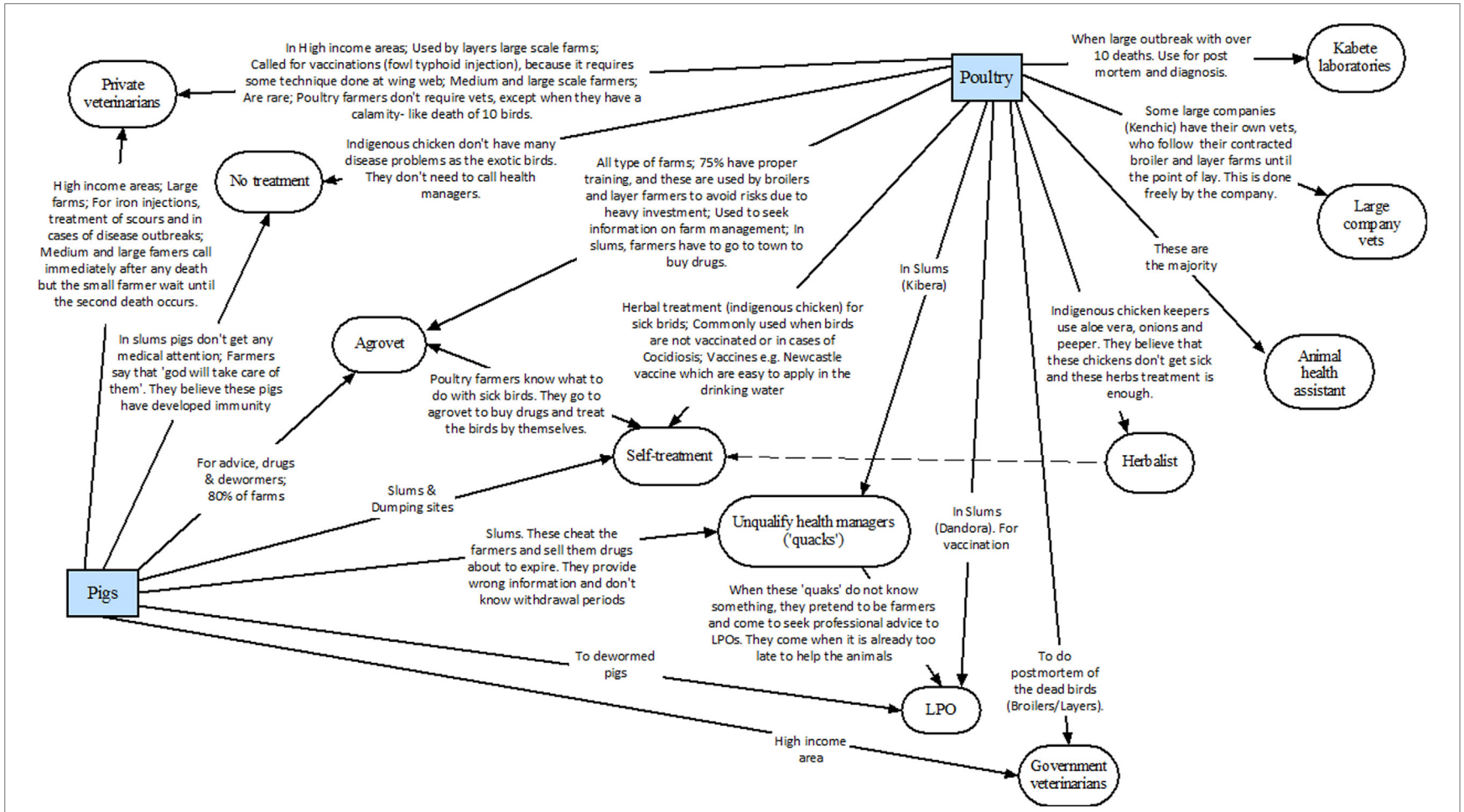

FIGURE 4 | Use of different health managers by poultry and pig farmers in Nairobi, as reported by livestock production officers (LPOs).

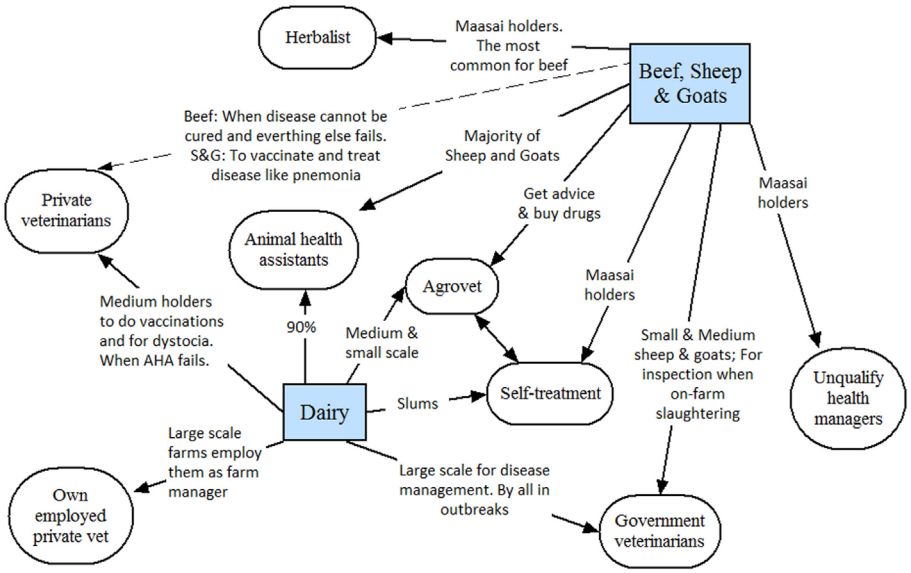

FIGURE 5 | Use of different health managers by beef, small ruminant, and dairy farmers in Nairobi, as reported by livestock production officers.

- *Kabete laboratories (government diagnostic service)*: it was reported to be used by poultry farmers when there is "disease outbreaks with more than 10 deaths."
- *No treatment*: many pig keepers in informal settlements and indigenous chicken keepers were considered to do not treat their sick animals, as they believe these are "resistant to disease" or fail to recognize disease in their animals.
- *Own-farmer treatment*: reported to be mostly done by dairy and pig farmers in the slums, Maasai beef keepers and indigenous chicken keepers. About 10% of livestock keepers were believed to provide self-treatment when animals get sick.

Management of Dead Animals and Main Food Safety Risks

Salient themes associated with management of dead animals and to existing food safety risks are shown in **Table 2**.

DISCUSSION

The existence of livestock keeping in the city responds to a series of factors related mostly to rapid urban growth and individual food security and income generating needs, which outpaces the growth of services and employment, resulting in the majority of urban dwellers being in the low income bracket and having limited purchasing power (3, 11, 12). This fast urban growth also reduces significantly food availability and accessibility, which is aggravated by the increasing number of wealthy consumers in the city competing for food purchases. Urban livestock keeping is, therefore, a source of food security that can release pressure on poor households (that spend 60–80% of income in food) and provide essential micronutrients to avoid malnutrition (7, 13–15). In this study, LPOs estimated that up to 25% of milk or 20% of eggs consumed originate from these urban farmers. Urban livestock is also a source of employment and income, and frequently used to pay for children's schools fees (16, 17). On the other hand, the high demand for animal source foods and increasing number of wealthy investors in the city generates livestock enterprises that employ low income people (18). All these factors explain the large diversity in profiles of livestock keepers in the city observed in this study. This diversity ranges from small scale with 1–2 animals mostly based on own consumption to large-scale commercial farms (with 10,000 broiler, over 2,000 layers, 300 dairy cows, 500 sheep, and goats) located in the peri-urban areas. These urban livestock systems also exhibit a wide variation of management practices as they exploit a number of ecological niches. These management systems ranges from well-structured commercial farms to small zero-grazed systems, transit farmers, temporary keepers, Massai fatteners, and small informal keepers that let pigs, ruminants, or poultry to scavenge freely.

The dynamic change in Nairobi, with increasing population and booming real estate ventures is potentially impacting livestock keeping in the city (6). Many livestock farmers in former rural areas have now become part of the city. Decrease in land size has also resulted in farmers being restricted on the type and size of livestock keeping. Consequently, farmers in the city are changing to intensive poultry and pig farming and to produce alternative species, such as rabbits (8). This is a pattern that is also being seen elsewhere in rapidly developing countries, which need to meet the food security needs of a growing population. The increasing demand for poultry meat and dairy products combined with the lack of cold chain and rapidly perishable products are also the likely reasons for the large number of urban and peri-urban poultry and dairy farmers. Dairy farming was also reported to be sustained in Nairobi due to lack of trust of consumers to milk from traders. For this reason, and due to higher profitability as Omore et al. (19) also identified, almost 95% of their milk is sold directly to consumers. The main reasons for the increase in pig farming has been related to increased

TABLE 2 | Themes related to the management of dead animals and existing food safety risks in urban livestock farms in Nairobi, as obtained from the focus group discussion with livestock production officers in Nairobi.

Species	Themes associated with management of dead animals	Themes associated with existing food safety risks
Dairy cow	Rarely thrown away; Black market where vets lives in slaughterhouses are threatened if they do not cooperate; 90% of dead animals on farms are eaten, with 60% passing through abattoirs; Only those with suspicion of anthrax or FMD are not eaten; Given to feed dogs, or to pigs or crocodile farms; Buried; Thrown to the roadside during night hours; Dairy farmers are literate and do not eat dead animals	Use of plastic containers for milk transport; Milk containers are cleaned only with water and no disinfection; Water used for cleaning of low hygienic quality; Small farmers do not feel responsible for food safety; Sick animals that do not respond to treatment are sent to the slaughterhouse; Farmers do not observe antibiotic withdraw period; poor personal hygiene of people in charge of milking; use of dirty equipment on farms; People doing the milking of cows do not have hygiene certificate; Adulteration of milk is done with water and drugs; Small farmers disposed the manure on the roads; In slums some farmers keep dairy animals inside the household (in their bedrooms); meat is left to dry in the sun; Many dairy animals are kept in dirty shelters, with poor structures, unhygienic conditions and in high populated areas
Beef, sheep, and goats	In slums, dead animals are sold to meat butcheries at low prices, but butcheries sell to consumers at normal prices; No perception of wrongdoing when selling dead animals for consumption; Maasai people know which are the diseases (e.g., anthrax and snake bites) where dead animals should not be eaten; Farmers test for anthrax by throwing a small piece of meat (from their dead animals) to the fire and wait to see if it jumps; The black market for dead animals (operated through a network of brokers) is powerful and organized; Brokers cheat farmers by telling them they will feed their dogs with the dead animals collected (while in reality they sell the meat to consumers); Vets get life threaten to stamp meat (from dead animals on farms) and accept collusion; Few people consume dead sheep because these are perceived to have more pathogens compare to goats; 60% of beef cattle found dead on farms are consumed; 50% of small ruminant found dead on farms are consumed and the rest buried; Small-scale small ruminant keepers burn or bury their dead animals; Cook the meat and sell it to dog owners; Dead animals in field are left for dogs and birds to scavenge on them	The Maasai and small-scale farmers slaughter their sick animals, mix their carcass with some herbs and consume it; Very sick beef cattle may be sent to slaughter quickly without any treatment; Sick animals that do not respond to treatment may be sent to the slaughterhouse (to enter the food chain); Maasai bring animals from outside Nairobi to graze in the city for up to 3 month until they are slaughtered and, therefore, can transmit diseases to other animals in the area; Farmers do not observe the antibiotic withdrawal period before taking the animals to the slaughterhouse; Beef keepers use antibiotics carelessly; Beef keepers do not notify the authorities of the presence of notifiable diseases
Pigs	In slums, dead pigs are sold secretly for consumption; Dead pigs parts are boiled and used to feed other pigs; In dumping site, dead pigs are eaten by the homeless people; Farmers do not eat dead pigs, as they fear them (their meat); Thrown to dumping site for other pig and vulture birds to scavenge on them; Farmers with land bury the dead pigs	In slums, sick pigs may be slaughtered and its meat sold; Farmers do not want to incur on extra costs of treatment of sick pigs; Adult pigs are slaughtered in backyard areas without any inspection; Meat inspectors cannot inspect all pigs that are home slaughter (about 5% are not inspected); Pig feeds that are collected from markets may be contaminated; Farmers like feeding their pigs in the dumpsite and these can therefore transmit pathogens to people through contact or consumption
Poultry	Indigenous dead chickens are thrown into dumping sites for dogs to eat; Vets come to do postmortem of dead birds; When massive deaths occurs (more than 50 birds), these are sold to pig farmers; Single dead birds are cooked and fed to dogs; Small and medium-scale farmers sell dead birds to consumers; In large-scale farms, dead birds are buried; Some people throw them onto the roadside; Layer and broiler farmers do not consume dead birds because of fears of getting sick	Slaughtering is done on farm without any inspection, except for large companies; Inspection at slaughter only done when selling to big outlets (supermarkets and large processors); Hygiene of the farms and of the birds are not inspected; Source and quality of water for slaughtering and washing of carcass cannot be verified; Water contamination at transport level; Antibiotic withdrawal period is not followed by some farmers; Farmers do not wait for sick animals to die, they eat them
Rabbits	Rabbit meat is not very popular, and dead animals are not eaten; Dead rabbits are fed to dogs; Dead rabbits are not eaten even in slums and dumping sites	No inspection of rabbits is done at slaughter except when selling to reputable retailers; There are minimal food safety issues with rabbits because these are fed relatively safe feeds; Farmers do not observe antibiotic withdrawal periods after treatment, and do this knowingly; Rabbits are housed in poor structures and with poor hygiene; Rabbit feed mixes with the urine and suffer from diarrhea

urban pork consumption, proximity to established breeders from a large company and closeness to the feed manufactures (8). However, LPO perceived that the important population of pigs kept in informal scavenging systems creates consumer aversion to pork consumption (as these are perceived as dirty animals and consumer do not trust their meat), presenting therefore an important barrier for its commercialization. Nonetheless, scavenging pigs, and indigenous chickens, are relatively easy to sustain due to lack of cost on feed and housing (pigs fed and live in dumping site areas) and could represent an important source of income and/or food security to their owners living in these settlements (20, 21). On the other hand, formal pig systems are hindered by the lack of pig abattoirs, feelings of being outlaws and the dominance of one large company. Beef and small ruminant

production were reported mostly as fattening and short-term activities, and mainly associated with terminal markets in the city. Indigenous chicken and small ruminants small-scale systems were supported based on rural origin of urban dwellers and mainly for consumption in festive seasons. All these reasons in combination with the analysis of the supply chains help to explain the role, existence, and evolution of different livestock keepers in Nairobi.

Nairobi was designed originally, in its master plan in 1964, as a green city, with large open spaces, to facilitate malaria control. This was reported as an important historical factor that explains the growth of urban agriculture and livestock keeping in the city (7). However, urban livestock keeping is an activity that is usually unplanned and uncontrolled by the state (7, 15). The role of urban livestock production in food security and livelihood presents, therefore, important tradeoffs with risks of pathogens transmission and environmental contamination, exacerbated with rapid informal urban growth (4, 18). Human contact with livestock in Nairobi is potentially important based on informal systems that keep animals scavenging outdoors, living inside households or in close proximity to these, but also based on continuous movement of animals for grazing (especially by ruminant from terminal markets) or in transit within the city. In addition, many of the farms kept in zero-grazed systems are fed with market waste, swirl from restaurants, and/or grass cut on road sides, and therefore increasing movement of pathogens throughout the city. Supply chain analysis indicates large numbers of animals being slaughtered in the households or retailer backyards, with little inspection and generating possible environment contamination to humans, wildlife, and other urban livestock. Moreover, water and sewage systems in the city are not designed for livestock production. Nairobi rivers that are polluted by industrial effluents and human waste are used and contaminated by livestock (7, 17, 22). Furthermore, results in this study indicate important waste management hazards, with cadavers disposed on roads and in many occasions sold and/or consumed, with existence of organized black markets. Manure disposal also was reported to be dumped along roadsides by some farmers. Results on the use of health managers illustrate these problems, with many small livestock keepers not treating their sick animals and slaughtering them, doing self-treatment, or getting advice from untrained health managers. This potentially contributes to generate several of the food safety risks occurring and shown in **Table 2**. There is, therefore, important scope to generate policies and city planning that can regulate these practices and minimize pathogens transmission.

As consequence of these risks, Nairobi by-laws (dating from 1961) declare that livestock production within city boundaries is an illegal activity, which can only be licensed under specific strict conditions (7). However, law enforcement has reported to be weak (17) and contradictory (3). In this study, LPOs reported that livestock keepers are continuously "being harassed by the city council," while other government officers (such as LPOs and Government Veterinarians) provide advice on how to start a farm and also on husbandry and disease management practices. This system dysfunctionality and conflicting structures have been described as a common pattern in developing urban cities, as "holistic solutions are not part of public administrators mandate nor these have been trained to do so" (18, 23). Furthermore, urban livestock is often seen as a sign of "backwardness," with authorities remaining hostile to these activities and few central government policies supporting it (18, 23). The situation for livestock keepers become even more difficult in informal settlements, where conflicts are created with food vendors and other business due to livestock eating their products or contaminating their environment (22). In Nairobi, control of these livestock keepers was reported in this study to present an important challenge, due to their "outlaw" status in the city, that makes them to avoid contact with government officers and generate "lack of trust"; their "general lack of training"; the "farmers lack of financial capabilities," especially those small scale and/or in informal settlements; and their "inaccessibility" due to "insecurity" of those located in informal settlements or because they are "temporal" or "transit" farmers and not always present or available. "Presence of NGOs that give money to farmers" was also another challenge reported, as these livestock keepers expect payment in training activities organized by the government. "Lack of funding," "government understaffing," and "officers lack of transport" were other factors mentioned related to poor regulation and training of livestock keepers. Since 2013, with the new constitution in Kenya and the devolution laws, Nairobi County has maintained the existing laws regarding urban livestock keeping and, hence, continue to be an illegal activity. However, LPO reported that attitude of the city council is currently changing as they "see them now as business and food security entities." Currently, new policies that will designate "areas for livestock farming" were reported to be under consideration, but it is unsure if these would be effective. However, in the authors' opinion, even though urban livestock could cause food safety and environmental risks, these could be taken care of through better management and educational programs. The importance of urban livestock to food security and livelihoods means that an outright ban should not be considered. Instead, policies aiming to educate farmers on the importance on animal and environmental health management and that can facilitate enforcement and access of government officer could potentially help to minimize risk practices occurring in urban farms. In addition, continuing understanding the role and challenges of the different livestock keeper is paramount for the implementation of policies.

Livestock production officers reported several gender differences in each of the urban livestock systems. In small systems of dairy cattle, small ruminant (including meat and dairy goats), poultry, and rabbit, women were perceived to have an important role in managing the animals. However, only for dairy cattle, dairy goats, rabbits, and indigenous chicken, women were also responsible for the selling of the animals. This may have implication on food security, as woman have been reported to better use the benefits to meet household food security needs, but also to have higher rates on unemployment (24, 25). Men were perceived to participate in the management of beef and pig systems, but generally also to maintain ownership rights in most of other livestock species systems. They were also reported to be more involved in managing animals in large-scale farms. These findings are consistent with other gender studies conducted in

Kenya and Africa (26). This understanding of gender differences is critical for designing policies and interventions aiming at reducing food safety and disease risks, but also at improving food security and other potential social issues associated with urban livestock keeping.

The information generated in this study summarizes LPOs experiences, knowledge, and perception of the livestock situation in the city. This represents the main limitation of the study, as other peoples' perceptions are not accounted for. Interpretation of the results, such as the existing food safety risks identified or the themes reported by LPOs on attitudes, behaviors, and beliefs of other stakeholders, should be interpreted with care, as larger field studies are needed to validate their representativeness. Some estimates obtained are, therefore, approximations on the overall patterns of livestock structure, supply chains, and disease management existing. Based on the size of Nairobi city, its diversity of settlements and the important population of urban livestock, this qualitative approach was required to understand the overall system. The role of LPOs in providing extension services (e.g., advice on housing, animal husbandry, hygiene, etc.) to farms and their contact with different types of livestock keepers situated them in an ideal position as key informants for this study. The results provided here represent a baseline structure that is useful to design future research focused on specific urban production systems or livestock species and that involves other stakeholders in the supply chain. These results are also useful for researchers and policy makers to further investigate and address potential issues on animal disease management and food safety risk practices of urban livestock keepers. Another limitation was the lack of time as many different species had to be investigated in each focus group. In this regard, information regarding multiple livestock species system could not be explored. Indeed, a common system observed in Nairobi is the combination of broiler, dairy, and pig keepers in peri-urban areas (authors' personal observations). Guendel (17) estimated that 50% of livestock keepers in Nairobi keep only one livestock species. The keeping of other exotic species, such as quails, ducks, and turkeys, in the city is also becoming popular and should be considered in future research studies.

The results obtained here provide a powerful background that can be used as a basis to design future studies aiming to investigate in more details the different urban livestock systems and their disease risks. The information obtained here is also crucial for policies aiming to control urban livestock and their possible impact on zoonotic disease transmission, environmental pollution, and food security.

AUTHOR CONTRIBUTIONS

The manuscript was written and the data analysis was done by PA and PM. The Data collection was done by PA, PM, MM, JA, and SK. Data entry was done by PM, SK, and MM. The discussion and interpretation of the results was done by PA, JR, and EF. The study design was done by PA, JR, and EF.

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SUPPLEMENTARY MATERIAL

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CONCEPTUAL ANALYSIS
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One Health Integration: A Proposed Framework for a Study on Veterinarians and Zoonotic Disease Management in Ghana

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In parallel with the recent world-wide promotion of One Health (OH) as a policy concept, a growing body of social science studies has raised questions about how successful OH policies and programs have been in managing some global health issues, such as zoonotic diseases. This paper briefly reviews this literature to clarify its critical perspective. Much of the literature on OH also is focused on health management at an international level and has paid less attention to implementation programs and policies for OH at the national and local levels, especially in low-and-middle-income countries (LMICs). Programs to implement OH often are linked to the concept of "integration", a notion that lacks a universal definition, but is nonetheless a central tenet and goal in many OH programs. At the local and national levels, strong differences in perspectives about OH among different professions can be major barriers to integration of those professions into OH implementation. Policies based on integration among professions in sectors like animal, human and environmental health can threaten professions' identities and thus may meet with resistance. Taking into account these criticisms of OH research and implementation, this paper proposes a research framework to probe the dominant social dimensions and power dynamics among professional participants that affect OH implementation programs at the local and national levels in a low-income country. The proposed research focus is the veterinary profession and one aspect of OH in which veterinarians are necessary actors: zoonotic disease management. Results from research framed in this way can have immediate application to the programs under study and can inform more expansive research on the social determinants of successful implementation of OH programs and policies.

Keywords: veterinarians, ghana, one health, zoonoses, perspectives, practices, relationships, integration

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SOME CRITIQUES OF ONE HEALTH

Human health is a globalized societal concern subject to complex global governance. It is replete with "wicked problems" underpinned by complexity, uncertainty and competing goals that resist straightforward understanding and resolution (1). One such wicked problem is emerging and re-emerging zoonotic diseases or zoonoses[1] which threaten the health of populations as well as economies, livelihoods, and even political regimes (2, 3).

[1]Zoonotic diseases can be defined as infections naturally transmitted between vertebrate animals and humans. Zoonotic

The concept of One Health (OH) became popular as a new health policy framework in the first decade of the 21st Century, initially to manage emerging disease threats. OH can be defined as "*a generalised and flexible term that captures the will to address the complexities and interrelations that exist between human, animal and ecological health*" (4). The OH concept is not new. It developed from the term "one medicine", which was coined by Calvin Schwabe in the 20th Century to signify the paradigmatic similarity between human and animal medicine and their mutual benefits (5). By 2004, the concept of OH was being promoted all over the world and significantly gained traction after the pandemics of SARS[2] (2003) and Avian Influenza (2005–2007) when the need for more multifaceted approaches in zoonoses research, policy and management was widely recognized (6).

A growing body of social science studies has raised questions about how successful OH policies and programs have been or can be in managing some global health issues, such as zoonotic diseases. Some see OH as a "*fragmented intellectual project*" used by different actors for different outcomes (7). Indeed, while a powerful rhetoric of advocacy for OH was developing internationally, with OH being portrayed as a methodology, approach, movement, strategy, or paradigm shift, critical views of OH were also emerging (8, 9).

The concept of "integration" is embedded in many policies and implementation strategies associated with OH. Integration is a notion that lacks an agreed-to definition but is nonetheless a central tenet and goal in many OH program plans. From a social point of view, integration can be defined simply as "*a way of describing the established patterns of human relations in any given society*", which does not imply that integration is either negative (implying conflict) or positive (implying order) (10). Integration can more usefully be defined as "*developments that determine connections of related diverse elements into the social whole, system, community, or other unit*" (11).

Many OH scholars treat integration as a positive goal, with more integration representing better organization of people in policies and actions around a particular OH goal (10). While there is no universal definition of "integration,", papers on OH often use the word interchangeably with "collaboration", and, to a lesser extent, with "cooperation" or "coordination," generally with respect to actors belonging to the domains of animal, human and environmental health. Thus, collaboration, cooperation and coordination are all seen as elements of, or complementary to, integration (12, 13). For the professionals engaged in OH programs, integration may lead to financial savings through sharing costs or to "holistic" thinking, planning across organisational hierarchies and paradigms via transdisciplinary work and consensus (14). It may also result in inclusion of the OH concept in training programs in many disciplines (15) and in recognising and articulating the "*implications of uncertainty on, and potential conflicts between, human values and political processes*" involving human, animal and environmental health (16).

Implementation of OH can be challenging. To start with, achieving integration among program actors is not always straightforward:

> *"…studies emphasize how the goals of collaboration and coordination are a good deal easier said than done. Professional competition, conflicting priorities, institutional inertia and myriad other factors in diverse contexts make the implementation of OH projects a major undertaking" (7).*

The majority of publications frame OH policies and programs as being international in scope, viewing zoonotic disease management, for example, as a problem best tackled through high-level international coordination (17, 18). Less attention has been paid to how the OH concept resonates in various national and local settings, beyond some broad recommendations on changing national health systems (19, 20, 21), and little has been published about how the global OH agenda fits into existing national or local structures and practices (22, 23). Yet, important components of OH, such as zoonosis management, are fundamentally determined by what happens at the national level (6, 17). As an example, the case of the 2014 epidemics of Ebola in West Africa emphasizes the critical importance of local health structures (24).

Hinchliffe (25) worries that emphasizing the global dimension of OH promotes narrow approaches to OH implementation that fail to account for the diversity within global health issues. Giles-Vernick et al. (26) and Coffin et al. (27) recommend that OH research consider a wide range of knowledges that people from different locations and lifestyles have developed and transmitted in local contexts, and that such OH research should focus on low-and-middle-income countries (LMICs). Health policy in LMICs, where resources are limited and the responsibilities for public health often are divided among various government sectors and non-governmental agencies, is poorly studied and requires special attention in relation to OH (6, 28).

Axelsson and Axelsson (12) propose that the biggest barriers to achieving integration in health programs are differences in values, cultures, interests and commitments among the principal actors, and these differences often are very specific to each particular profession. Significant differences of perspectives on OH issues and their solutions can be expected across the veterinary, medical and environment sectors (29).

Kingsley and Taylor (7) recommended studying integration through a systemic approach that takes complexity into account because policies and actions can be intertwined through non-linear complex systems and processes which are embedded in the dynamics of power and politics vis-a-vis policy making and implementation in local, national and global contexts (30). It has been recommended that these complex processes be studied in a development context with an ethnographic approach that captures the social dimensions underpinning interactions between multiple actors from various institutions (31, 32).

agents are bacteria, viruses, fungi or other communicable disease agents (WHO). In 2008, zoonoses were shown to represent at least 60% of infectious human diseases and over 75% of emergent infections (39).

[2]Severe acute respiratory syndrome.

A RESEARCH FRAMEWORK TO EXPLORE THE SOCIAL DIMENSIONS OF ONE HEALTH IMPLEMENTATION

To address some of the criticisms of OH research and implementation, and in recognition of the potential utility of a better understanding of integration in the OH context, this paper offers a research framework to probe the dominant social dimensions and power dynamics among professional participants that affect OH implementation programs at the local and national levels in a low-income country. This framework is essentially the research plan for an on-going study of aspects of OH implementation in Ghana for which the results and analysis are not yet complete. The research focus is the Ghanaian veterinary profession and one aspect of OH policy and programs in which the veterinary profession is a necessary actor: zoonotic disease management. The overall objective of this research framework is to document how one professional group perceives and participates in management of zoonoses and the nature and dimensions of the relations veterinarians[3] have with other professions and with each other.

Portrayed as one of the "historical One Health actors" and "super One Health professionals," veterinarians already are dominant players in OH research internationally (13, 33–37). However, and particularly in LMICs, veterinarians generally are in short supply, are under-resourced, and their contributions to public health are underestimated (35, 38). There is little in the literature on the complexities of the context in which the veterinary profession operates and strives to achieve OH outcomes in policy and practice. An understanding of the roles veterinarians play among other stakeholders in managing zoonotic diseases and how their roles might be enhanced at a national and local scale in LMICs is a missing piece of the information with respect to integration in OH.

Situated on the Gulf of Guinea in West Africa, a "hotspot" for zoonotic disease emergence (39), Ghana is a low-income country in which zoonotic disease risk is of substantial concern (40, 41). Ghanaian veterinarians have been involved in research on emerging and endemic zoonoses and in programmes that emphasize the need for integration in zoonosis surveillance and control, such as the WHO/AFRO strategy for Integrated Disease Surveillance and Response (1998); the assessment of the Ghanaian veterinary services by the OIE-PVS[4] (2011); and the creation of the Ghana Field Epidemiology and Laboratory Training Programme, FELTP (2007). Nevertheless, Ghana does not have an organization, government department, or official plan with a clear mandate to pursue OH.

To identify the social dimensions influencing integration of veterinarians and other relevant professionals within policies and programs for zoonotic disease management in Ghana, this research framework proposes data collection on three main topics. The first is differences in professional **perspectives** on zoonoses associated with the variability of how knowledge and expertise are shaped in different branches of the contemporary natural sciences (42). The second is the professional **practices** by which veterinarians engage with the OH concept, with each other and with other professionals, and through which the concept of OH is transformed into field activities (43). The third is the **relationships** between veterinarians and other relevant professionals such as physicians and environmental scientists. These relationships are critical factors in the dynamics of integration and are the medium through which veterinarians as well as other professionals must broker and translate their technical knowledge to other actors in networks (31).

Thus, the proposed research framework provides an approach to the study of OH integration in terms of how veterinarians, as a professional group, think about their role(s) (perspectives), practically manage (practices) and interact (relationships) in their day-to-day routines in relation to zoonotic disease management in a LMIC. This research framework thus seeks to determine how veterinary perspectives, practices and relationships concerning policy and action around zoonoses can influence the scope of One Health integration.

CONCEPT 1: PERSPECTIVES

Background: OH integration requires that actors from different professions work together towards common OH goals, but professions differ in their perspectives on why and how to apply the OH concept operationally.

Analyses of the political economies of epidemics have shown that zoonoses and the associated policy responses to them may be understood differently by people and institutions with different interests and priorities (44, 45). Thus, different, and potentially contradictory, framings and agendas can create tensions regarding the implementation of OH in specific contexts. Competing narratives which called for different sets of policy responses have been noted in disease outbreaks (45). Differences in perspectives about zoonoses also are manifest in differences between international and local discourses (46).

While veterinary perspectives on health and disease management are expected to differ from those of other professionals (29), very few studies have carefully examined how in-country scientists or other professionals embedded within a national context frame zoonoses and OH (47, 48). Professional perspectives also can interfere with OH integration policy processes through divergent framings among disciplines (30, 49). For example, new acute zoonotic diseases potentially leading to pandemics may compete as priorities with endemic zoonoses in LMICs where both are present (32). Furthermore, dealing with major outbreaks through emergency-oriented and short-term interventions can occur at the expense of long-term, crucially-needed, health measures in LMICs (50).

Research framework: The data that will be most informative regarding veterinary perspectives on OH will be those documenting (1) the values and interests of veterinarians as a profession, (2) competencies attributed to veterinarians, including technical skills

[3]In this paper, "veterinarian" is defined broadly to include people who have graduated (or are about to graduate) with a degree in animal health and are practising animal medicine and/or the management of animal diseases in an official government position or in private practices. This broad definition includes para-professionals, also known as technicians.

[4]Tool for the Evaluation of Performance of Veterinary Services developed by the World Organization of Animal Health (OIE).

and knowledge, (3) historical evolution of veterinary institutions and attitudes toward these institutions and (4) effects of these veterinary perspectives on veterinary integration in zoonotic disease management programs.

To a large extent, professional values and interests derive from a profession's notion of professionalism. During acquisition of professionalism, people select particular sets of values, orientations and beliefs (51) which evolve along with changes in society (52). Professionalism also represents a form of social control, based on processes of inclusion and exclusion of individuals among categories within a bureaucratic structure according to recognized qualifications and standards (51, 53). For veterinarians, this professional control can be exerted, for example, via veterinary associations (51). In Ghana, animal health services can be delivered by practitioners with different qualifications: veterinary surgeons, technicians, and community animal health workers (54). Elsewhere, the roles of these different kinds of veterinary service providers have been shown to overlap and to create tensions (55, 56). Thus, inquiry into veterinarians' views of their own professionalism offers an entry point for documenting veterinary perspectives.

Inquiry into veterinary competences is another point of entry for research (57). Such competences entail both systems and interdisciplinary thinking, and the development of highly technical skills for multi-species health and illness through veterinary training (58–60). Data on how veterinarians define their professional competences, whom they view as having them and whom not, and how this differs among different veterinary employment scenarios will be key to assessing the social dimensions of OH integration.

Galaz and colleagues have written that perspectives on integration in OH have been driven by "*the legacy of each profession's embedded histories*" (45; 61). For example, when veterinary medicine was institutionalized in Ghana, government veterinarians were within the Ministry of Health. After Ghana's independence in 1957, they were transferred to the Ministry of Food and Agriculture (MoFA) (62), a change that very likely influenced veterinary perspectives regarding OH. Elsewhere in Africa, the veterinary profession has been shaped by institutional reforms such as decentralisation and privatisation (63–65) which likely also contribute to current veterinary perspectives. In this research framework, information on the history of veterinary institutions in Ghana - governmental, educational and professional - is to be gathered to serve as essential background information for evaluating current veterinary perspectives on OH.

CONCEPT 2: PRACTICES

Background: While some research has examined the influence of OH concepts on professional practices (66), the influence of routine professional practices on the implementation of OH programs at local and regional levels often has been overlooked in the literature (23, 67). Hamilton (68) argues that looking at the importance that "material things" play in practices helps explain veterinary attitudes on the ground; in an ethnographic study of British farm veterinarians, she showed that material items, like faecal samples, were linked to particular meanings and to prestige differences within veterinary teams in which people had different qualifications.

Veterinary practice often includes considerable discretion, practitioners acting in ways that do not strictly fit official procedures in order to privilege certain interests, be they their own personal gain, the interests of certain clients, or public health interests (69–71). Discretionary behaviours in veterinary practice could either favour or impede veterinary integration in zoonosis management by implementing national guidelines versus emphasising local needs which may contradict these guidelines. As street-level bureaucrats (SLB), veterinarians often must find intermediary positions between compassion and flexibility that comes with caring for the circumstances of their local context, and impartiality with its rigid application of orders coming from top managers (69; Hasenfeld, 1992 in 71).

The notion of street-level discretion is generally portrayed as a negative factor that undermines policy implementation. Some recent studies, for example, have revealed resistance by local stakeholders, for socio-economic reasons, to cooperating in surveillance operations for avian influenza, which thereby limited the detection of avian influenza cases (38, 72). However, other studies of local health practitioners as SLB suggest a more positive impact of discretion vis-à-vis policy implementation. For example, Axelsson and Axelsson (12) argue that SLB in public health are likely to "*identify more with their clients than with their parent organisation*" and that the clients thus empowered represent opportunities for bottom-up policy integration. (73 showed that medical doctors in rural South Africa used discretion to "*align their practices with policies*" and "*compensate for inefficiencies and failures … in how the system functioned*".

Zoonotic disease management is based on animal disease surveillance programmes aimed at early detection of zoonotic pathogens in domestic and wild animal populations in order to prevent outbreaks in humans. Public veterinarians[5] are key actors in this surveillance, which involves continuous monitoring of the health of human or animal populations and evaluation of associated disease risk factors (74). The success of surveillance operations at the local level depends on the active collaboration of multiple stakeholders on the ground, such as veterinarians, farmers, traders and abattoir workers.

Research framework: The key research approach proposed to study current veterinary practices in Ghana and their influences on veterinary integration in zoonotic disease management is an observation of the routine practices of a sample of veterinarians. Important areas of inquiry within this observation include (1) the veterinarians' interactions and views of the material components of their practices, (2) practitioners' identification of, and values attributed to, major veterinary competences and different levels of training of veterinary service providers, (3) characterisation of veterinarians' discretionary judgements and actions and the effects these may have on practices and on practitioners, and (4) the alignment or otherwise of current practices with effective zoonotic disease surveillance and potentially other forms of disease management.

[5]In Ghana, like in many other LMICs, most veterinarians work for the government and thus they work at the interface between citizens and the veterinary service bureaucracy.

CONCEPT 3: RELATIONSHIPS

Background: Relationships between OH actors, such as policy-makers, practitioners and researchers, in professional networks are a key dimension of the power dynamics at play in policy processes (30). Studies of professional relationships and OH generally have targeted large international networks (75) or international research activities (13, 37). Very few papers on OH have examined how interdisciplinary, cross-sectoral and inter-professional relationships actually work to advance OH integration in OH programs, particularly at a local or national level.

Work relationships are a form of social capital, which can be defined as "*the sum of the actual and potential resources embedded within, available through, and derived from the network of relationships possessed by an individual or social unit*" (76). Social capital can lead to collective action (77) and to integration of knowledge across organizations (78). Therefore, social capital is a useful window through which to study inter-professional relationships in the context of OH.

While social capital has been categorized according to various typologies, such as structural, relational and cognitive (76), or opportunity, motivation and ability-related dimensions (79), two main aspects of social capital cut across these typologies and are particularly relevant to the analysis of relationships in regard to veterinarians: (1) the social network and its structure, and (2) the potential benefits and assets mobilized through that network (76).

Social capital may favour or impede integration of veterinarians into zoonotic disease management. On the one hand, research has shown that relationships across sectors can facilitate collaboration on common issues even in the absence of formal structures and platforms for such collaboration. Inter-sectoral policy integration requires relationships which involve rational dialogue and mutual agreement (80). This link between dialogue and inter-sectoral collaboration has been picked up in the literature on integration in healthcare practice and is imbedded in the notions of "mutual adjustment" (81) and "power-sharing" (82). Vandersmissen and Welburn (75) consider "soft governance," which relies on self-organisation in networks independent of control through hierarchy or legislation, to underpin OH, and Glouberman and Mintzberg (81) write:

> *"(The notion of networks) suggests the linking together of interdependent organizations in all kinds of ways; to foster better communication in order to solve mutual problems. In between the authority of the hierarchy and the competition of the market sits the network of mutual relationships."*

All these positive views of social capital express the idea that, assuming a good level of communication and trust exists between different health professionals, networks will spontaneously organise and engage actors in collaborative practices.

On the other hand, relationships in OH may not be associated with positive outcomes for integration. Binot et al. (13) remarked that long-term and collaborative relationships between veterinarians and professionals in other sectors, like agriculture, rural development or the environment, were insufficient globally. In the literature on health systems, inter-professional relationships often are presented as tense negotiation processes among different sectors' interests through sectoral advocacy (83), with relationships framed as competitions in which power dynamics do not facilitate collaboration. In such advocacy coalition framing, relationships are competing networks of alliances. In conflicts over policy issues, the most powerful coalition will decide rather than decisions being based on a consensus achieved through collaboration (84).

Research framework: To explore the social capital present in the relationships of veterinarians among themselves, with other professionals, and with any other people or groups, data are needed that qualify and quantify (1) the social networks of veterinary relationships that exist and (2) the positive and negative impacts of these relationships on the OH focus of this research framework: zoonotic disease management. The first aspect, the network and its social structure, can be approached by determining (a) the presence or absence of relationships and how actors are connected, and (b) which relationships function within veterinary social networks, why they function as they do, and at what frequency of interaction (85, 86). Relationships with frequent interactions between veterinarians and other professionals associated with zoonosis management are an important focus for study because these may offer particular insight into the scope for OH integration in Ghana (13, 48, 87, 88).

The second aspect requires assessment of the quality of relationships (hostile or positive) in terms of facilitating or impeding actions and achievements which depend on these relationships. What do veterinarians' relationships with other professionals mean to the veterinarians themselves and what assets do they represent vis-à-vis potential collaboration in zoonosis management? Data are required on how veterinarians maintain relationships with other professionals and whether these relationships are based on trust and reciprocity (77).

CONCLUSION

This paper explores recent criticisms of OH implementation and the theoretical foundations for research on the notion of integration in OH. To respond to concerns that much of the research on OH has targeted international programs aligned with the priorities of wealthy nations, a research framework is proposed that targets implementation of OH at local and national levels in a low-income country. The proposed research framework offers an approach to qualifying and quantifying the social dimensions of OH implementation by investigating the professional perspectives, practices and relationships of veterinarians associated with their roles in zoonotic disease management in Ghana.

AUTHOR CONTRIBUTIONS

SV designed and implementated the research as well as wrote the manuscript.

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METHODS
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A Systems Approach to Evaluate One Health Initiatives

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Challenges calling for integrated approaches to health, such as the One Health (OH) approach, typically arise from the intertwined spheres of humans, animals, and ecosystems constituting their environment. Initiatives addressing such wicked problems commonly consist of complex structures and dynamics. As a result of the EU COST Action (TD 1404) "Network for Evaluation of One Health" (NEOH), we propose an evaluation framework anchored in systems theory to address the intrinsic complexity of OH initiatives and regard them as subsystems of the context within which they operate. Typically, they intend to influence a system with a view to improve human, animal, and environmental health. The NEOH evaluation framework consists of four overarching elements, namely: (1) the definition of the initiative and its context, (2) the description of the theory of change with an assessment of expected and unexpected outcomes, (3) the process evaluation of operational and supporting infrastructures (the "OH-ness"), and (4) an assessment of the association(s) between the process evaluation and the outcomes produced. It relies on a mixed methods approach by combining a descriptive and qualitative assessment with a semi-quantitative scoring for the evaluation of the degree and structural balance of "OH-ness" (summarised in an OH-index and OH-ratio, respectively) and conventional metrics for different outcomes in a multi-criteria-decision-analysis. Here, we focus on the methodology for Elements (1) and (3) including ready-to-use Microsoft Excel spreadsheets for the assessment of the "OH-ness". We also provide an overview of Element (2), and refer to the NEOH handbook for further details, also regarding Element (4) (http://neoh.onehealthglobal.net). The presented approach helps researchers, practitioners, and evaluators to conceptualise and conduct evaluations of integrated approaches to health and facilitates comparison and learning across different OH activities thereby facilitating decisions on resource allocation. The application of the framework has been described in eight case studies in the same Frontiers research topic and provides first data on OH-index and OH-ratio, which is an important step towards their validation and the creation of a dataset for future benchmarking, and to demonstrate under which circumstances OH initiatives provide added value compared to disciplinary or conventional health initiatives.

Keywords: transdisciplinary, integrated approaches to health, evaluation framework, one health, one health index, one health ratio

INTRODUCTION

Many current health challenges, such as spread of zoonotic infectious diseases, environmental pollutants, antimicrobial resistance, climate or market-driven food system changes with consequences on food and feed supplies, malnutrition including obesity and many more arise from the intertwined spheres of humans, animals, and the ecosystems constituting their environment (1, 2). They are recognised to be wicked problems and need to be tackled using integrated approaches to health (3–5). Here, we consider integration as inter-[T1] or transdisciplinary[T1] (annotated terms are explained in detail in **Table 1**) approaches. Such approaches consider the needs, values, and opinions of multiple disciplines and sectors. They also bring together the scientific and non-scientific communities, influencing, or influenced by, the challenge and their combined know-how and resources (6–8). Due to the existing, historically contingent, separation of sectors and disciplines, developing integrated approaches is difficult, and the realisation of benefits can be delayed. There is a need to provide evidence on the added value of these integrated and transdisciplinary approaches to governments, researchers, funding bodies, and stakeholders (9–11).

For One Health (OH), as a typical integrated approach to health, the COST Action TD1404 "Network for Evaluation of One Health"[1] (NEOH) was initiated to develop a science-based evaluation framework and apply it to a set of case studies (21). The NEOH framework uses a systems approach and regards the context of an OH initiative as the system within which it operates, and the initiative itself as a subsystem, which has a potential to affect the system to a smaller or larger degree. Drivers, operations, supporting infrastructure, and outcomes were identified as fundamental characteristics of any OH initiative (7). The NEOH evaluation framework relates the aspects of operations (i.e., OH thinking, OH planning, and OH working) and supporting infrastructure (i.e., systemic organisation, learning, and sharing) summarised as OH process characteristics ("OH-ness"), to changes and outcomes evoked by a specific initiative. This is an important step towards identifying added value arising from integration across disciplines and sectors (i.e., transdisciplinarity).

PROPOSED EVALUATION FRAMEWORK

Overview

Figure 1 provides an overview of the NEOH evaluation framework. There are four overarching Elements (grey boxes) in the evaluation process, namely:

Element 1: defining and describing the OH initiative and its context (i.e., the system, its boundaries, and the OH initiative as a subsystem), providing information for the further Elements;

Element 2: assessing expected outcomes based on the theory of change (TOC) of the initiative, and collecting unexpected outcomes emerging in the context of the initiative;

Element 3: assessing the "OH-ness", i.e., the implementation of operations and infrastructure contributing to the OH initiative; and

Element 4: comparing the degree of "OH-ness" and the outcomes produced.

The framework relies on a mixed methods approach that combines a descriptive and qualitative assessment with a semi-quantitative evaluation (scoring) for the evaluation of the "OH-ness" with an OH-index, while including conventional metrics for outcomes in a multi-criteria-decision-analysis.

The framework can be used for either external or self-evaluation. It is recommended that the evaluator is comfortable with systems thinking (14, 22) to approach the complex structures and dynamics of OH initiatives and their context. Data and information can be gathered from actors[T1] and stakeholders[T1] using methods such as open or semi-structured interviews, focus group discussions, or other qualitative data collection approaches. These can stem from resources used or produced by the initiative (23), and related (external) primary or secondary datasets.

In the present manuscript, we describe a concept for the process of generating evaluation data (Elements 1–3), while Element 4 is analytical and is described in the evaluation handbook of the NEOH (for details see text footnote 1). The text is conceived as a set of short theoretical and methodological syntheses for each of these Elements. For their implementation, we present an exemplified application of Element 1 (definition of the initiative and its context) with a description and an illustration; an overview of categories of outcomes to consider in Element 2 (TOC and assessment of outcomes); and a short description of a consolidated file with six evaluation protocols (Table S1 in Supplementary Material) including OH-index calculations for Element 3 (assessment of OH-ness). For examples that apply the method presented here, the readers can refer to the case studies included in this Frontiers research topic on "Concepts and experiences in framing, integration and evaluation of OH and EcoHealth".[2] Paternoster et al. evaluated integrated surveillance of West-Nile virus (24), Radeski et al. applied the framework to an animal welfare centre (25), Léger and co-workers evaluated a research project on antimicrobial resistance involving four faculties, the industry, and health authorities,[3] Buttigieg et al. compared control strategies for Brucellosis in Serbia and Malta,[4] Muñoz-Prieto et al. assessed a study on factors affecting obesity in dogs and dog-owners,[5] Laing et al. evaluated a

[1] http://neoh.onehealthglobal.net.

[2] https://www.frontiersin.org/research-topics/5479.

[3] Léger A, Stärk K, Rushton J, Nielsen LR. A one health evaluation of the University of Copenhagen Research Centre for Control of Antibiotic Resistance. *Front Vet Sci* (2017). (under review in this Research Topic).

[4] Buttigieg SC, Savic S, Cauchi D, Lautier E, Canali M, Aragrande M. Comparing the control and eradication of brucellosis in Malta and Serbia: a one health evaluation. *Front Vet Sci* (2017). (under review in this Research Topic).

[5] Muñoz-Prieto A, Nielsen LR, Martinez-Subiela S, Mazeikiene J, Lopez Jornet PL, Savic S, et al. Evaluation of one health operations and supporting infrastructure in a questionnaire-based study of obesity among dogs and their owners in 11 European countries. *Front Vet Sci* (2017). (under review in this Research Topic).

TABLE 1 | Glossary of terms and abbreviations used in this manuscript.

Term	Abbreviation	Explanation	Reference
Multi-disciplinary	MD	The multi-disciplinary approach is typically understood as the sequential or additive combination of ideas or methods	(8), or http://www.arj.no/2012/03/12/disciplinarities-2/
Interdisciplinary	ID	The interdisciplinary approach involves the integration of perspectives, concepts, theories, and methods to address a common challenge	(8, 12), or http://www.arj.no/2012/03/12/disciplinarities-2/
Transdisciplinary	TD	The transdisciplinary approach entails not only the integration of approaches, but also the creation of fundamentally new conceptual frameworks, hypotheses, and research strategies that synthesize diverse approaches and ultimately extend beyond them to transcend pre-existing disciplinary boundaries. The term transdisciplinarity refers to scholarship that transgresses the boundaries between academia and communities outside academia. By doing so, OH enables inputs and scoping across scientific and non-scientific stakeholder communities and facilitates a systemic way of addressing a challenge	(8, 12)
Sector		A sector is an area of activity aimed at benefits to society, characterised by common processes and institutions. Examples include agriculture, health, transportation, education, and environment. Sub-sectors would be units within the sector; for example, in agriculture these could be livestock, crops, agro-forestry, fishing, and aquaculture	
System, social-ecological system	SES	A system is a set of interacting, interrelated, or independent components that form a complex and unified whole (13). Human made systems are usually conceived to achieve a defined aim (14). However, this may not be the case for social-ecological systems (SES), which were defined as a hierarchy of subsystems and internal variables at multiple levels analogous to organisms composed of organs, organs of tissues, tissues of cells, etc. The core subsystems of an SES are resource systems, resource units, governance systems, and users (15)	(13–15)
Component		Systems are composed of a set of interacting or interdependent components that form a complex whole. Components may be tangible (e.g., humans, animals, forests, lakes) or intangible (e.g., cultural behaviours, values, norms, language expressions) and are linked by interactions	(13, 16)
Context		The system or SES within which the initiative is aiming to evoke change towards a health outcome	
Resource system		Resource systems are core subsystems of an SES such as forested areas, wildlife, water systems, national parks, etc. We extend the idea of Ostrom and consider social systems as resource systems too, e.g., health care system, local community, food chains, etc. They "provide" or host resource units such as trees, shrubs, susceptible persons, traders, food items, etc. which contribute to the system	(15)
Resource units		Resource units are product or component of the resource system and represent a link of the resource system to other components. In contrast to Ostrom, we do not differentiate between users and resource units, because users may represent a resource from, e.g., a disease perspective	(15)
Governance system		Governance systems are a further core subsystem of a social-ecological system and represent the system that is managing specific resource systems.	(15)
Stakeholder		Stakeholder is "*any individual, group or organisation who may affect, be affected by, or perceive themselves to be affected by a decision or activity*"	(17)
Actor		Actors are a subgroup of stakeholders such as "*any individual, group or organisation who acts, or takes part*" in the context of the OH initiative	(17)
One Health	OH	OH emphasises the commonalities of human, animal, plant, and environmental health. In this perspective, it can be regarded as an "umbrella" term that captures integrative approaches to health across these highly interlinked components	(7)
One Health initiative	OH initiative	Any initiative, such as research projects, developmental programmes, policy, etc. that relies on the concept of OH as described above. In a generic way, an OH initiative aims at generating change in a SES (context) towards improved health of humans, animals, and/or ecosystems. We do *not* refer to the *pro bono* Kahn–Kaplan–Monath–Woodall–Conti "One Health Initiative" at http://www.onehealthinitiative.com	(7)
Network for evaluation of One Health	NEOH	A network funded by the European Cooperation in Science and Technology (TD1404) with the aim to enable future quantitative evaluations of OH activities and to further the evidence base by developing and applying a science-based evaluation protocol in a community of experts	http://neoh.onehealthglobal.net
Evaluation design		A plan for conducting an evaluation	

(*Continued*)

TABLE 1 | Continued

Term	Abbreviation	Explanation	Reference
Scale		Identical to level. Systems are organised in hierarchical order. This hierarchy implies that different levels of the hierarchy can be in the focus of attention. As an example in the hierarchy of life, one can look at individuals, populations, communities, or ecosystems, i.e., different scales of the same quality (life)	(18)
Level		Used as synonym to scale	
Dimension		Systems are organised in hierarchical order. Hierarchies depend on a fundamental quality that defines this order. Examples for dimensions are life with its different organisational levels; within the semantic space (dimension) expands the hierarchy of meanings of words; within the dimension of faith various beliefs are organised within larger clusters, but also governance, time, geographical space, and many more are dimensions	(18)
Space		Here used as synonym to dimension	
Theory of change	TOC	The TOC explains all the different pathways that might lead to the desired effect of an initiative. It not only shows the outputs, outcomes, and impact of an initiative, but also requires outlining (and explaining) the causal linkages. Each effect is shown in a logical relationship to all the others	(19) and http://evaluation.lshtm.ac.uk/process-evaluation/#toc
Logic model		Logic models graphically illustrate the components (inputs, activities, outputs, outcomes, impacts) of a programme in a structured, logical, and sequential way	http://www.theoryofchange.org/wp-content/uploads/toco_library/pdf/TOCs_and_Logic_Models_forAEA.pdf
Impact		Positive and negative, primary, and secondary long-term effects produced by a development intervention, directly or indirectly, intended or unintended	(20)
Output		The products, capital goods, and services which result from an OH initiative; may also include changes resulting from the intervention which are relevant to the achievement of outcomes	(20)
Outcome		The likely or achieved short-term and medium-term effects of an OH initiative's outputs	(20)
Outcome mapping		An approach used for planning and assessing programmes that focus on change and social transformation. It provides a set of tools to design and gather information on the outcomes, defined as behavioural changes, of the change process	https://www.outcomemapping.ca/

project mitigating the effects of the unexpected domestic re-use of containers employed for organophosphates in a tick control programme (26), Fonseca et al. applied the framework to evaluate a cross-sectoral observatory of taeniasis and cysticercosis,[6] and finally Hanin et al. evaluated an international and inter-sectoral centre for infectious disease surveillance (27).

Definition of the Initiative and Its Context

Before designing an evaluation, the evaluation question(s) must be clearly stated. To answer these questions and to select an adequate evaluation design[T1], it is then important to gain a principle understanding and overview of the activities to be evaluated (28). The framework presented here uses a systems approach and regards the context[T1] of an OH initiative[T1] as the system[T1] within which it operates, and the initiative itself as a subsystem conceived to induce change in this context. Systems have been defined in many different disciplines and frameworks [e.g., Ref. (14, 21–24)]. A fundamental feature is that systems are composed of a set of interacting or interdependent components[T1] that form a complex whole (13). This implies a hierarchical organisation and a concept of levels[T1] or scales[T1] within different dimensions[T1] (18). Although the term "level" is used ambiguously in science, the concept used here is that of "grades of being ordered," which captures what biologists and social scientists refer to as "levels of organisation" (29). Three such grades or levels can be identified at which OH outcomes are usually measured: individual level of health, population level of health, and ecosystem level of health (30). Systems can be considered as a network of components[T1], which can be tangible (e.g., humans, animals, forests, and lakes) or intangible (e.g., cultural behaviours, values, norms, and language expressions) and which are linked by interactions (13, 16). The system's components depend on the perspective and determine its boundaries, which are important for evaluation (23). While the perspectives of stakeholders (and thus system boundaries) may differ, the stakeholders may become agents of change or part of a pathway towards successful solutions (24, 26, 28). OH initiatives might create additional opportunities to produce relevant—expected as well as unexpected—outcomes by including stakeholders and system boundaries explicitly (**Figure 1**).

Element 1 of the evaluation framework (**Figure 1**) consists of a general overview (see the section "The General Overview"), a visual representation and a textual description of the system in which the initiative operates (see the section "Visual Representation and Textual Description of the Context"), and an analogous illustration and description of the initiative within

[6]Fonseca AG, Torgal J, De Meneghi D, Gabriel S, Coelho AC, Vilhena M. One health ness evaluation of the surveillance design of Taeniasis and Cysticercosis in Portugal (a neglected disease in Europe). *Front Public Health* (2017). (under review in this Research Topic).

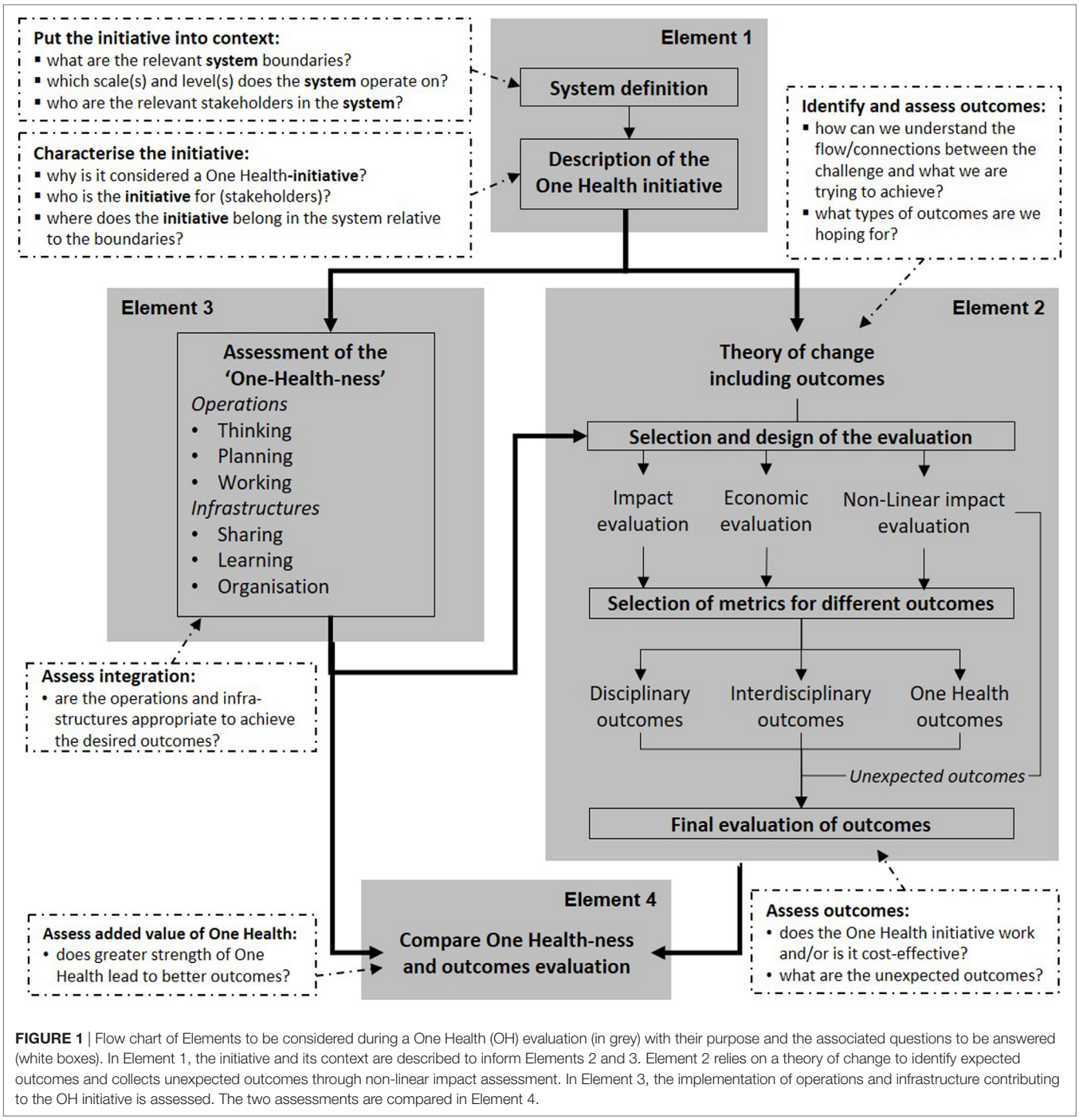

FIGURE 1 | Flow chart of Elements to be considered during a One Health (OH) evaluation (in grey) with their purpose and the associated questions to be answered (white boxes). In Element 1, the initiative and its context are described to inform Elements 2 and 3. Element 2 relies on a theory of change to identify expected outcomes and collects unexpected outcomes through non-linear impact assessment. In Element 3, the implementation of operations and infrastructure contributing to the OH initiative is assessed. The two assessments are compared in Element 4.

this context (see the section "Illustration and Description of the OH Initiative within the Context"). They do not need to be developed in sequence, but may evolve iteratively, and may be developed by a group of evaluators or by the stakeholders of the initiative, or by the two groups in collaboration.

The General Overview

For the general overview, the evaluator should put together a concise description of the background, objectives, key features, and rationale of the OH initiative under evaluation so that the user is aware of the important characteristics that can affect the evaluation.

Visual Representation and Textual Description of the Context

Here, the focus is specifically on the system targeted by the OH initiative; in other words, the wider context within which the initiative operates. We will describe the initiative itself later. For

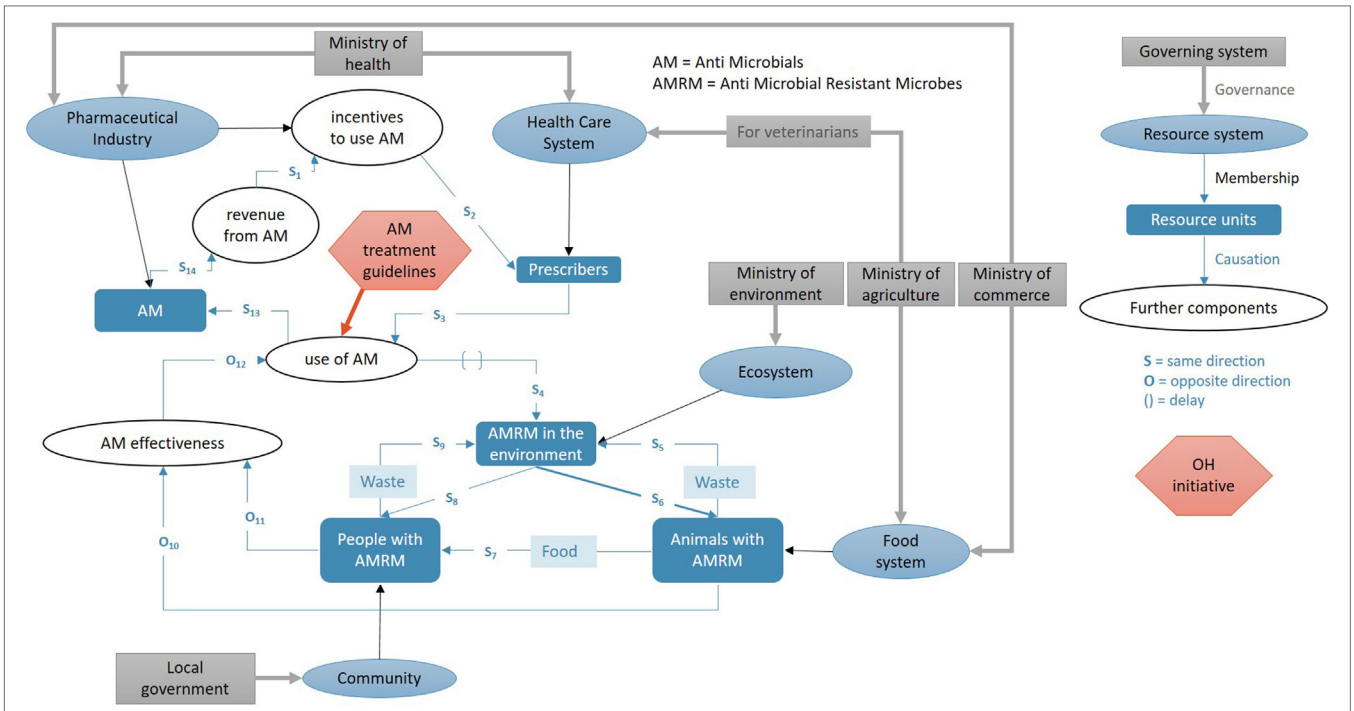

FIGURE 2 | Example for visual representation of an initiative in its context exemplified by occurrence of antimicrobial resistance within a given system: resource systems (blue ovals), resource units (dark blue boxes), and governance systems (grey boxes) within which an initiative operates. Furthermore, tangible and intangible components (white ovals) are included. Relationships (arrows) are classified as governance (grey), membership (black), and causal interactions (blue) with explanatory text (light blue boxes). Letters designate changes of two components in the same (S) or opposite (O) direction, respectively. The red hexagon represents the initiative with arrows where it impacts the system.

the visual representation of the system, we propose a combination of the socio-ecological system framework by Ostrom and a causal loop diagram (13, 15).

To capture the socio-ecological system, three core subsystems are plotted first (**Figure 2**): the *resource systems*^{T1} (blue ovals), the *resource units*^{T1} they provide (dark blue boxes), and the *governing systems*^{T1} (grey boxes). In the next step, further tangible and intangible components relevant to the system (white ovals, e.g., use of antibiotics, effectiveness of antimicrobials) are added. For legibility of the graph, it is recommended to use nouns that fit into phrases such as "the level of…," to avoid verbs and to use neutral terms, e.g., "use of antimicrobials" rather than "increase of antimicrobial use." Finally, *relationships* are added as arrows, namely governance relations (grey), membership relations (black), and causal relations (blue). For causal relations, it is useful to note the relation using S for "same direction change" and O for "opposite direction change," in order to identify later reinforcing and balancing loops. Subscripts and explanatory text as well as annotations of time delays can be convenient for later reference.

Visual representation is powerful, but lacks any dimension beyond the plane and therefore hinders the depiction of overlapping subsystems or nested hierarchies. Hence, to explore further the system in which the OH initiative operates, it is recommended to include a textual description. It is guided by three questions formulated by Williams (28): (A) to understand interrelationships: what is the reality we are dealing with? (B) to engage with perspectives: how do we understand/how do we see that reality? (C) to reflect on boundaries: how do we decide to do what needs to be done? (28). In **Table 2**, we adapted the tabular system description by Boriani et al. (31) for a broader application. It allows capturing the aim of the system, the stakeholders and actors and their interactions, the system dimensions with corresponding boundaries, and the system evolution.

The aim and/or indicators of the system are not to be confused with the aim of the initiative and should answer the question "why does the system exist?" or "what does it produce?" e.g., the result of a food chain may be to "produce Salami." A social-ecological system may not have an explicit aim, but it can be characterised by indicators that allow describing selected attributes, such as resilience, productivity, or health. In this evaluation framework, we differentiate among the declared aim by the system and the observed, enacted, and the perceived aims. The declared aim of a veterinary practice may be to provide animal health services. However, this will be enacted within a socio-economic context, which may result in therapeutic choices that prioritize practice income over animal welfare. These actions may be observed by a subset of clients, while others do not notice them. Each stakeholder may have a different perception of the declared aim and again, each of them can have a different way to interpret how the system is performing in relation to its aim (13). In socio-ecological systems, the perceptions differ mainly in regard to the way one verifies whether the system is healthy and/or intact. This is important as it explains the motivational background and sets

TABLE 2 | An overview of how to describe the system at which the One Health (OH) initiative is targeted, i.e., the context of the initiative.

Aspect	Description	Secondary questions	Evolution
Aims	What is the context of the OH initiative—why does this system exist? What does it produce? For social-ecological systems that have no explicit aim, what are indicators that the system is intact/healthy?	Perspectives What does the system declare to do? Are there different declarations? What do the actors and stakeholders perceive the system does and how do those perceptions differ? (For social-ecological systems: how do the actors and stakeholders perceive/evaluate that the system is intact/operational?) Are there measurable outcomes/indicators of the system? How do the declared, perceived and measured aims/outcomes relate?	Do the various aims/indicators change as the system evolves with time?
Actors	Who are the actors? Who acts within the system?	Relationships How do they affect the other actors/stakeholders and the aim of the system? How are they affected by the other actors/stakeholders and the aim/indicators of the system? How are the relationships distributed/arranged? Which are the most important links? What are the processes between the related components? How can the links be characterised (slow/fast, strong/weak)?	Do the actors change their activity and behaviours as the system evolves (new trade-offs)? Does the system have secondary effects on the actors?
Stakeholders	Who are the stakeholders? Who is affected by the system?	Relationships How are they affected by the actors and the dynamics of the system? How are the relationships distributed/arranged? Which are the most important links? What is the nature of the processes between the related components? How can the links be characterised (slow/fast, strong/weak)?	Does the system have secondary effects on the stakeholders?
Geographical dimension	Which geographical space does the system occupy and where is it situated (surface concerned, climate, and location)?	Boundaries How is the system delimited in geographical area? How do these boundaries affect the system aims/indicators and dynamics?	Does the system have secondary effects in geographical space within the boundaries? Does the system produce "externalities" in geographical space?
Temporal dimension	Which is the most important time scale in which events are happening in the system (e.g., minutes, months, and years)? Are there other important time scales?	Boundaries How is the system delimited in time? Is it infinite, terminated, transient? How does this time limit affect the system aims/indicators?	Does the system affect the frequency of events or its own time limit? Does the system produce "externalities" in time (accelerating or slowing down external systems)?
Governance/institutional dimension	Which governance entities/levels are involved (shire, agglomeration, state, nation, or international space)? What institutional structures (companies, corporations, and organisations) play a role?	Boundaries How is the system delimited in the governance/institutional dimension? How do these boundaries affect the system aims/indicators?	Does the system have secondary effects in the governance/institutional dimension within the boundaries? Does the system produce "externalities" in the governance/institutional dimension?
Further dimensions	How does the system extend within this dimension and how many levels of this dimension are part of the system?	Boundaries How are these dimensions delimited? How do these boundaries affect the system aims/indicators?	Does the system have secondary effects in these dimensions within the boundaries? Does the system produce "externalities" in these dimensions?

of values of the concerned stakeholders. Indicators specific for the system aim should be identified in a participatory process and compared with indicators used by different stakeholders to assess their perceived aim(s), thereby shedding light on discrepancies and ways of resolving them.

Following the interactive terminology for Europe (17), we define *stakeholders*[T1] as "*any individual, group, or organisation who may affect, be affected by, or perceive themselves to be affected by a decision or activity*," while actors[T1] are a subgroup of stakeholders such as "*any individual, group, or organisation who acts, or takes part*" in system activities. To gain clarity about roles of stakeholders, we recommend referring to the visual representation of the system exemplified in **Figure 2** and probe for "who is involved in the system as an *actor* and who is merely *affected*?" For example, the pharmaceutical industry produces a certain compound, people can decide whether to take that compound or not, while animals are affected by a certain preparation distributed to them by an actor in the system (e.g., veterinarian or owner). An overview of relevant actors and stakeholders allows delimiting further the system under evaluation. Stakeholders

could be actors at the same time, and in these situations, it should be differentiated in what capacity a group represents a stakeholder or actor, respectively.

In order to understand the context of the OH initiative, it is important to understand how the components of the system are arranged or interact (28). There are four aspects of relationships that should be considered and described: (a) the structure or arrangement of the links between the components (topology); (b) the nature of the processes between the components (e.g., information flow, transfer of goods, etc.); (c) the characteristics of the links (slow/fast, strong/weak, antagonistic/synergistic, etc.); and (d) identifying the links that are most important in the system.

Dimensions [T1] are defined as spaces in which levels of organisation according to Bunge occur (29). In other words, entities within a dimension feature the same quality (e.g., metric) but to a different degree. Examples include geographical space, time, governance/institutional, economic, linguistic, faith, and value dimensions. Within these dimensions, we consider scales[T1] or levels [T1] of analysis, e.g., cell—organism—population in the dimension of life (18). These levels are important, because they will determine the relation between the resolution of the analysis and the resolution of observations and what can be measured or evaluated in the system in a particular dimension. Due to their importance, *geographical*, *temporal*, and *governance/institutional dimensions* are included in **Table 2**. Particularly time is related to the scale in other dimensions, i.e., the larger the system the larger its characteristic time, which is the time at which the average change occurs (e.g., cells react within milliseconds, individuals within minutes to hours, ecosystems is within years or decades, the same applies to the adaptability of laws at different scales or the frequency that vocabulary is used in a language) (18). Together with geographical space, time is a particularly important dimension, because it will characterise if the system is evolving over seconds, hours, days, years, decades, or even longer. It can be considered in the past, present, or future, and opportunities to affect the system are highly dependent on time due to the system disposition (the same intervention may have different effects when applied at different times). Furthermore, causes and effects may occur in different time scales, where short actions may result in effects with a time lag of years. The governance/institutional dimension will determine which organisational levels (ranging from international governance mechanisms to household structures) are represented and addressed in an initiative. Considering scales is important, because initiatives may aim to change systems at different levels than where the necessary governance could be influenced and consequently, well intended initiatives may remain ineffective if they do not address all appropriate levels.

Further dimensions are the *Dimension of Life* (or Biology) comprising nested living entities from cells to biosphere with levels such as "cell," "organ," and "individual," the *Economic Dimension* defined by rules and institutions involved in decisions on production, trade, and exchange of goods and services, the *Linguistic Dimension* delimited by languages and dialects used, the *Faith/Value Dimension*, which represents the values and beliefs underlying the system. Other dimensions may also be relevant to the system, such as communication, transportation, legal frame, sociocultural dimensions, and many others.

The primary importance of a systems approach to evaluation implies less the idea of being comprehensive, but rather being "thoughtful, smart, and aware about what you are leaving out" (28). The evaluator(s) will need to be transparent about the consequences of choices and declare their relation to the initiative, the system, and the evaluation *per se*. Although the dynamics and boundaries and stakeholders of a system are clear, they will be constrained by physical limits (e.g., a mountain range, river), social limits (e.g., country, community), regulations (e.g., quotas, prohibitions), and/or other norms (e.g., social norms, religious norms) that are either imposed by the systems nature or selected by the evaluators (23). Many restricting factors will lie in one of the system dimensions identified earlier. For example, a food system can be limited due to production regulations (e.g., the previous milk quotas system in Europe), food hygiene standards (e.g., restrictions on raw milk consumption), or cultural practices (e.g., no pork consumption in certain faith groups). The system boundaries characterise the interaction between the context of the initiative with the broader world in which it is imbedded, and determine how this affects the aim of the system (23). Finally, dimensions can also interact and may even be so closely correlated that it may not be useful to differentiate them (e.g., when religious beliefs are prescribed by the law).

The *evolution of a system* can be regarded as interaction of time with other dimensions in terms of iterations and pathways along those dimensions and time. Apart from the aim of the system, the interactions in the system may produce secondary effects within the system and "externalities" beyond the boundaries as it evolves. Highly self-organising systems may even change their (aim) dynamics and boundaries as time goes by.

Illustration and Description of the OH Initiative within the Context

In a next step, the OH initiative can be added to the visual representation of the context to illustrate its effects on various components[T1] and their interactions. If an affected component is missing, it is added and the system graph corrected accordingly. In the example in **Figure 2**, we have included a hypothetical OH initiative that involves new antimicrobial treatment guidelines for veterinarians and general practitioners (prescribers) that are assumed to impact directly on the amount and distributions of types of antimicrobials used in the system.

The user should now have a clear understanding of the system in which the OH initiative is situated. Next, the initiative itself is described using the template in **Table 2** in analogy, namely as a nested subsystem of the context, which it aims to change. Many elements may be congruent, but the boundaries of the initiative will inevitably be smaller and there will be fewer actors, stakeholders, and more limitations than in the description of the system. Care should be taken, as actors and stakeholders and their particular roles, may not be identical in the initiative and in the wider system. The initiative may be likely to consider fewer dimensions compared with the system, but it is important to identify how it will influence the context and what the limitation of the actions are. A key question in this description is: how is OH conceptualised by the various participants and is there a common understanding?

TOC and Assessment of Outcomes

Element 2 involves elaborating the TOC[T1], which helps to explain how an initiative is intended to produce the desired (or expected) outcomes. It is an important step to define the evaluation question and to choose the evaluation methods and metrics. It entails generating hypothesis about the causal mechanisms by which the components and activities of the initiative produce outcomes by asking pertinent questions about: (A) why people expect the initiative to bring about the change(s) and the outcome(s) they seek, (B) to question their assumptions about how the change process will unfold, and (C) to be clear about how they are selecting outcomes for the evaluation. Identifying and developing a theoretical understanding of the likely process of change is critical when evaluating complex initiatives (32). Measuring (or assessing) change in multiple outcomes, facilitates the evaluation of whether the OH initiative works as intended and whether it is cost-effective. In addition, unexpected outcomes may arise from an OH initiative. A good description and understanding of the system and OH initiative in Element 1 facilitates the identification of interactions and dynamics that may lead to unexpected and indirect outcomes not specified by the TOC. This framework standardises the evaluation through a systematic approach based on the TOC, while explicitly remaining open for potentially emerging systemic effects through the non-linear impact evaluation (**Figure 1**).

Description of the TOC

Essentially, the TOC presents a roadmap with all building blocks required to bring about a desired (long-term) goal and hence spells out the logic behind the initiative. The presentation of the TOC can be assisted by a graphical presentation (e.g., **Figure 3**), or its description can refer back to the illustration of the system used in Element 1.

The impact[T1] is defined as the long-term effects (or goals) to be induced by an OH initiative. It is a change that continues to exist after the end of the initiative, and can be direct (first order) or indirect (second order) impacts. Outcomes[T1] are changes

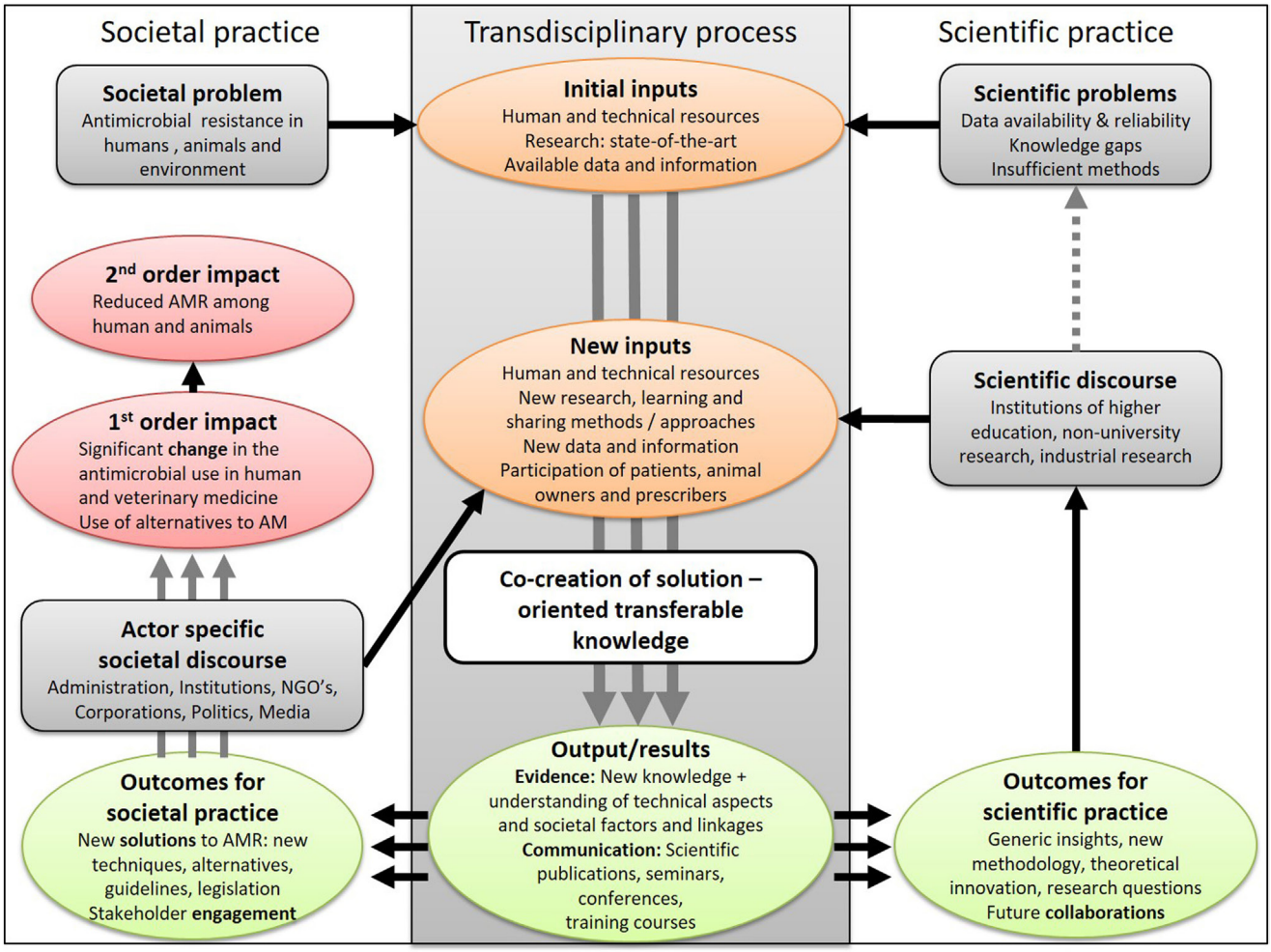

FIGURE 3 | The change pathway for a fictive One Health research initiative aiming to mitigate the development of antimicrobial resistance in a transdisciplinary process. It illustrates the inputs from science and society to co-produce outputs that are taken up by society and the scientific community and disseminated through a specific discourse before resulting in first- and second-order impacts and scientific progress. On the way to impact(s) several iterations with new inputs and outputs of the transdisciplinary process may be needed.

(e.g., improvement, learning) resulting from the initiative that can be considered to be stepping stones for progress towards the longer-term goals. In a transdisciplinary process, the outcomes are situated in societal and scientific practice and can be of multiple natures (e.g., technical, economic, social, sanitary, and political) (33). Outputs[T1] are products, goods, and services, which result from the transdisciplinary process of an OH initiative and are necessary for the achievement of outcomes. For illustration, we use an example from a fictive research project aiming to produce new knowledge and methods to combat the development of antimicrobial resistance (**Figure 3**): OH research outputs (new data and knowledge) result in new treatment guidelines (outcome for societal practice) leading to new regulations restricting (and hence lowering) the use of specific antimicrobials in farmed animals (first-order impact of political nature), which then may reduce the development of antimicrobial resistance in farmed animals and the associated transmission to people (second-order societal impact). The impacts can be realised at different political levels (e.g., individual, institutional, regional, national, and international) and can consist of different types of effects (positive or negative; direct or indirect). Outcomes for societal and scientific practice (e.g., an improved integrated surveillance programme for antimicrobial resistance or a new simulation model, respectively) are disseminated, adapted, and applied by other actors to result in societal impact or scientific progress. Between the initial problem formulation and the expected impact(s), new inputs might be required as a result of intermediary outcomes and will feed a further iteration of knowledge co-production. An example could be new research collaborations as the outcome of an OH initiative, which may lead to new knowledge or tools for improved control of infectious diseases in a second initiative. The sequence of inputs (i.e., resources needed to perform the actions), outputs, outcomes, and impact can be graphically represented by a change pathway also known as an impact pathway (34) or a logical framework[T1] or logic model[T1], which presents the flows in a "logical," sequential way (19). Importantly, the classification into outputs, outcomes, and impacts depend on the perspective that is taken for the evaluation and may differ among stakeholders (35). It is therefore important to elaborate the TOC in collaboration with the entity contracting the evaluation.

A methodology related to the TOC is outcome mapping[T1], which can be used for planning and assessing (development) activities focusing on change and social transformation. It places people and learning at the centre of development and conceptualises unanticipated changes as potential for progress and innovation. Consequently, it can be a useful tool to use for OH initiatives, either in combination with TOC or on its own if it fulfills key assumptions of dependence on human behaviour, limits to the influence of interventions, active contribution of people to their well-being, co-existence of differing yet valid perspectives, and resilience dependent on interrelationships (36).

Expected Outcomes and Impacts

The description and definition of outcomes and impacts are dependent on the problem the OH initiative is addressing and the associated boundaries of the system, objective, rationale, and consequently the resulting TOC. Given the diversity of OH initiatives, there is no single outcome that summarises OH endeavours, but rather a wide range of different outcomes (37–39). However, at the longer-term impact level, there are commonalities OH endeavours appear to strive for (7). The outcomes and impacts to be measured need to be selected as best fit for the specific OH initiative and its TOC. Because of their nature, OH initiatives will commonly span different sectors and disciplines and therefore are likely to produce disciplinary, interdisciplinary, and OH outcomes and impacts. Evaluators consequently need to be aware of disciplinary paradigms, data, and approaches as well as methods of combining outcomes from different disciplines.

Disciplinary outcomes relate to outcomes that are measurable within a distinct discipline or sub-speciality within the natural or social sciences. Examples of disciplinary outcomes include health outcomes such as decreased levels of non-communicable or infectious diseases; nutrition outcomes such as reduced levels of undernutrition or obesity; economic outcomes such as increased productivity or savings in the health care system; social outcomes such as improved societal stability; and ecological outcomes such as slower rates of biodiversity reduction or improved water or air quality. Importantly, these outcomes can be achieved in disciplinary or sectoral approaches (e.g., promotion of a new anti-diabetes treatment or childhood vaccination in a national health service), but more often, they rely on collaborations across disciplines and sectors. Interdisciplinary activities by definition have an impact on multiple fields or disciplines and produce results that feed back into and enhance disciplinary or sectoral work. In these instances, the pathway to the outcome may be characterised by collaboration and contributions from different disciplines and sectors, but the outcomes may still be conceptualised (and consequently measured) at the level of a field or discipline. Combining these disciplinary outcomes in methods such as multi-criteria decision analysis gives a solid basis for an assessment of the achievements of the OH initiative. In *interdisciplinary outcomes*, individuals from different disciplines create new knowledge and understanding through sharing of ideas and bringing together different perspectives result in a product or measure, which explicitly reflect the shared responsibility among disciplines for outcomes (16, 22, 40). Consequently, interdisciplinary outcomes occur in the realm of at least two disciplines simultaneously, e.g., food security as an interdisciplinary outcome of successful alignment of multiple sectors (i.e., food availability, food access, and food utilisation), which contribute different skills and expertise (41). Other examples are the human development index, the environmental performance index, and the planetary boundaries, which combine a diversity of indicators into a single or a few measure(s). An improvement in the index cannot be achieved with a disciplinary approach, but needs activities in health (e.g., investment in health service capacity, public awareness campaigns), education (e.g., build infrastructure, attracted attract talented teachers, and provide incentives for school attendance), social protection (e.g., policies to reduce poverty and vulnerability of disadvantaged population groups), and economics (e.g., promotion of efficient labour markets, robust governance). Interdisciplinary outcomes are ideally measured in a common metric, i.e., they should rely on a consensus on how to assess and weigh the particular outcomes.

Such metrics are even more policy relevant and effective if they are produced and measured in a transdisciplinary process, which transcends both horizontal boundaries between scientific disciplines, and vertical boundaries between science and other societal fields (private sector, public agencies, and civil society) (42). Like this, stakeholders share different perspectives and can therefore improve the contextualization of the problem and its potential solutions and targets (43).

One Health outcomes or impacts occur as result from a broader integration of activities in the system at stake. The main domains of OH outcomes are the three pillars of sustainability, i.e., society, environment, and economy. Typical examples are interspecies equity, health stewardship, human and animal welfare, efficiency, and effectiveness (7). Clear causal attribution to the OH initiative may be difficult, but a contribution of the OH initiative can be assessed.

Given the perspective chosen and the resource availability for the evaluation, the description of the TOC, and the selection of associated outcomes may be more or less comprehensive and complex. However, the evaluator should make sure to pay careful attention to the contributions from different disciplines and sectors, their integration and the resulting positive and negative effects.

Unexpected Outcomes and Impacts

By definition, unexpected outcomes and impacts cannot be planned or covered by a TOC, even though attempts are sometimes made to capture a wide range of eventualities. Throughout an OH initiative within its system, interactions among components and feedback loops frequently produce rapid, non-linear, and unanticipated changes (23, 44, 45). Typically, integrated approaches in complex systems generate unexpected added value, e.g., a new stakeholder organisation, but may also result in unexpected negative impacts, e.g., discrimination among stakeholders (23), which is why capturing unexpected outcomes constitutes an essential process of OH evaluation. Other examples would be emerging diseases due to new contact rates or closer contact between previously isolated populations, or due to new social behaviours in urbanised environments (46). If unexpected outcomes are not captured, evaluation fails in informing adaptive management that seeks to improve outcomes in complex dynamic environments (47). An expanding array of qualitative and quantitative methods for complexity-enabled monitoring, evaluation and learning is available for use in the fields of development and peacebuilding (48–50), many of which can be contextually adapted for OH projects and programmes.

Assessment of OH-Ness

Aspects of implementation of initiatives (i.e., the structures, resources, and processes through which delivery is achieved, and the quantity and quality of what is delivered); mechanisms of impact (i.e., how activities, and participants' interactions with them, trigger change); and context (i.e., how external factors influence the delivery and functioning of activities) are examined through process evaluation (51, 52). Process evaluations allow seeing how an initiative develops, its structures, environment, and associated activities like communications and marketing. An implicit characteristic of any OH initiative is its focus on sharing, exchanging, collaborating, learning (from each other), reflecting and generating change across disciplines, and sectors in an enabling environment (7). Consequently, this affects the delivery of an OH initiative (e.g., availability of training, learning about other fields, provision of resources), the mechanisms of impact (e.g., the responses of participants and their interactions with the initiative), and context factors (e.g., shaping of theories on how an initiative works). We refer to the sum of these characteristics as OH-ness composed of six aspects outlined below and hypothesise that they need to be an integral element of any (process) evaluation in OH. We collate scores and indices that have been suggested in a variety of contexts, adapt them to OH, and combine them in a OH-index (OHI) and OH-ratio (OHR) for a holistic appreciation. The six assessment tools have been standardised for use and are made available together with the calculation of the indices and automatic spider diagrams in an Excel workbook for download (Table S1 in Supplementary Material). Each assessment tool consists of a series of up to 17 questions to be answered and an associated scoring system with values between 0 and 1 as well as spider diagrams. The questions were developed by working group 1 of the NEOH and probe for the specificities of each aspect (outlined below) that can be captured in a semi-quantitative way. They are based on the concept of SMART goals (specific, measurable, achievable, relevant, and timely) and wherever appropriate, were adapted from existing evaluation tools. They were then circulated in the NEOH community and revised in several workshops throughout the Action. The scoring recommendations were determined so that scores close to one reflect a high degree of realisation of the different OH characteristics. Here, it must be emphasised that the authors do not presume that a high degree of implementation necessarily results in a high impact or effectiveness and underline that at this stage, the benchmark still needs to be established. Each question has the same weight, with exception of the learning assessment, where different levels of organisational learning are weighted according to their level of influence on institutional learning. Consequently, care was taken to balance the number of questions across all assessment tools to provide equal representation in the overall OHI. The underlying assumption is that each question contains equivalent information to describe the OH initiative. However, because there is no measurable gold standard for each of the questions, the questionnaire and primarily the OHI, and OHR are then assessed for their usefulness and representativeness using case studies as outlined in the overview and a meta-analysis of further published studies. Similar to Element 1, the assessment of the characteristics in this element should ideally be informed by a group of evaluators or (preferably) by relevant stakeholders identified in Element 1.

OH Thinking: System Thinking and Match between Context and Initiative

One Health as a systemic approach with corresponding methodology is of little worth if not based on a foundation of systems thinking (14). This tool assesses how an OH initiative conceptualises the system in which it operates and in how far it considers

features specific to complex adaptive systems. The fundamental idea is that a complex initiative addresses multiple dimensions of the system in which it operates (see Element 1 above). The first set of questions (Table S1 in Supplementary Material) measure the number of dimensions and the scales within each to gain a semi-quantitative appreciation of the context and the embedded OH initiative. The following questions assess the match between the dimensions of the initiative and its context. Particular attention is given to the scales in different dimensions and whether the initiative reflects the reality of the context in which it operates. A third set of questions probes for concepts and thoughts typically contained in a systems approach (13, 53). To assess systems thinking in written documents, e.g., in a retrospective evaluation or in a proposal, we refer to a method based on statistical semantics proposed by Whitehead and Scherer (54).

OH Planning: Cross-Sectorial, Integrated Planning

One Health planning is essentially the unfolding of the OH thinking into operational features of the initiative that should facilitate OH working towards achieving the aims and objectives during as well as after the OH initiative. The planning of OH initiatives go beyond the type of planning that is required for disciplinary and interdisciplinary projects in which it might be easier to maintain control of what tasks, engagement, and resources are required. For instance, OH initiatives typically require human resources with competences in transdisciplinary working methods and excellent communication skills to bridge disciplines and sectors (8). It is important that the planning includes appropriate methods to engage all of the essential actors and stakeholders, who should be aiming to reach a common goal. Part of the planning evaluation is to assess whether the planned structure, location, and timing of the initiative support the OH outcomes aimed for. Due to the complex and trans-domain characteristics of OH challenges, another important aspect of OH initiatives is the ability to self-assess, learn, reflect, and adapt to new knowledge and changing conditions, constraints, and opportunities over time (55). Therefore, adaptability features prominently in the evaluation of the planning of OH initiatives. Finally, the planning evaluation helps assessing the tasks and resources allocated to each task employed to achieve the specified objectives of the initiative. The questions in Table S1 in Supplementary Material were developed to probe if the challenges of complex initiatives described here are addressed in the planning phase and if funding as well as organisational aspects are set up to accommodate adaptive behaviour by the participants. High scores are recommended for a strong support of adaptability and flexibility.

OH Working: Transdisciplinarity

Interdisciplinary collaboration brings together people with different skills and expertise to tackle complex problems, which often have a high-societal stake and require an understanding of the human behaviour (9, 56, 57). Appreciating potential contributions of multiple disciplines requires examining the limits imposed by a discipline, and rejecting or accepting different disciplinary theories based on their relevance and credibility in order to gain a new understanding about the defined challenge (12, 58). In the context of OH, interdisciplinarity[T1] has developed towards a participatory approach in the form of transdisciplinarity[T1] (57). Both inter- and transdisciplinarity rely on appropriate leadership and management to promote strategic dialogue and shared decision-making (40, 59), which in turn will foster a non-hierarchical relationship between the different disciplines and members within the team. It must also allow for self-reflection, flexibility, and recursiveness (40, 42, 57, 60), to be able to challenge and modify underlying assumptions and concepts and thereby enrich understanding. It must be emphasised that such transdisciplinary work demands a high level of commitment and collaboration of all participants to establish personal relationships founded within a climate of trust (9, 42, 59). The questions probing for transdisciplinarity (Table S1 in Supplementary Material) focus on disciplinary diversity, team building, and adaptability and were adapted based on the work cited above.

Further aspects of trans- and interdisciplinarity may be assessed, namely for (A) evaluating (academic) participants and (B) assessing scientific outputs of an OH initiative. However, because individuals may have different roles in an OH initiative, assessing their trans- and interdisciplinary capacity may not always be required or relevant. Also, printed scientific output may not be a primary objective of an OH initiative and occurs with some delay, thereby contributing more to the assessment of outputs than to the implementation *per se*:

(A) The transdisciplinarity of (academic) participants may be assessed based on the interdisciplinarity of publications [see method (B) below]; interdisciplinarity of teaching, other academic activity (e.g., teaching experience in other disciplines than the own, co-teaching with experts from other disciplines/sectors, etc.); previous experience with various non-academic communities (e.g., public debate, main stream media, sports and leisure organisations, politics, NGOs, volunteering, etc.); involvement in other disciplinary and interdisciplinary networks (e.g., social and natural science networks other than the own expertise, explicitly interdisciplinary initiatives, science policy, etc.);

(B) A framework to evaluate the interdisciplinarity of knowledge production based on citation network analysis can be found here: https://www.mcgill.ca/msr/msr-volume-4/evaluating-knowledge-production-systems. It must be emphasised that this only represents the written knowledge published in peer reviewed journals, which does not reflect the actual knowledge production occurring in the field.

Systemic Organisation: Adaptive and Shared Leadership

In many complex settings, change-oriented leadership has helped to overcome the fallacies of conventions, norms, and traditions (61, 62). Complex systems have leverage points where they can be influenced according to their potential to modify a systems behaviour (53). The use of these points by an OH initiative determines the dimension(s) and scales at which the initiative is effective. However, in order to be effective, the implementation of the initiative needs to be facilitated by corresponding leadership behaviour. Yukl classifies leadership into four meta-categories with specific objectives (62): for (A) task-oriented behaviour, the

primary objective is to accomplish work in an efficient and reliable way. For (B) relations-oriented behaviour, the primary objective is to increase the quality of human resources and relations, which is sometimes called "human capital." For (C) change-oriented behaviour, the primary objectives are to increase innovation, collective learning, and adaptation to the external environment. For (D) external leadership behaviour, the primary objectives are to acquire necessary information and resources, and to promote and defend the interests of the team or organisation. These leadership behaviours can be related to the leverage points in a system according to their objectives (**Table 3**).

Yukl emphasises that all leadership behaviours and particularly their flexible applications are relevant for effective leadership. The table simply illustrates that the lack of a particular leadership behaviour may hamper the implementation of a well-conceived OH initiative. The effectiveness of leadership behaviours also depends on the extent to which the leader is trusted by people to be influenced. Most types of leadership behaviours can be used in ethical or unethical ways. Moreover, a leader, who is not trusted because of unethical behaviour will have less influence. Values, namely honesty, altruism, compassion, fairness, courage, and humility may further catalyse effects of good leadership behaviour. In contrast, excessive institutional structure and organisation can nullify these effects (62). Rooke and Torbert identify further common personality traits of leaders that effectively manage wicked problems: they can challenge the prevailing view without provoking outrage or cynicism; they can act on the big and small picture at the same time, and change course if their chosen path turns out to be incorrect; and they lead with inquiry as well as advocacy, with engagement as well as command, operating all the while from a deeply held humility, and respect for others (63).

A further challenge for leading OH projects is that there may be less interest, commitment, and collaboration if one discipline dominates. Consequently, other disciplines may retract their activity and reinforce the disciplinary silo mentality. To ensure that disciplines are effectively engaged and involved in decision-making from the planning to the implementation stages of projects, shared/distributed leadership, and governance should be implemented involving all stakeholders (64, 65).

Consequently, the selection of questions for the systemic organisation of OH initiatives focuses on the structure of teams, as well as management, social, and leadership skills of key players and its implementation (Table S1 in Supplementary Material). The questions were taken from the leadership assessment tools and the published questionnaires on team work and transdisciplinarity described in Section "OH Working: Transdisciplinarity". High scores were recommended for strong teams, change-oriented leadership skills, clear competences, goals, and criteria of success.

Learning Infrastructure

Learning is a change in cognition, potential behaviour or actual behaviour through better knowledge, and understanding (66, 67). Organisations, such as OH initiatives, learn when they "encode inferences from history into routines that guide behaviour" (68). This is achieved when discoveries, evaluations, and insights by individuals are successfully embedded in the organisation's mental models or cognitive systems and memories (69). This requires that organisational learning takes into account the learning that takes place at the individual, group, and organisational levels (70) and the interplay between them (69). The three levels of learning work together and influence each other and are thus not clearly distinct and mutually exclusive (71). Nevertheless, each level of learning has its characteristics for evaluation.

Individuals can engage in single-loop or double-loop learning. Single-loop learning happens when the output is corrected or existing competences, procedures, technologies, and paradigms are improved, without necessarily examining or challenging the underlying beliefs and assumptions. In contrast, double-loop learning involves seeing beyond the situation and questioning operating norms. It results in modification of the organisation's underlying norms, policies, and objectives.

TABLE 3 | Ranked list of leverage points at which to intervene in complex systems, from least to most effective, according to Meadows (53), in relation to leadership behaviour according to Yukl (62).

Leverage point	Leadership behaviour
Constants, parameters, numbers (such as subsidies, taxes, and standards) The sizes of buffers and other stabilising stocks, relative to their flows The structure of material stocks and flows (such as transport networks, population age structures)	Task-oriented leadership: clarifying, planning, monitoring, and problem solving
The lengths of delays, relative to the rate of system change The strength of negative feedback loops, relative to the impacts they are trying to correct against The gain around driving positive feedback loops The structure of information flows (who does and does not have access to information) The rules of the system (such as incentives, punishments, and constraints)	Relation-oriented leadership: supporting, developing, recognising, and empowering
The power to add, change, evolve, or self-organise system structure The goals of the system	Change-oriented leadership: advocating change, envisioning change, encouraging innovation, and facilitating collective learning
The mindset or paradigm out of which the system—its goals, structure, rules, delays, parameters—arises The power to transcend paradigms	Change-oriented and external leadership: networking, external monitoring, and representing

Individual learning is not a sufficient condition for organisational learning (72). Teams enable the interplay between individual and organisational learning, because they can better share the knowledge (72–74) and include more people in the learning process. As a result, team members share awareness of each individual member's expertise, knowledge, and skills, and build a transactive memory system (8). Thus, the evaluation should examine the knowledge shared through teams, to what extent it is shared and how it is shared. The conclusion should show whether the teams provide the appropriate interplay between the individual and the OH initiative. Without supporting the development of a transactive memory system within and across teams, the initiative may have individuals who learn, but it cannot engage in organisational learning (75). It is important to assess how knowledge is gathered, stored, and distributed within an OH initiative (76), and if and how it provides working environments, technology, rewards, systems, structures, and policies that will support learning (73).

Finally, the context in which the OH initiative is located has influence on the organisational learning (77). The context can be divided into the direct system in which it operates and general environment (78). The direct system consists of other components with which the initiative interacts, e.g., actors and stakeholders with various relationships. The general environment consists of less specific elements that might affect learning like economic, technological, sociocultural, and other factors. The questions probing for learning are taken from a tool to change organisations towards learning organisations (79) and focus on the frequency single-loop and double-loop learning occur at the level of individuals, teams, and the OH initiative, as well as how the system and broader environment support learning (Table S1 in Supplementary Material).

Sharing Infrastructure and Processes

In a broad sense, data and information sharing is a catalyser of knowledge generation (80). Data are often a pre-requisite for the operational gears to function. In OH initiatives, data and information are often the "raw material" that ultimately will lead to better understanding and a more inclusive and sustainable way of tackling the challenge. If managed appropriately, data and unbiased information sharing can foster trust between participants, as well as minimise misconduct in data management and reporting (81, 82). Additionally, this process can avoid duplication of data collection, ensuring an optimisation of resources (83).

A central benefit of data sharing is that the data can be analysed to a much greater extent than if only the data owner examines them. This brings benefits to the data owners themselves, as the analysis of others might lead them to further develop their knowledge on the systems the data originated from or the strengths and limitations of their datasets, as well as raising the awareness of the existence of the data in the wider community (80, 84, 85). Despite these benefits, data and information sharing often lead to barriers for establishing collaborations (86) and are hampered by confidentiality issues, time delays, and even mistrust in established collaborations. Consequently, data sharing is not as frequent as desirable, and needs to be incentivised to become a natural part of the science and governance cultures. For example, in some countries research relies on a tripartite agreement to share information and collaborate between academia, government institutions and industry, but public access to data may also be reinforced through legislation.

A frequent barrier to data procurement is the bureaucratic process to access data, particularly its complexity and duration. Moreover, fees and technical constraints may arise (87), and often too little resources are set aside to for data extraction from databases. Data accessibility and ownership are further critical factors, with data owned by collaborating parties contributing more to knowledge generation than public data or data owned by third parties. Data confidentiality may affect its sharing, as participant consent is usually collected for a specific purpose. This consent might not extend to new studies or alternative purposes, and therefore, security measures may be required to warrant confidentiality. Sharing sensitive data and information within a broader group might entail higher risks for confidentiality breaches (88). Alternatively, anonymization may reduce that risk, but may also reduce the utility of the data. Finally, it needs to be stressed that knowledge about the data origin and data collection processes is key for the quality and usefulness of stored data, and respective documentation must be available. For example, without knowledge about potential bias throughout the data generating process, it is extremely challenging to merge or combine data from multiple sectors in an OH initiative. The questions in Table S1 in Supplementary Material derive from a workshop held by NEOH on data and information sharing, in which critical aspects of data sharing were discussed. High scores are recommended for strong facilitation of sharing. The questions focus on the sharing mechanisms, available resources, data quality and accessibility, storage, and the resilience of these to change in the system.

OH Index and Ratio

Given the lack of current, commonly accepted benchmarks and the fact that OH initiatives are strongly context specific, it is recommended to assess them in relation to a context-specific benchmark. Hence, the evaluator should determine what the perfect situation in the given context would look like (using benchmarking data where they exist) and what proportion of this maximum is achieved with the OH initiative.

The aim of the OH-index (OHI) is to combine the assessments conducted in the previous sections of Element 3. To visualise the six assessments, we suggest a spider diagram (**Figure 4**), in which each assessment is represented by a spoke. The diagram depicts the operational aspects "OH thinking," "OH planning," and "OH working" opposed to the infrastructure for "learning," "sharing," and "systemic organisation." Thus, the operational aspects on the top left of the diagonal are opposed to the infrastructure on the bottom right. Each spoke is scaled to cover a range of values between 0 and 1. Consequently, the plot not only illustrates the degree of integration by the surface, but it also shows the balance between the operation and the supporting means through its symmetry over the diagonal, numerically represented as the OHR.

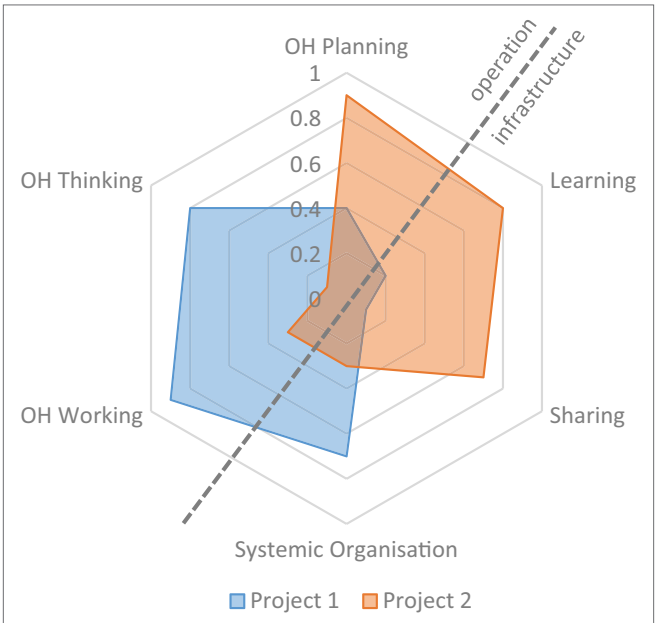

FIGURE 4 | Example of the One Health (OH)-ness spider diagram for two fictive OH projects.

In **Figure 4**, two exemplary fictive projects are depicted, an example with real data of a comparison of two OH initiatives can be found in the article by Buttigieg et al. (see text footnote 4). The fictive Project 1 depicted here has a highly developed transdisciplinary team with a very comprehensive multi-dimensional approach. However, it appears to lack learning and sharing infrastructure and has a mismatch between the responsibilities, authorities, and means which affects the trans-disciplinary working and hence potentially the OH outcomes. On the other hand, Project 2 has well-developed infrastructure and well-defined tasks with sufficient funding, but does not explore the interdisciplinary space nor does it aim at serving multiple species.

The OHI corresponds to the ratio of the surface enclosed by the lines to the surface enclosed if all spokes were equal to 1 (a detailed derivation is provided in Data Sheet S1 in Supplementary Material). Thus, the OHI is

$$\mathrm{OHI} = \frac{\left\{\begin{array}{l}(\mathrm{Sc_P}\times\mathrm{Sc_L})+(\mathrm{Sc_L}\times\mathrm{Sc_P})+(\mathrm{Sc_S}\times\mathrm{Sc_L})\\ +(\mathrm{Sc_O}\times\mathrm{Sc_S})+(\mathrm{Sc_W}\times\mathrm{Sc_O})+(\mathrm{Sc_T}\times\mathrm{Sc_W})\end{array}\right\}}{6} \quad (1)$$

where $\mathrm{Sc_P}$ is the score obtained in OH planning, $\mathrm{Sc_L}$ is the score obtained in learning infrastructure, $\mathrm{Sc_S}$ is the score from sharing infrastructure, $\mathrm{Sc_O}$ is the score from systemic organisation, $\mathrm{Sc_W}$ is the score from OH working, and $\mathrm{Sc_T}$ is the score from OH thinking.

The OH-ratio (OHR) is the relation of the surface covered in the top left of the diagonal to the one in the lower right (a detailed derivation is provided in Data Sheet S1 in Supplementary Material). To compute the OHR, the surface of the top left surface ($\mathrm{SUR_{operation}}$) is calculated

$$\mathrm{SUR_{Operations}} = \frac{\sqrt{3}}{4}\left\{\left(\frac{\mathrm{Sc_O}\times\mathrm{Sc_W^2}}{\mathrm{Sc_O}+\mathrm{Sc_W}}\right)+(\mathrm{Sc_W}\times\mathrm{Sc_T})+(\mathrm{Sc_T}\times\mathrm{Sc_P})+\left(\frac{\mathrm{Sc_P^2}\times\mathrm{Sc_L}}{\mathrm{Sc_P}+\mathrm{Sc_L}}\right)\right\} \quad (2)$$

and divided by the surface of the lower right ($\mathrm{SUR_{infrastructure}}$)

$$\mathrm{SUR_{Infrastructure}} = \frac{\sqrt{3}}{4}\left\{\left(\frac{\mathrm{Sc_P}\times\mathrm{Sc_L^2}}{\mathrm{Sc_P}+\mathrm{Sc_L}}\right)+(\mathrm{Sc_L}\times\mathrm{Sc_S})+(\mathrm{Sc_S}\times\mathrm{Sc_O})+\left(\frac{\mathrm{Sc_O^2}\times\mathrm{Sc_W}}{\mathrm{Sc_O}+\mathrm{Sc_W}}\right)\right\} \quad (3)$$

resulting in the following equation:

$$\mathrm{OHR} = \frac{\begin{array}{l}(\mathrm{Sc_O}\times\mathrm{Sc_W^2}/(\mathrm{Sc_O}+\mathrm{Sc_W}))+(\mathrm{Sc_W}\times\mathrm{Sc_T})\\ +(\mathrm{ScT}\times\mathrm{Sc_P})+(\mathrm{Sc_P^2}\times\mathrm{Sc_L}/(\mathrm{Sc_P}+\mathrm{Sc_L}))\end{array}}{\begin{array}{l}(\mathrm{Sc_P}\times\mathrm{Sc_L^2}/(\mathrm{Sc_P}+\mathrm{Sc_L}))+(\mathrm{Sc_L}\times\mathrm{Sc_S})\\ +(\mathrm{Sc_S}\times\mathrm{Sc_O})+(\mathrm{Sc_O^2}\times\mathrm{Sc_W}/(\mathrm{Sc_O}+\mathrm{Sc_W}))\end{array}} \quad (4)$$

DISCUSSION

This new evaluation framework for OH relies on a systems approach to characterise OH (7) and elaborate guidance for its evaluation. Although several of the identified approaches and methods were established and used previously, their combination in the context of OH is new. Moreover, several modifications and enhancements were made to take into account OH specific characteristics and provide a foundation for comparison across different initiatives and the generation of new insights into the implementation of OH initiatives. The systems approach to evaluation presented here does not resolve the problem of delimitation, partiality, and bias, but the framework helps to address these factors explicitly. It also shows that the evaluator(s) is (are) part of the system of which they try to gain an understanding, as much as an OH initiative is not external to the system it tries to affect. This is particularly important when considering stakeholder perspectives, because the relationship between the evaluator(s) and the informant has an influence on the content of the feedback. Consequently, the framework formalises reflections on system dynamics and includes emerging properties in all elements. Further, it consolidates thinking, planning, working, sharing, learning, and systemic organisation in a single OHI and OHR. However, these aspects may also be investigated separately for specific circumstances. Like many systems approaches the implementation of the NEOH framework is limited by resources, but also by political and managerial endorsement. Constructive use of the evaluation framework presented demands advanced leadership skills and a facilitating learning environment. The scope of the evaluation and delimitation of the system are pivotal for the outcome of the evaluation and it is eminently important to declare how these choices impact on the results. In analogy to systems thinking in public health the concept relies critically on multi-stakeholder endorsement (89) and is vulnerable to misconceptions and misapplications (90).

Finally, care must be taken not to prejudge that a higher OHI would mean a "better" OH initiative. The authors hypothesise

that there may be an optimal range of values for the OHI, outside which too little or too strong integration may hamper implementation at both ends. Also, the optimal OHR remains to be identified. As outlined earlier, the case studies reported in the present Frontiers special topic (24–26, 27), show practical applications of the evaluation framework for a variety of contexts and in different types of OH initiatives. They also provide first data on OHI and OHR, which is an important step towards their validation and the creation of a dataset for future benchmarking. Importantly, they highlighted that the qualitative evaluations are equally important to understanding the context-relevant shortcomings and strengths of the individual initiatives. However, qualitative evaluations are more difficult to compare in a meta-study compared with quantitative data due to their heterogeneity in findings. Despite this limitation, the case studies provide the foundation to improve the framework further and validate it, as they highlight ambiguities and shortcomings in practical application.

AUTHOR CONTRIBUTIONS

The manuscript bases on extracts of an iterative process for the production of the handbook for evaluation of One Health of the COST Action TD1404 "Network for Evaluation of One Health." The working group preparing the handbook was co-lead by SR, while the COST Action was chaired by BH. SR prepared the manuscript, which was revised primarily by LN and BH. Conceptual and text contributions were made by SB, MS, MA, MC, TE, IC, EB, MR, KQ, and MB.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at http://www.frontiersin.org/articles/10.3389/fvets.2018.00023/full#supplementary-material.

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Brucellosis Control in Malta and Serbia: A One Health Evaluation

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Brucellosis, also known as "undulant fever" or "Malta fever", is a zoonotic infection caused by microorganisms belonging to Brucella, a genus of gram-negative coccobacilli that behave as facultative intracellular pathogens of ruminants, swine and other animals. Brucellosis is a threat to public health, hence identifying the optimal way of preventing disease spread is important. Under certain circumstances, integrated, multidisciplinary "One Health" (OH) initiatives provide added value compared to unidisciplinary or conventional health initiatives. Conceptualizing and conducting evaluations of OH approaches may help facilitate decisions on resource allocation. This article historically describes and compares Malta's 1995–1997 with Serbia's 2004–2006 brucellosis control programmes and quantitatively assesses the extent to which they were compliant with a OH approach. For both case studies, we describe the OH initiative and the system within which it operates. Characteristic OH operations (i.e., thinking, planning, working) and supporting infrastructures (to allow sharing, learning and systemic organization) were evaluated. We scored the different aspects of these programmes, with values ranging from zero to one (1 = strong integration of OH). Malta demonstrated a higher OH index (0.54) and ratio (1.37) than Serbia (0.49 and 1.14 respectively). We conclude that context and timing are key to determining how, when and why a One Health approach should be applied. The adoption of a true OH approach that involved systemic organization, leadership clarity and transdisciplinary communication, collaboration, and co-ordination was essential to Malta's successful eradication of brucellosis after several failed attempts. In contrast, contextual factors in Serbia permitted the successful adoption of a primarily sectorial approach for short term control of brucellosis. However, while a fully-fledged transdisciplinary OH approach was not initially required, it is likely to be key to maintenance of brucellosis control in the medium and long term. Through these two case studies, we demonstrate that One Health initiatives should be applied at the right place, at the right time, with the right people and using the appropriate conditions/infrastructure. Lastly, OH evaluations should include economic assessments to identify optimal of resources in these situations, thereby justifying funding and political support required.

Keywords: brucellosis, control, evaluation, Malta, one health, Serbia, zoonosis

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INTRODUCTION

Brucellosis is one of the most common zoonotic infections worldwide, and remains a major public health concern (1–4). Known variously as "Mediterranean fever," "undulant fever," or "Malta fever," the infection is caused by microorganisms belonging to *Brucella*, a genus of gram-negative coccobacilli that behave as facultative intracellular pathogens of ruminants, swine and other animals (4). Currently at least 8 species of *Brucella* are known, of which four, namely *Brucella melitensis*, *Brucella suis* and *Brucella abortus* and *Brucella canis* are known to have moderate to high human pathogencity. *Brucella melitensis*—the most frequent aetiological agent in sheep and goats (5)—is the main pathogen responsible for human brucellosis, followed by *Brucella abortus* and *Brucella suis.* The disease causes clinical morbidity in humans, as well as a considerable loss of productivity in animal husbandry in the developing world (5, 6). Animal infection is characterized by increased likelihood of abortion, impaired fertility and reduced milk production, with serious potential financial consequences for the individual livestock holder and communities (7). Humans are accidental hosts, who readily acquire brucellosis through consumption of unpasteurized dairy products; direct contact with infected animals, placentas or aborted fetuses; or inhalation of aerosols (4, 5, 7). The disease typically manifests in humans as an acute febrile illness which may progress to a chronically incapacitating illness with severe complications (5). Any organ and system of the human body may be implicated, yet it is often unrecognized and frequently goes unreported (4). Osteoarticular and reproductive disease are most common complications, whereas endocarditis remains the principal cause of mortality if the disease is not adequately treated by protracted, combined antibiotic administration (2, 4, 5). Relapses, at a rate of around 10%, may occur in the first year after infection as a result of inadequate treatment (5). Its duration and associated prolonged convalescence period means that brucellosis has important medical, as well as economic implications, such as infected persons' absenteeism from work. Brucellosis is considered to be an occupational hazard in shepherds, abattoir workers, veterinary surgeons, workers in the dairy industry, and microbiological laboratory personnel (4). Vaccination is the cornerstone of control programs in livestock; vaccines for cattle, sheep and goats have been developed, however a human vaccine for brucellosis does not yet exist (8).

Brucellosis is still endemic in many parts of the world, particularly where geographical and climatic conditions together provide the perfect medium leading to dissemination of the disease. Factors contributing to these conditions include poor grazing lands that do not permit the grazing of cattle (but are favorable for sheep and goats), and situations where farm animals are kept in close proximity to humans (9). The epidemiology of human brucellosis has changed drastically in recent decades as a result of political and socioeconomic factors, improved surveillance systems, animal-based control programs, and growing international tourism and migration (7, 10). While there are no reliable data on the global burden of brucellosis, a figure of 500,000 new cases per year is usually accepted as a global estimate (1). Although there has been significant progress in controlling the disease in many countries, areas where the infection persists in domestic animals remain. Consequently, transmission to humans is common, particularly in Mediterranean countries, north and east Africa, the Middle East, south and central Asia, and Central and South America (4). Few countries are officially free of the disease (1, 7).

The prevention, control and eradication of brucellosis typically require collaboration across a number of sectors (4). According to the One Health Initiative (www.onehealthinitiative.com), "One Health" is an umbrella term referring to the commonalities between people, animals, plants and the environment. It recommends integrative approaches to health by expanding interdisciplinary collaboration across these highly interlinked components (11–13). The participation of representatives from Malta and Serbia in the EU COST action TD 1404 "Network for Evaluation of One Health"—these being two countries where efforts to control or eradicate brucellosis have been mostly successful: in Malta during the last decade of the twentieth century after several failed attempts (9, 14), and in Serbia during the first decade of the twenty first century (15, 16)—led to this study. The objectives of this comparative study are 2-fold. First, we aim to provide a short historical account of the process and co-ordination of actions in both countries, and compare Malta's 1995–1997 with Serbia's 2004–2006 control and eradication programmes. It should be noted that contextual and temporal differences between the two countries led to the adoption of substantially different approaches to brucellosis control. Furthermore, in June 1999 the "United Nations Security Council resolution 1244" established the United Nations Interim Administration Mission in Kosovo (17). Subsequently, brucellosis data from Serbia did not include Kosovo. Any mention of Kosovo in this manuscript therefore refers solely to pre-1999 data, when Kosovo was administratively part of Serbia. Second, we will quantitatively evaluate "One Health-ness" of the programmes through the calculation of an index and ratio—developed by the Network for Evaluation of One Health—to assess the extent to which they were compliant with a One Health (OH) approach. For both case studies, we describe the OH programme or initiative (i.e., drivers, operations, supporting infrastructure and outcomes) and the system (i.e., dimensions, boundaries, aim, actors, and stakeholders) within which it operates (12). The major elements evaluated through the One Health framework are social, environmental, and economic in nature. Different characteristic OH operations (i.e., thinking, planning, working) and supporting infrastructures (to allow sharing, learning and systemic organization) are also examined (12, 13).

Successful control of brucellosis in Malta and Serbia was only achieved and maintained when the strategy to address the infectious disease in both countries demonstrated OH characteristics of leadership clarity and transdisciplinary communication, collaboration, and co-ordination. This evaluation is intended to inform scholars, practitioners, and communities involved in the surveillance, control and management of brucellosis about the salient features and potential usefulness of adopting the OH approach. Although, the

evaluation is being conducted retrospectively, it should provide a useful roadmap prospectively.

Historical Account

The following is a historical commentary upon the two countries' brucellosis control strategies, approached primarily from a social and environmental perspective. In Malta, the eradication process was steered by the Ministry of Health's Public Health Department, whereas the Ministry of Agriculture's Directorate for Veterinary Medicine led the Serbian control initiative. This is primarily because Malta lacks an academic department for veterinary science, and control of infectious diseases is the legal responsibility of the Superintendent of Public Health. Brucellosis is a notifiable disease in both Malta and in Serbia, hence reporting the disease is mandatory if it is suspected or diagnosed in humans or animals.

Malta

Brucellosis (namely *Brucella melitensis*), had long been endemic in Malta, to the point where it was known as "Malta fever" (9). From an environmental perspective, Malta has poor grazing lands that are only favorable for the herding of small domesticated ruminants (sheep and goats]. The proximity of humans to these animals and regular consumption of unpasteurized goat milk was highly prevalent in Malta at the beginning of the twentieth century, resulting in a continuous potential source of infection for the general population. Despite seminal work on the pathogenesis of the disease carried out by Sir Themistocles Zammit—a Maltese doctor—which led to the identification of unpasteurized goat milk as the major source of infection in 1905 (18, 19), there was a lack of knowledge among the general population that goats were the primary reservoirs of infection. Furthermore, throughout the twentieth century there was persistent cultural resistance to the notion that unpasteurized goat's milk and related products—typically considered to be "healthy" and "wholesome"—were in any way related to the disease (9). Goat herders in particular were notoriously reluctant to comply with authorities, and a portion of the population persisted in consuming raw milk (9). This unwillingness among the population to change traditional behavior was the primary reason for multiple failed attempts at eradication during the twentieth century, in addition to a *Brucella melitensis* eradication programme launched in 1956 which was never properly implemented (9).

During the late 1980s, several Government departments—including the Public Health, Veterinary Services, Agriculture and Consumer Affairs departments—worked together in an attempt to secure the entire production chain of fresh cheeselets (small round cheeses made from milk, salt and rennet) and milk. Policy makers were highly engaged in the process and introduced effective legislation that required the registration of all herds in Malta. In 1987, the Veterinary Services Department (VSD) launched the "Test and Slaughter" scheme (20) across all milk-producing herds in Malta. Goats and sheep above 6 months of age were identified through ear tagging or freeze branding, thus facilitating a more effective, systematic 6-monthly screening process. Infected animals were slaughtered within 14 days. If more than 10% of animals in a herd were infected, the herd was depopulated and the farm disinfected (21, 22). The Director of Agriculture issued new regulations making it obligatory for farmers to notify any movement of animals from one farm to another and supported the tattooing, freeze-branding or ear-tagging of the animals (22). Between 1986 and 1996, prevalence of infection within herds fell from 23 to 1% (22). However, despite these initiatives, an outbreak of the disease occurred in 1995, when around 238 cases of human brucellosis were diagnosed (22). The 1995 outbreak revealed weaknesses in the system, demonstrating that more work needed to be done to achieve control of brucellosis.

Following the 1995 outbreak, an intersectoral outbreak committee was set up. The Ministry of Health and the Department of Public Health led the brucellosis eradication initiative of 1995–1997, which was characterized by interdisciplinary collaboration between the major stakeholders. These included public health inspectors, public health doctors, microbiologists, medical doctors, the police, and veterinary surgeons. A clear case definition for identification of brucellosis in humans was established. Any person presenting with one of the following symptoms: fever; weakness; headache; chills; arthralgia; localized suppurative infection or encephalopathy, who also had a *Brucella* antibody titer of > 1 in 320 dilution or a positive culture of *B. melitensis*, or who had a member of their household with a *Brucella* antibody titer > 1 in 320 dilution (with or without symptoms), was classified as a case. The Disease Surveillance branch of the Department of Public Health extensively sampled and tested cheeselets sold in shops, street vendors and supermarkets across the Maltese islands. The Department of Agriculture was subsequently notified regarding suspect herds, which were examined further and blood testing carried out (21). The main source appears to have been three farmers who kept so-called "phantom" herds concealed from routine VSD inspections. Further spread to other herds occurred when these owners fragmented their unregistered herds and sold them off cheaply in order to avoid depopulation (22).

The outbreak committee also communicated regularly with the general public and issued several press releases during this time. The Public Health Department also delivered a mass media educational campaign to foster awareness of the potential ill-effects of consuming unpasteurized cheeselets among the general public. Additionally, the Agriculture Department organized a series of talks delivered to farmers and herders that focused on hygiene and the importance of pasteurization. Detailed leaflets regarding the best method of manufacturing cheeselets were prepared. The national dairy company offered pasteurization services to the producers and created its own branded cheeselets, marketing them as "guaranteed safe" to reassure the public. Draft regulations were implemented to control the hygienic processing, transport and sale of cheeselets: new packaging and labeling practices required the introduction of a "lot" number, "best before" dates, the producer of the cheeselets and whether they were made from pasteurized or unpasteurized milk (9). The sale of fresh unlabeled cheeselets by weight was banned. Although the outbreak committee focused primarily on human infection, its efforts were supported by a highly active health inspectorate

who confiscated 930 kg of cheeselets from 27 producers, 12 wholesalers and 384 retailers during this period, as well as VSD staff who destroyed 116 caprines, 68 bovines and 43 ovines after screening 3,416 herds in Malta and 1,449 herds in Gozo (9). Malta was declared free from locally acquired human brucellosis in 2005 (23), and from bovine brucellosis in 2016 (24).

Serbia

A lack of knowledge about the mechanisms of spread of *B. melitensis* and *B. abortus* among animals and in humans, and non-regulated import of infected animals from neighboring countries, characterized the Serbian scenario. In the former Yugoslavia, brucellosis was reported for the first time in the district of Istra in 1947, but was eradicated within a few years (15, 25). It reappeared in the 1960s, in Macedonia, probably through sheep imported from Israel (26). By the late 1970s, sheep-borne Brucellosis had appeared in most territories of Macedonia, in Kosovo and Metohija, as well as in south Serbia (27). While the epidemiological situation in the Republic of Serbia was relatively stable up to the 1980s, with around 40 human cases identified between 1951 and 1970 (27), this was not maintained over the following two decades. Incidence increased from 1985 and peaked in 1991 (25). During the 1990s, brucellosis spread to central and north Serbia as a consequence of armed conflicts and uncontrolled movement of infected sheep (15). The disease has also spread to south Serbia, in the region bordering with Kosovo and Metohija, in recent years (15).

A critical increase in cases of Brucellosis was observed in the territories of Kosovo and Metohija, with 241 cases being reported in 1991 (28). The disease also reappeared in areas that had previously been considered to be free of the disease. For example, brucellosis had not been diagnosed in either humans or animals in Vojvodina, a province in the northern part of Serbia, during a thirty-year period from 1971. However, a positive diagnosis was made in two farm workers in the South Banat district of Vojvodina in 1999 (15). Subsequently, foci of brucellosis continued to multiply and spread to neighboring counties, probably due to the uncontrolled movement of infected herds (e.g., illegal trade, nomadic livestock herding) compounded by poor implementation of countermeasures ordered by the Veterinary Service. Farm workers were exposed to infected animals, and consumers of milk products—such as cheese produced from unpasteurized sheep milk—were also infected. There was also some cross-species spread, as brucellosis was identified in other farm animals such as swine and dogs (28). By late 2004, new foci had been identified in five counties, and human brucellosis cases had been diagnosed in 12 settlements. Overall, 1,521 cases of human brucellosis were identified between 1980 and 2008 in Serbia (25).

The Ministry of Agriculture led the Serbian control programme of 1999–2005 through the Directorate of Veterinary Medicine, in collaboration with other actors including policy makers, veterinarians, medical doctors and police. In Serbia, the outbreak committee mostly focused on animals. An outbreak committee consisting of veterinary health specialists, veterinary inspectors, public health doctors, and microbiologists who established the case definition (i.e., any animal presenting with symptoms of fever, weakness, and/or abortions, with a positive antibody test of *B. abortus*, *B. melitensis*, or *B. suis*) was set up. During this period, a "test and slaughter" programme similar in scope to that described for Malta was established. Overall, the veterinary services destroyed 1,497 animals (cattle, pig, sheep and goats) in the northern part of Serbia after screening 1,485,702 animals. No data is available for the southern part of Serbia. The number of infected humans and animals significantly decreased in northern Serbia (Vojvodina province) after 2006, and in southern Serbia after 2009, and overall Brucellosis incidence now shows a declining trend (16). In Serbia, brucellosis may still occur in animals if these are illegally imported in the country (7). Controlling the trade in animals is likely to be a key method of controlling and preventing the spread of brucellosis (25). However, there are reports that wild boars and rabbits are reservoirs of *B.suis,* whereas dogs are reservoirs of *B. canis* in Serbia (29).

METHODS

We applied methods developed by the EU COST action TD 1404 "Network for Evaluation of One Health" (NEOH, http://neoh.onehealthglobal.net) (12). The NEOH evaluation framework is a mixed method approach that covers the definition of the initiative and its context, the theory of change (TOC), the process evaluation of operational and supporting infrastructures ("the One Healthness"), and an assessment of the association(s) between the process evaluation and the outcomes produced (12). This comparative case study *retrospectively* identifies drivers, outcomes, operations and infrastructure of the One Health approach to Brucellosis eradication and control (as applied in Malta and Serbia respectively) in an integrated manner, namely through the holistic assessment of these aspects. This analysis includes a historical account intended to offer insight into the geopolitical context of Brucellosis outbreaks and to identify and delimit the systems within which the OH initiatives were developed to differing extents. The TOC (30) underlies this process. To aid our analysis, we developed a visual approach for system identification and delimitation (see **Figures 3**, **4**, below) and the further identification of costs related to Brucellosis in humans and animals (**Figures 6**, **7**).

Theory of Change

Within a OH approach, the TOC defines the objectives of the initiative, as well as the changes required to achieve these goals (13). Therefore, in line with NEOH guidelines, the TOC for brucellosis eradication and control provides a conceptual framework that enables retrospective analysis of the control and eradication committees' actions in both countries and definition of the short-, medium-, and long-term objectives that ultimately led to successful control (in Serbia) and eradication (in Malta). **Figures 1**, **2** illustrate the pathway of change (representing the TOC) applied to brucellosis eradication in Malta between 1995 and1997 (**Figure 1**), and brucellosis control in Serbia between 2004 and 2006 (**Figure 2**). For inputs, activities and surveillance, Serbia mainly relied on the veterinary services and lessons learnt from other countries. Although the 2004–2006 brucellosis

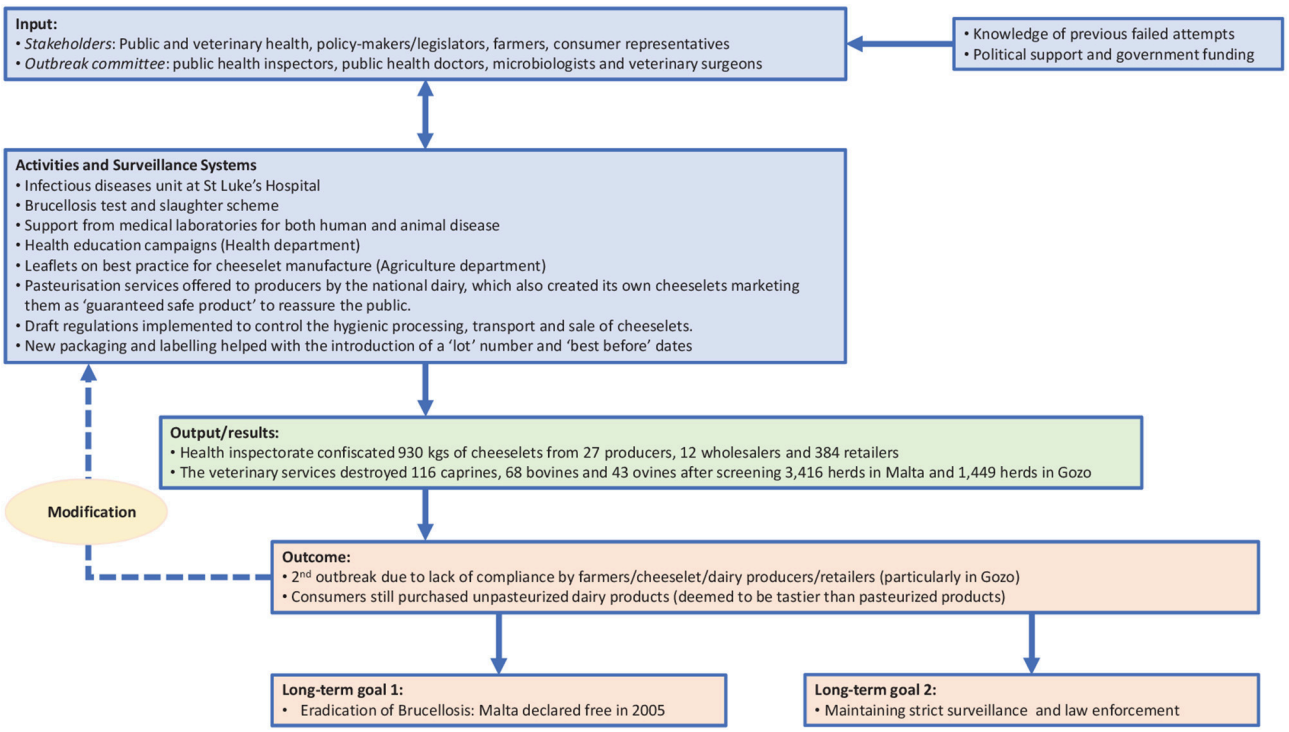

FIGURE 1 | Pathway of Change representing TOC in brucellosis eradication in Malta.

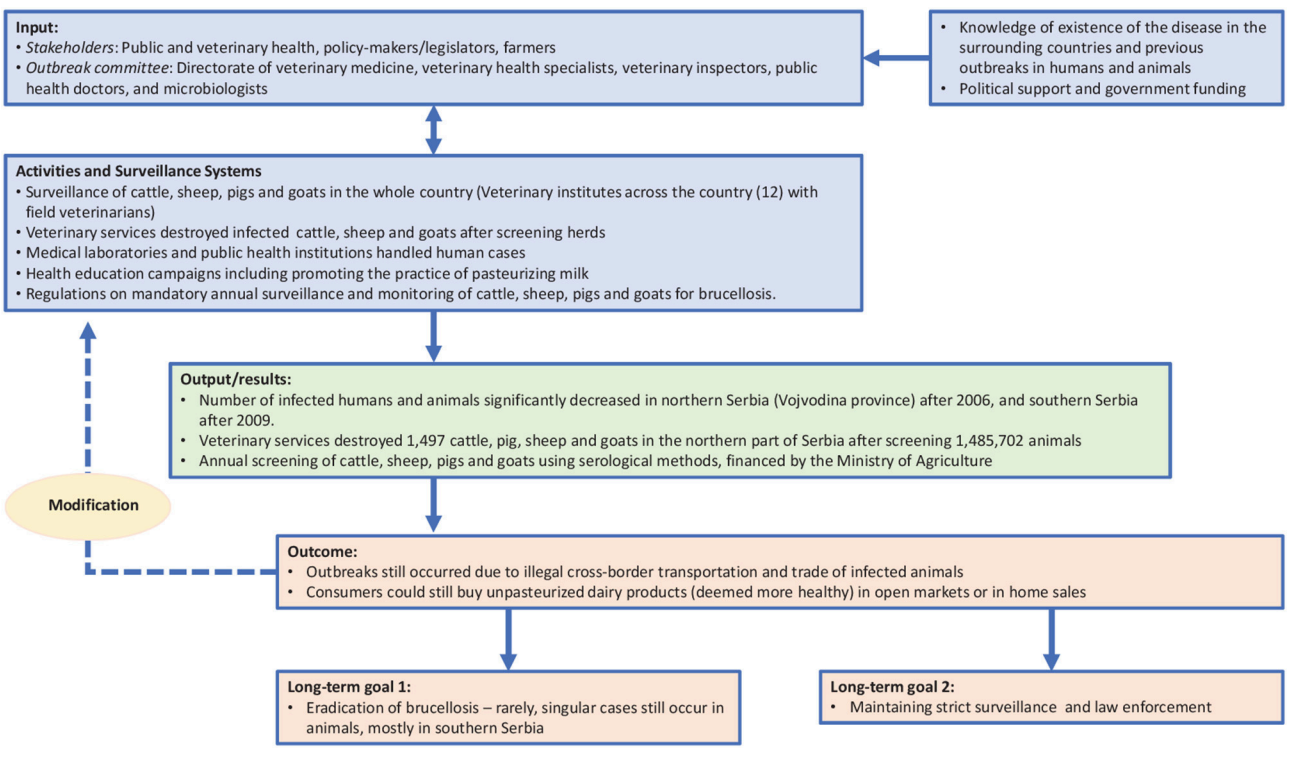

FIGURE 2 | Pathway of Change representing TOC in brucellosis control in Serbia.

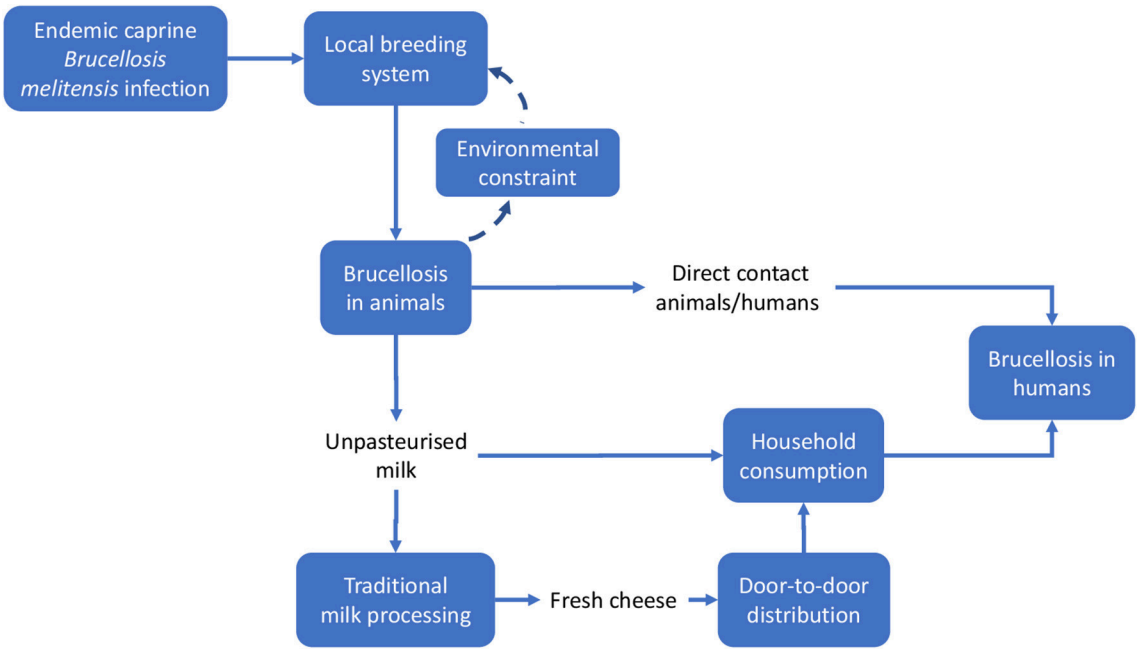

FIGURE 3 | System identification in Malta. Solid lines indicate direct relationships or flows between elements; dashed lines stress potential reinforcement effects (feedback) of local brucellosis reservoir due to the use of pastureland.

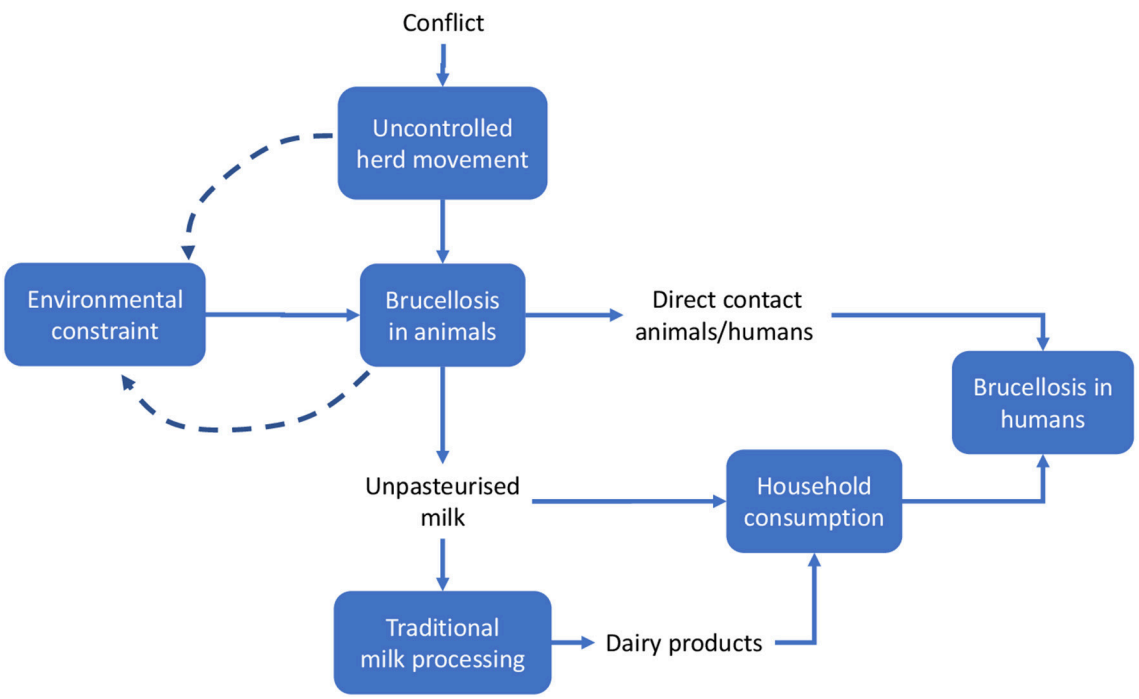

FIGURE 4 | System identification in Serbia. Solid lines indicate direct relationships or flows between elements; dashed lines stress potential reinforcement effects (feedback) of local brucellosis reservoir due to the use of pastureland.

outbreak in Serbia was ultimately controlled, the risk of infected animals being illegally brought into the country remains high, hence it is difficult to declare the country entirely free of brucellosis.

Search Strategy

A non-systematic literature search around brucellosis was conducted between January 2016 and April 2016 using Google Scholar, PubMed and EMBASE to identify scientific articles and

gray literature that would inform the background of this study. The following search terms and key words were used: Brucell* AND Malta OR Serbia. Furthermore, the bibliography of articles emerging from the search were reviewed to identify additional potentially relevant literature.

Data Collection

Using a case study approach, the authors obtained information primarily through 15 documented interviews carried out in both countries. In Malta, these interviews were recorded and transcribed by John Rizzo Naudi prior to 2005 (9) and involved key stakeholders across several disciplines, including main actors in animal health, human/public health and food safety/consumer health. A mix of telephone and face to face interviews with key stakeholders in Serbia were conducted by SS between 2015 and 2017. In both Malta and Serbia, a purposive sampling approach was adopted. This is a non-probability sampling technique, used when there are limited primary data sources available, that was judged by the researchers to be the most appropriate in order to identify relevant stakeholders in the brucellosis control programmes. All participants consented to be interviewed. With regard to animal health in particular, officials from the Veterinary Services Department (Ministry of Agriculture), veterinary service practitioners, and farm/animal owners in Malta were interviewed; whereas the Directorate of Veterinary Medicine (Ministry of Agriculture) as well as veterinary service practitioners and farm/animal owners were the interviewees in the case of Serbia. In view of potential biases arising from interviewees by virtue of the discipline they represent, we triangulated the data and information arising from the interviews using document analysis of legal documents, archival material from public health and veterinary sources, and other published material (9, 15). Document analysis is a component of qualitative research that involves in-depth assessment and interpretation of documents so as to substantiate the accounts provided by the interviewees (31).

We therefore retrospectively identified and discussed the various steps and systemic changes that needed to take place for brucellosis eradication or control to be achieved. Assessment of the following aspects: Thinking, Planning, Working, Sharing, Learning and Systemic organization—was conducted. The dimensions within each aspect—where each "dimension" refers to an entity that can be captured by the same metric or concept, such as geographical space or time—were scored in increments of 0.2 (where 0 = not considered; 1 = essential) by SB for Malta and SS for Serbia. Information on the scales for the different dimensions can be found in the appendices. Scoring of the NEOH evaluation tool (13) was then carried out by a focus group involving six professionals involved in public health and veterinary science in both countries. SB and SS were participants in this focus group. Ultimately, comparable OH-indices and ratios for the initiatives in Malta and Serbia were derived.

Lastly, a conceptual essay for economic evaluation that assesses the flow of cost and benefits is provided. This offers a basis for further evaluation aiming at assessing the advantages of the OH approach in comparison with traditional approaches toward disease control and eradication.

RESULTS

The Public Health Department (Ministry of Health) was the main actor for Malta, whereas the Directorate of Veterinary Medicine was the main actor for Serbia. Public health services in both countries included reference laboratories for human diagnostics; physicians, and hospitals. The Public Health Department assumed responsibility for these services in Malta, whereas Local Health Authorities were responsible for public health services in Serbia. Food safety/consumer health was only relevant to the Maltese scenario and involved the Superintendence of Public Health and Department of Consumer Affairs. Other major stakeholders included health education/promotion and policy makers from the Health, Agriculture, Justice and Internal Affairs Ministries in the case of Malta; and policy makers from the Ministry of Agriculture and Ministry of Internal Affairs in the case of Serbia.

System Dimensions and Boundaries

Meadows and Wright define a system as a "*set of elements or parts that is coherently organized and interconnected in a pattern or structure that produces a characteristic set of behaviors, often classified as its 'function' or 'purpose.'*" (32). The application of this definition to the two country cases being analyzed led to the identification of the main elements that determined the emergence of the disease and its perpetuation. We outlined the system and the system boundaries in the two cases using a comparative approach, stressing similarities and differences. **Figures 3**, **4** schematically visualize the basic epidemiological models in Malta and Serbia respectively. We expanded the basic scheme of an epidemiological model to outline links and feedback loops connecting the emergence of brucellosis to the overall systemic contexts, identifying in particular both environmental and social factors. In the case of Malta (**Figure 3**) the presence of Br. in herd animals is a consequence of its endemic presence and the specific characteristic of the breeding system, based on the use of environmental resources (feeding on pastureland) where Br. is spread, reinforcing the emergence of the disease (blue dashed arrows). Environmental, breeding and distribution sub-systems transmit the disease to human beings *via* direct contact and food (i.e., the use of non-pasteurized milk in processing). Social practices and behaviors, as well as the general state of knowledge about mechanisms of disease spread, are of relevance to the wider socio-cultural sub-system which determines the insurgence and the persistence of the disease in the society (i.e., interaction between humans and animals inside and outside breeding places; traditional food distribution and consumption habits; and the misleading representation of product authenticity).

Other relevant elements of the system could not be shown in **Figure 3**, namely:

– The institutional framework, i.e., the institutions charged with solving the *Br.* problem, their organization and strategies (i.e., policy measures). The institutional framework can be considered to be a sub-system permeating and affecting the functioning of the basic system outlined in **Figures 3**, **4**, thus enlarging its boundaries.

– The evolution of the institutional framework over time. Together with geographic space, time is a relevant dimension of the system, particularly because of the sequence of repeated attempts to control *Br*., the accumulation of scientific knowledge and of what was effective (i.e., through the failures of prior intervention measures) and the increase in social awareness, finally leading to the implementation of the OH-like model of intervention.

In the case of Serbia (**Figure 4**), the same approach was adopted, but some differential elements contributed to the identification of the system.

Based on the system identification process outlined above, we developed a comparative approach between the two cases. General similarities between the two countries include the basic contextual units of the system, such as the general epidemiological features of the disease and—assuming that the geopolitical territory of Malta and Serbia respectively represents the spatial limits of each system—its dissemination to human beings via direct contact and through the food supply chain (i.e., milk or milk products such as consumption of unpasteurized fresh cheese). Additional similar elements include:

i. Local breeding systems reliant on the use of pastureland by different herds moving across the countryside (which promotes the dissemination of the disease within farms or family production units), characterized by prolonged close contact between animals and humans;
ii. The health system, in particular the lack of effective counter-measures and governance to address brucellosis;
iii. Limited knowledge regarding the risks related to brucellosis among the general population, which in turn determines local practices and behaviors in production, processing and consumption. In the case of Malta, this explained the social mis-representation of dairy product safety and led to the persistence of traditional processing and consumption practices, despite health measures implemented several times over a number of decades.

On the other hand, some features uniquely characteristic to each country may explain, at least in part, differences in the timeline and key characteristics of brucellosis development in the Maltese and Serbian systems. In particular, the unique geographical characteristics of the two countries resulted in different patterns of disease emergence and resilience to eradication and control, particularly in combination with:

i. The differences in the political context (e.g., in Serbia, movement of people and herds during the conflict made it difficult or impossible to control the importation of infected animals from neighboring countries)
ii. The differences at institutional or organizational levels (i.e., animal health research capability; human health systems and public health systems)
iii. The greater relevance of traditional consumption habits in Malta, in comparison to Serbia, which resulted in a greater emphasis on the food supply chain for OH initiatives in that country
iv. Last but not least, Malta had a pioneering role in the discovery of brucellosis epidemiology. This probably contributed to the differences in timing and method of intervention strategies between the two countries.

A further step in system identification concerns the institutional and governance aspects of the health measures adopted in 1995–1997 and 2004–2006 in Malta and Serbia respectively. While Serbia's strong Veterinary Services played a leading role in the control of brucellosis, Malta's veterinary services were not developed to an equivalent extent and hence could not lead the control and eradication programme. Instead, Malta relied on a historically powerful public health sector, which was in a position to take on a leadership role in the most recent outbreak. These have been amply described in this paper.

Table 1 below synthetically compares the relevant systemic elements of the case studies.

Drivers and Rationale

The rationale of the eradication and control processes in both countries was to address the infectious disease, with efforts primarily focused on systemic organization, leadership clarity and transdisciplinary communication, collaboration, and co-ordination. The following drivers spurred the intensity of efforts to control brucellosis in the two countries:

i. *Economical*: high health care cost of treating human brucellosis; costs of surveillance; costs of government subsidies to farmers whose animals are eliminated because of the disease
i. *Emotional/Psychological*: suffering of patients (humans, animals) affected by brucellosis; suffering of family and friends, particularly in fatal cases. Human cases of brucellosis were more prominent in Malta than in Serbia, where the disease seemed to have caused substantial emotional and psychological distress
iii. *Geographical*: Malta's island status contributed to the recognition of disease vectors and also helped to contain and maintain eradication of the disease. This driver was more of a challenge in Serbia, since the importation of infected animals was facilitated by porous land borders. Hence geographical location is a crucial consideration—Serbia depended on the actions of neighboring countries to manage its Brucellosis control process, whereas this was not the case for Malta
iv. *Social*: Malta's sister island—Gozo seemed to be less receptive to public health warnings regarding brucellosis, as manifested by the lingering belief that aseptic (clean) farming and retail environments were sufficient to ensure food safety of milk/products. The social driver in Serbia was primarily related to the country's post-war relations with neighboring countries and the lack of communication and trust between people from different (Former Yugoslavia) regions.

Evaluation of "One Health-ness"

This section of the results deals with the quantitative evaluation of the "One-Health Index." Each of the six assessments outlined below is represented by a spoke in the spider diagrams for Malta

TABLE 1 | Synopsis of case studies comparison.

Relevant elements/sub-systems of the system	Malta	Serbia
Br. origin	Endemic, probably imported	Uncontrolled herd flows due to regional conflict
Breeding system	Family breeding, pre-industrial Transhumance	Family breeding, pre-industrial Transhumance
Environmental system	Use of common pastureland	Use of common pastureland
Processing system	Use of unpasteurized milk to produce traditional cheeselets	Use of unpasteurized milk in dairy products
Transmission mechanism	Direct contact	Direct contact
Social and cultural system	Traditional consumption habits Mis-representation of product authenticity Lack of scientific knowledge Lack of social awareness	Traditional consumption habits Lack of social awareness
Institutional system	Department of Public and Environmental Health as leader, in close collaboration with Departments of Agriculture and Veterinary Services, consumer Affairs, Justice and Police	Directorate for Veterinary Services as leader and prime mover, collaborating with Public Health, and Police
Policy and measures	*Laws of Malta*: Measures for the eradication of Brucellosis, Tuberculosis and Leucosis S.L. 437.86. Law transposed into policies across Government Departments for continued control and surveillance. The scope of these rules is to implement the rules contained in the European Union Council Directive 77/391/EEC concerning the introduction of Community measures for the eradication	Record keeping on brucellosis cases exists since 1984, when the Law on Infectious Diseases was passed. European Union (EU) has implemented various laws and restrictions regarding import and export of cattle and pig (EC 64/432), sheep and goats (EC 91/68), as well as regulations regarding products of animal origin, animal identification, and tagging

and Serbia (**Figure 5**) where thinking, planning and working (operational aspects) on the top left of the diagonal contrast with learning, sharing and systemic organization (infrastructural aspects) on the bottom right. The hexagonal surface represents the degree of integration, calculated as the One Health Index (OHI), whereas its symmetry or otherwise represents the balance between the operation and the supporting means of the OH initiative. This symmetry is numerically represented as the One Health Ratio (OHR) (13). Each assessment and its component dimensions are outlined in further detail below and in the appendices. **Figure 5** shows that Malta and Serbia had identical scores for all assessments except for thinking, where Serbia scored lower. The details of the workings pertaining to Malta and Serbia can be found in the Supplementary Material.

Thinking

Thinking refers to the way actors and stakeholders think within and about the system and the One Health initiative. This includes an assessment of how the dimensions and scales under consideration (e.g., local, regional or global scales within geographical space; an understanding of the timeframe of the initiative; life; network or organization; economy; legislation; governance; and value constructs such as interest groups) may support or limit the outcomes and impacts of the initiative. The overall scores are 0.80 for Malta and 0.60 for Serbia. A major strength for both countries was the integrated health approach adopted during the eradication process. The lower overall score for Serbia is attributed to the lower sub-scores in the different dimensions' coverage and balance, and to sustainability and socio-ecological considerations. The focus in Serbia was timely control of the disease in animals before it spread to humans, hence fewer dimensions were covered and less importance was given to sustainability once there was successful control and effective law enforcement by the Veterinary Service. Although Malta's score for thinking is higher, this was mainly due to Malta's previous failed attempts at eradicating the disease, and reflects the fact that more stakeholders needed to be involved in order to finally achieve success.

Planning

One Health planning requires that aims, problem formulation, responsibilities, resource allocation and financing of the initiative are systematically organized. It also requires clarity in establishing roles, tasks, responsibilities, and competencies of participants (13). In this case study, this included consideration of whether stakeholder engagement during the process of Brucellosis control and eradication was planned, and whether mechanisms existed to feedback stakeholders' knowledge into the governance of the initiative. Such questions and other elements underpin the OH approach and contribute directly to OH outcomes, therefore planning may influence other assessments of the OH initiative under consideration (such as working, sharing, learning and systemic organization). The overall score for both Malta and Serbia was 0.80. In the case of Malta, the main focus of planning during the eradication process was the control of human disease and protection of consumers (i.e., from ingesting infected dairy products) while attempting to eradicate brucellosis in animals. In contrast, the major focus for Serbia included identification and registration of animal herds, rigorous blood sampling of animals and strict annual surveillance, led by the veterinary services.

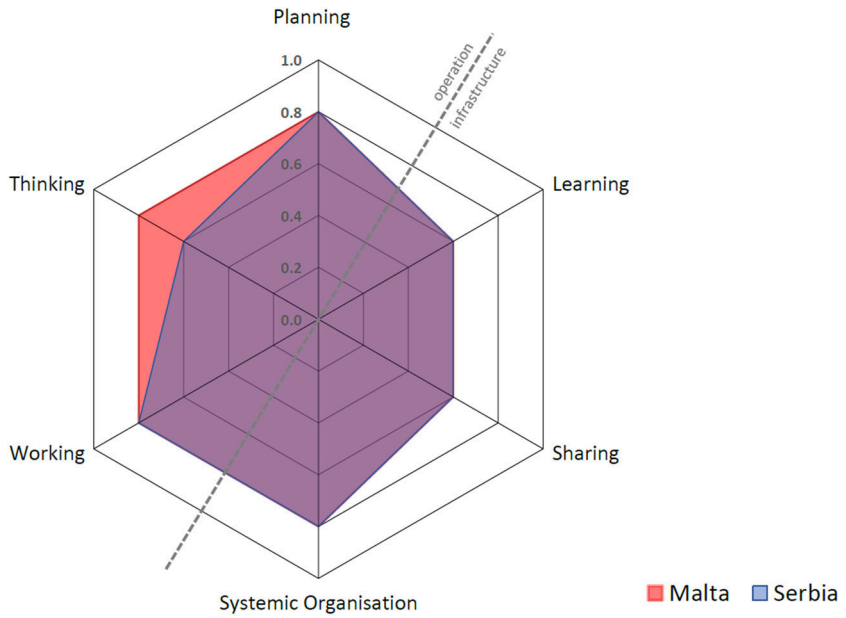

FIGURE 5 | Malta and Serbia's One Health Index for the process of brucellosis control.

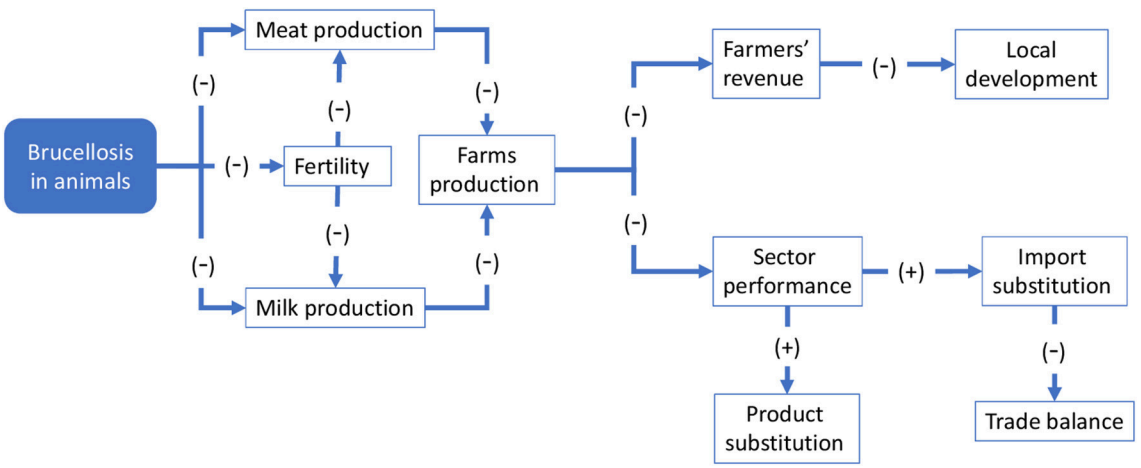

FIGURE 6 | Economic consequences of brucellosis at farm and sector level.

Working

This assessment explores the extent to which engagement in the OH initiative was interdisciplinary and participatory (i.e., transdisciplinary) (13). Transdisciplinarity relies on appropriate leadership and management (i.e., system organization) to promote the establishment of non-hierarchical relationships, strategic dialogue, and shared decision-making between team members coming from different disciplines. The overall scores are 0.80 for both Malta and Serbia. Malta scored higher on collaboration between all the major stakeholders involved in policy, human health, animal health, retailing and consumer protection. Serbia scored higher for flexibility and adaptation, reflecting the successful leadership of the veterinary services.

Sharing

Sharing refers to the information and data-sharing infrastructures in One Health initiatives (13). Elements that were considered in this assessment include whether appropriate internal or external mechanisms were used for sharing information; whether resources were allocated to facilitate and ensure sharing of data; and what mechanisms in place for safeguarding access to data. The overall scores are 0.60 for both Malta and Serbia. Malta's scoring showed some resistance in sharing data and information, which partly explains prior failed attempts and the difficulties with law enforcement, particularly in Gozo.

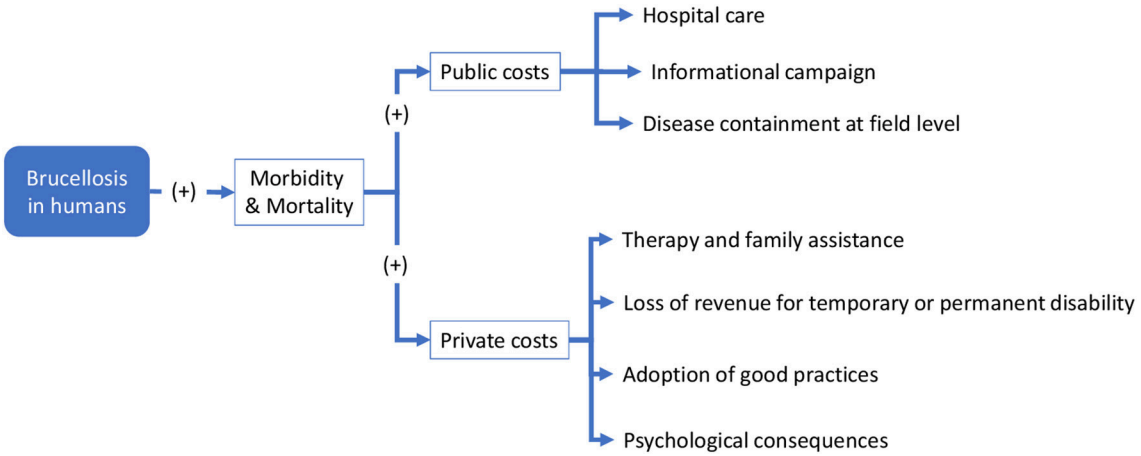

FIGURE 7 | Economic consequences of Brucellosis across society.

Learning

The learning infrastructure within the One Health initiative comprises the learning style (i.e., whether basic, adaptive or generative) and setting (i.e., at the individual, team and organizational level). It also encompasses the type of environment: namely the stakeholders involved ("direct" environment), and the cultural, economic, and political situation surrounding the OH initiative ("general" environment). Our assessment considered whether these learning styles and environments supported a OH approach. The overall scores are: 0.60 for Malta and 0.60 for Serbia. Malta showed slightly greater emphasis on adaptive and generative individual, team and organizational learning, as a result of the crisis that ensued following the emergence of Brucellosis in humans.

Systemic Organization

This assessment probes whether implementation of the OH initiative was facilitated by change-oriented leadership and effective teamwork, and therefore is closely related to and influenced by OH Planning. The overall scores are 0.80 for both Malta and Serbia. Despite differences in the methods leading to control and eradication, both countries manifested a rather strong sense of systemic organization as reflected by social and leadership structures and skills, team structures, competence and focus on innovation.

Table 2 shows that the overall Index and Ratio are slightly higher for Malta. This is attributed to the higher score of "thinking," as well as to the greater degree of transdiciplinarity.

TABLE 2 | "One-Healthness" of the systems in Malta and Serbia.

	Malta	Serbia
One health index	0.54	0.49
One health ratio	1.37	1.14

Measured or Estimated Outcomes of the Initiative or Programme

Malta

Following the 1995 outbreak in Malta and subsequent efforts to eradicate the disease, there have been no cases of brucellosis in humans recorded since 1997. The control of the process, including monitoring and pasteurization of milk and cheese production and the enforcement of labeling and packaging is now co-ordinated by four collaborating departments: The Veterinary Services Department, the Public Health Directorate, the Agricultural Department and the Department for Consumer Affairs. Sharing and linking of information in inter/trans-disciplinary groups was well established in the 1995–1997 outbreak, which ultimately led to successful eradication. The information was successfully shared by representatives of disciplines on the outbreak committee and also to the non-scientific communities through information packages released by Ministries of Health and Agriculture.

Seminars and education activities are organized in order to increase the knowledge on the disease and involve stakeholders in surveillance activities, e.g., seminars and courses targeting official veterinarians and practitioners, medical doctors in hospitals and family doctors, and educational outreach campaigns targeting the general public.

Serbia

Sharing and linking of information between the Ministry of Health and Ministry of Agriculture was not carried out officially. While annual reports on zoonotic disease cases in humans (including brucellosis) are publicly available online, annual reports on animal screening from the Directorate of Veterinary Medicine are not publicly available. The yearly prevalence of brucellosis in animals can be found on the web site of the World Organization for Animal Health. Therefore, in contrast

to Malta's isolation as an island state, which facilitated control of Brucellosis, Serbia remains susceptible to importation of the disease unless strict, vigilant border control is continuously maintained.

Conceptual Framework for Economic Evaluation

This section focuses on the economic outcomes of brucellosis. It is likely that political support is more forthcoming when the adoption of an approach like One Health translates into economic gains. Although this study involves a conceptual, rather than an empirical, economic evaluation, potential economic impact of brucellosis may be identified through the schematic models in **Figures 6**, **7**. For the sake of simplicity, we will start by making reference to the common traits of the system outlined for the two cases, assuming a static view concerning the pre-OH initiative scenario. Economic impacts are described starting from the boxes "Brucellosis in animals" and "Brucellosis in humans" of **Figures 3**, **4** above respectively—these represent the relevant outcomes of the epidemiologic models in Malta and Serbia, and the critical points of economic impact for the breeding system and the social system (i.e., households), according to the dissemination mechanism. White boxes in **Figures 6**, **7** represent the series of sequential effects stemming from Br. in animals and humans (indicated by the blue arrows between boxes). Signs in brackets show the direction of the effect (positive or negative) on the subsequent effect (see detailed explanation below). In particular, brucellosis in animals is responsible for the flow of effects along the food supply chain, starting from primary production and finally affecting consumers through processing and distribution). Brucellosis in humans concerns the effects of human infection across society (stemming from the consumption of unpasteurized milk and cheese and from direct contact between animals and humans).

Figure 6 outlines the potential economic effect of brucellosis at farm and sectoral level (where the sector is composed of the multiplicity of farms that breed sheep and goats). Brucellosis in animals leads lowered milk and meat production [as shown by (−) signs in brackets] due to premature births in infected animals. Fertility is also impaired, resulting in a lower natality rate that in turn also negative impacts milk and meat production. These effects result in a global reduction of farm production, which negatively affects sales and farmers' revenue. Depending on the relevance of the breeding to the local economy, this may have broader economic implications. At sectoral level, it could result in a global reduction of output, leading to a decline in competitivity of the local sector in comparison with other production areas. Consumers' welfare may be reduced, including through reduced product availability or diversity (not mentioned in **Figure 6**), but higher prices may induce substitution imports of similar products from elsewhere and/or determine product substitution [i.e., consumers would demand similar products to compensate for the original missing products, e.g., cheese and meat of other species, as indicated by the (+) signs]. Substitution imports may have negative macroeconomic outcomes—for example, through a worsening of the country's import/export balance—whereas product substitution may paradoxically benefit other competing sectors.

As shown in **Figures 3**, **4**, brucellosis is a food borne disease that spreads across the food supply chain. It emanates from the production system (which is a part of the supply chain) and ultimately affects humans by way of direct contact, food processing and distribution, and consumption of dairy products. As outlined earlier, **Figure 7** starts from the final box of **Figures 3**, **4** (brucellosis in humans) and further identifies the economic consequences of the disease across society. In simplistic terms, brucellosis in humans may translate into increased morbidity and mortality rate [as shown by (+) signs], which put an increased economic burden [marked by (+) signs] on private and public costs:

- *Public costs:* arrows commencing from these boxes list the type of public costs, mainly incurred by the public health system (i.e., Hospital care for infected people; Informational campaign costs (mass media emissions, printed matter, direct information to communities, etc. to inform about the risk of, and avoid the persistence of, inappropriate practices); and Disease containment (such as food safety control; geographical delimitation of the infected area; field and laboratory analysis; implementation of active strategies to address the disease post-containment etc.)
- *Private costs*: similarly, arrows staring from these boxes list the types of private costs (i.e., Therapies and family assistance (e.g., health care costs of the households, time spent for assistance at home); Loss of revenue due to temporary or permanent disability, which translates into costs for individuals, families and society, depending on the social relevance of the disease; Adoption of good practices in milk/dairy product preparation and consumption; and Psychological suffering due to uncertainty around health status).

The positive and negative economic impacts outlined in **Figures 6**, **7** typically occur simultaneously (e.g., product substitution may benefit the producers of substitute products). The sum of these costs/benefits should be contrasted with the possibility of avoiding the negative effects (costs) altogether by intervening at an early stage, before disease spread. This is considered to be a benefit of any potential intervention. Economics provide different criteria to categorize intervention costs and related benefits, however a more detailed economic evaluation would focus the costs and benefits the OH-ness and its main dimensions (thinking, planning, working, sharing, learning, systemic organization). Though economic evaluation is not a key aim of this article, the concepts above offer a more precise idea of the complexity of the economic evaluation in the context of One Health, as well as a preliminary agenda for further development of the evaluation process to include OH-ness evaluation as briefly described in this article.

DISCUSSION

These two case studies, despite their common goal of eradicating or controlling Brucellosis, have quite diverse backgrounds and show different degrees of "One Health" thinking in their respective approaches. In both countries, control was only possible due to constant reminders to farmers and animal owners that the disease could easily spread to humans, together with strict enforcement of legislation. The Malta case study spans a century of failed measures and setbacks, and demonstrates a paradigm shift in the approach to brucellosis eradication over time. The measures implemented ranged from initially relatively isolated actions such as processing of milk through pasteurization (introduced prior to the second World War), to a more sectorial approach adopted in the 1980's. However, it was only upon the adoption of a true "One Health" transdisciplinary approach in the mid-1990's that Brucellosis eradication was successfully achieved and maintained. Enforcement of existing and newly implemented legislation was crucial to this success, and required collaboration by all stakeholders involved including public health, veterinary health, policy-makers and legislators, as well as farmers and consumers' representatives.

The Serbian context differed from the Maltese scenario. Serbia did not have a long history of brucellosis, which was largely sporadic before the mid-1990's and became endemic only as a result of the non-regulated importation of infected cattle and sheep from neighboring countries. There was no cultural resistance to the destruction of potentially infected herds of cattle and sheep, and a greater willingness to accept the scientific rationale for culling within the general population. Additionally, Serbia was able to capitalize on the experience and knowledge of OH thinking adopted in other countries, which explains the somewhat predominantly sectorial approach adopted by the Veterinary Directorate. This proved effective, so that escalation to a fully-fledged transdisciplinary OH approach was not required. It should be noted that the geopolitical conflict in Serbia that ultimately led to "United Nations Security Council resolution 1244" (17) meant that there is a lack of brucellosis-related data for Kosovo after 1999. Given this situation, any challenges regarding brucellosis in Kosovo could not be followed up to the period under study, representing a gap in our assessment.

While brucellosis control was the primary concern in the short term, surveillance and ongoing monitoring remain important medium and long term concerns. This is also reflected in the timing and extent of adoption of OH thinking in the two countries: in Serbia a true OH approach was not required for control, however it is likely to be key to its maintenance in the medium and long term. In Malta, the OH approach was critical in the short term in order to eradicate brucellosis, and together with strict enforcement of legislation remains key to ensuring that the disease does not return. The strength of the OH approach has been tested in recent years. In 2012 a "phantom" herd of unregistered (hence illegal) sheep was identified in Gozo, leading the Veterinary Services Directorate to commence testing and culling of 216 potentially infected sheep. The farmer launched a court case to prevent the remainder of the herd from being depopulated, and a series of appeals and counter-appeals followed with the farmer, the Attorney General, the Police Commissioner and the Director General of Veterinary Services as the main protagonists (33).

There are several lessons to be learnt. In these two case studies, we hope to showcase that One Health initiatives should be applied at the right place, at the right time, with the right people and using the appropriate conditions/infrastructure. One should not adopt a OH approach purely for its own sake or rather wait for all the disciplines to be involved before concrete action is taken. In other words, the One Health transdisciplinary action should not replace but should reinforce the unidisciplinary initiatives taken at the stages of problem identification and action. For example, on the one hand, in the case of Malta, because of the failed attempts at eradication due to fragmented unidisciplinary efforts, only when the Maltese rigorously adopted the OH approach in a transdisciplinary manner, namely by also actively involving the non-scientific community, did they achieve success. The Serbian case study on the other hand showed that the health and agricultural authorities could rely on the aggressive action taken by the Directorate of Veterinary Medicine before moving onto the One Health approach mainly for surveillance prevention. It was the case because most of the infection appeared in animals and number of infected humans was not as high as in Malta. The disease mostly developed in cattle and sheep leaving most of the consequences in economic losses in animal breeding.

The timing of the OH approach is particularly important: in Malta, the right conditions took decades to develop and lessons were painfully learnt over a long period of time, whereas in Serbia the OH approach followed the drastic intervention and leadership of the veterinary department. Sustaining the processes that prevent the re-emergence of brucellosis, however, are likely to require a OH approach.

Limitations

There are a number of limitations to the method used in this study, including potential bias in the selection of interviewees. In both countries, the fact that the interviewers were "insiders"—members of the outbreak teams—might have influenced the purposive sampling approach used in this study (34). Further limitations include recall bias during interviews, even though we made every attempt to counteract this by triangulating interview data with data mainly from legal documents, archival material from public health and veterinary sources. The application of the NEOH evaluation framework (12) is a novel approach to evaluating One Health and is only recently published. Our experience of using this evaluation tool, is that it requires substantial specific data that is not all available, in particular in view of the retrospective nature of this study. Therefore, some degree of inaccuracy may have resulted in the scoring. The NEOH evaluation tool is based on the systems theory and applies mixed methods, namely descriptive and qualitative with a quantitative scoring. Therefore, capturing the diversities that exist between Malta and Serbia regarding the various sections of the NEOH tool proved to be challenging despite our effort in ensuring rigor throughout the comparative exercise. This case study is one in a series of case studies published under the same research topic that have utilized the NEOH evaluation

tool, all providing the first results on One Health Index and One Health Ratio for various One Health initiatives. This will enable validation of the NEOH framework and tool by providing comparisons on the use of the tool and the challenges faced during evaluation and scoring. One Health evaluation should therefore be complemented with other evaluation models for example cost-benefit analysis (costs and benefits expressed in monetary terms) and cost effectiveness analysis (costs vs. project results in units).

CONCLUSION

This comparative case study shows that context and timing are key to determining how, when and why a One Health approach should be applied. We conclude that one need not wait for the start of a fully-fledged One Health approach to address a potential health crisis. Instead, each relevant discipline should be on the alert and perform its key responsibilities at an early stage, before scaling up to a transdisciplinary level becomes necessary. Nevertheless, as evident in this article, adopting a OH approach has provided added value not only during the periods of crisis but also in the medium and long term, particularly in the areas of disease prevention and control, surveillance, health promotion and health education. Adopting a OH approach may also translate into cost savings. We therefore propose that OH evaluations should include economic assessments, in order to be able to better understand the optimal use of resources in these situations, thereby justifying funding and political support required.

AUTHOR CONTRIBUTIONS

SB and SS were responsible for data collection and providing the first framework of the paper. SB, SS, DC, and EL were responsible for preparing the first draft. MC and MA were responsible for the system dimensions, boundaries, elements, relationships, and functioning, as well as the theoretical perspective regarding an economic evaluation and providing advice in the early stages of formulating the case study. All authors contributed in the preparation of the manuscript for submission.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2018.00147/full#supplementary-material

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The Degree of One Health Implementation in the West Nile Virus Integrated Surveillance in Northern Italy, 2016

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West Nile virus (WNV) is endemic in the Po valley area, Northern Italy, and within the legal framework of the national plan for the surveillance of human vector-borne diseases, WNV surveillance has over time been implemented. The surveillance plans are based on the transdisciplinary and trans-sectorial collaboration between regional institutions involved in public, animal, and environmental health. This integrated surveillance targets mosquitoes, wild birds, humans, and horses and aims at early detecting the viral circulation and reducing the risk of infection in the human populations. The objective of our study was to assess the degree of One Health (OH) implementation (OH-ness) of the WNV surveillance system in three North Italian regions (Emilia-Romagna, Lombardy, Piedmont) in 2016, following the evaluation protocol developed by the Network for Evaluation of One Health (NEOH). In detail, we (i) described the OH initiative (drivers, outcomes) and its system (boundaries, aim, dimensions, actors, stakeholders) and (ii) scored different aspects of this initiative (i.e., OH-thinking, -planning, -sharing, -learning, transdisciplinarity and leadership), with values from 0 (=no OH approach) to 1 (=perfect OH approach). We obtained a mean score for each aspect evaluated. We reached high scores for OH thinking (0.90) and OH planning (0.89). Lower scores were attributed to OH sharing (0.83), transdisciplinarity and leadership (0.77), and OH learning (0.67), highlighting some critical issues related to communication and learning gaps. The strengths and weaknesses detected by the described quantitative evaluation will be investigated in detail by a qualitative evaluation (process evaluation), aiming to provide a basis for the development of shared recommendations to refine the initiative and conduct it in a more OH-oriented perspective.

Keywords: One Health, evaluation, West Nile virus, integrated surveillance, zoonoses, Northern Italy

INTRODUCTION

West Nile virus (WNV) is endemic in the Po valley area, Northern Italy. Within the legal framework of the national plan for the surveillance of human vector-borne diseases (WNV disease, chikungunya, dengue, Zika virus disease), WNV surveillance has over time been implemented in this area. Such surveillance is based on the transdisciplinary and trans-sectorial collaboration between regional institutions involved in public, animal, and environmental health. This integrated surveillance targets mosquitoes, wild birds, humans, and horses and aims at early detecting the viral circulation and reducing the risk of infection in the human population. Moreover, it is expected to enhance the surveillance efficiency and to save resources, by implementing targeted measures. To improve the surveillance sensitivity, data sharing mechanisms have been established among North Italian regions in 2016.

Considering the complex transmission cycle of WNV (see Identification of the System), a multi-disciplinary approach and a cross-sectoral collaboration between institutions involved in public, animal, and environmental health (i.e., a "One Health" approach) are better in obtaining knowledge on WNV circulation and subsequently prevent WNV transmission, as compared to a single-discipline and a uni-sectoral approach.

By following the evaluation protocol developed by the Network for Evaluation of One Health (NEOH), our evaluation quantitatively assessed how far the WNV surveillance system in 2016 is compliant with a One Health (OH) approach ("One Health-ness"), by considering three regions of Northern Italy (Emilia Romagna, Lombardy, and Piedmont). In detail, we quantified different aspects of the OH approach: the thinking and planning at the basis of the implementation of the surveillance system ("OH thinking" and "OH planning"); the commitment and involvement of actors and the infrastructure enabling a collaborative working and information sharing ("Transdisciplinarity and leadership" and "OH sharing"); and the individual and institutional gain in knowledge ("OH learning") resulting from the initiative.

This quantitative evaluation of OH-ness, also in combination with other evaluation approaches (e.g., a process evaluation or a cost–benefit evaluation) enables the detection of strengths and weaknesses of the surveillance system and may thus be a basis for fine-tuning and implementing the initiative in a more OH-oriented perspective.

IDENTIFICATION OF THE SYSTEM

West Nile virus is a flavivirus maintained in a transmission cycle between wild birds and mosquitoes. While birds usually act as non-affected reservoirs, some mammalian species such as horses and humans may develop neurological disease (1). WNV was first described in 1937 after its isolation from a febrile woman in the West Nile region of Uganda but has been detected in Europe starting with an outbreak in horses and humans in the Camargue region, France, in 1962/63 (2). To date, WNV is endemic in several south European countries including Italy, where it first appeared in 1998 (3, 4) and then re-emerged in 2008 (5, 6). The transmission cycle of WNV is complex: it involves wild birds and mosquitoes, including their respective habitat, and humans and horses are at risk to develop (sometimes fatal) neurological disease. A holistic approach is thus needed to comprehend and influence the transmission system.

Over time, WNV-integrated surveillance was implemented by the regional health authorities in several regions of Northern Italy: Emilia-Romagna, Lombardy, Piedmont, Veneto, Friuli Venezia-Giulia. The rationale of the surveillance initiative is to use a multi-disciplinary approach to learn about all aspects of WNV circulation. The aim is the early detection of viral circulation in the species targeted by the surveillance activities, and subsequently reducing the infection risk in humans.

Infection in humans is mainly due to mosquito bites, but additional risks are related to infected blood transfusions and solid organ transplantations. Mitigating the risk of new WNV infections in the human population results in increased welfare (fewer individuals to suffer from West Nile disease) and consequently in reduced health care costs.

In our evaluation, we consider Emilia-Romagna, Lombardy, and Piedmont regions (study area), that cover the larger part of Italy's Po Valley, a suitable breeding habitat for mosquitoes. The surveillance systems were implemented since 2009 in Emilia Romagna, and since 2014 in Lombardy and Piedmont. The evaluation will focus on 2016, when all three regions participated in the surveillance initiative with similar plans, and data sharing mechanisms among regions started (7–9).

All regions have the same sociocultural background and Italian is the main language. Additionally, the jurisdiction for all three regions is comparable for both animal health (veterinary national plan for arthropod-borne diseases in horses, national plans for wild and domestic birds, regional plans on wild animals) and public health (national plan to prevent transmission of WNV -and other arboviruses- by blood transfusion and organ transplantation).

Since WNV transmission is facilitated by mosquitoes as vectors, the transmission season for WNV overlaps with the activity of *Culex pipiens*, the main vector of WNV. Therefore, the European Centre for Disease Prevention and Control (1) assumes a theoretical transmission season for WNV from May to October. Accordingly, surveillance activities targeting wild birds, mosquitoes, humans, and horses are focused on that season (described in Section "Detailed Description of the Initiative and Scientific Background").

DESCRIPTION OF THE INITIATIVE

The Initiative within the System

Detailed Description of the Initiative and Scientific Background

To conform with the complex transmission cycle of WNV, involving birds, mosquitoes, and dead-end hosts, the initiative is comprised of four complementary parts: (i) active surveillance of avian target species, and passive surveillance of wild birds found dead (ii) active surveillance of mosquito target species, (iii) active and syndromic surveillance of horses with neurologic

disease, and (iv) syndromic surveillance of human patients with neurologic disease.

All diagnostic tests are performed in public laboratories. Tests on avian species, horses, and mosquitoes are carried out by the official animal-health laboratories [Istituto Zooprofilattico Sperimentale (IZS)]. Tests on human samples (blood donations, organs, and samples collected from patients with neurological disease) are run in the reference laboratories of the Regional Health Services.

Avian target species (Eurasian magpies, *Pica pica*; carrion crows, *Corvus corone*; Eurasian jays, *Garrulus glandarius*) are shot within specific wildlife population control programs for agricultural pests, approved by the Italian Institute for Environmental Protection and Research. A fixed monthly number of these birds is collected, depending on their respective regional population size, density and distribution, and is submitted to the laboratory from each administrative province (from May to October in Emilia-Romagna, April to November in Lombardy, August to November in Piedmont). Brain, spleen, heart, and kidney samples are collected and analyzed using real-time RT-PCR, sequencing, and lineage determination. The sample is supplemented by passive surveillance of wild birds found dead.

Mosquito target species (*Culex pipiens*, *Cx. modestus*) are trapped from June to October. In Emilia-Romagna and Lombardy, the surveillance is carried out in the plain area, which is split into 11 and 20 km grid cells, respectively. In Piedmont, mosquitoes are trapped in plains and foothills, and surveillance areas (20 km grid cells) were selected by a risk-based approach. One entomological trap is placed in each cell or area under surveillance, for a total of 182 georeferenced stations. Collection is carried out fortnightly using CDC-CO2 dry ice-baited traps, BG-sentinel and gravid traps. Pools are analyzed using real-time RT-PCR, sequencing, and lineage determination.

Syndromic surveillance of neuroinvasive disease in dead-end hosts is carried out continuously throughout the year in all the three regions.

All horses with neurological signs are mandatorily notified to the veterinary authorities. From suspect cases, a blood sample is taken by the official veterinarian and tested for the presence of antibodies against WNV (IgM ELISA), and for the presence of virus specific RNA (real-time RT-PCR). In positive cases, this is followed by sequencing and lineage determination. In Lombardy, passive surveillance is supplemented by active surveillance on blood sera collected from horses in non-endemic provinces.

Syndromic surveillance of neuroinvasive disease in human patients is carried out continuously throughout the year in all three regions. All human patients with fever and one symptom of neuroinvasive disease [e.g., acute flaccid paralysis, acute polyradiculoneuritis ("Guillain–Barré syndrome"), aseptic meningitis, or encephalitis] are considered suspect cases of West Nile neuroinvasive disease (WNND). Plasma, serum, and cerebrospinal fluid are tested using real-time RT-PCR. In positive cases, sequencing and lineage determination are performed. This surveillance for suspect autochthonous cases of WNND is intensified in the period overlapping with mosquito activity in the regional territories, and particularly following the first viral detection at local level.

Adding to the complexity of the approach, not only the multi-species transmission cycle was taken into account when designing the surveillance system but also the different dimensions of life which should be targeted. The following dimensions were considered: populations (mosquito, bird, human, horse) to detect the infection rate; individuals (human, horse) to detect whether neurological signs may be due to a WNV infection; and tissues/organs to detect whether blood reserves or organs allocated for donation are infected with WNV.

Three trans-disciplinary working groups were created, in which experts of every health sector (animal, public, environmental) are represented:

(A) Animal health: IZSLER (IZS della Lombardia e dell'Emilia-Romagna, IZSLER, for Emilia-Romagna and Lombardy), IZSTO (IZS del Piemonte, Liguria e Valle d'Aosta, IZSTO, for Piedmont), Veterinary Services (Local Health Authorities—LHU); practitioners, horse owners, hunters, rangers.
(B) Public health: Public Health Services (Local Health Authority and Units), regional blood centers, reference laboratories for human diagnostics; physicians, hospitals.
(C) Environmental health: entomology centers (Centre for Agriculture and Environment, CAA, for Emilia-Romagna, Institute for Plants and Environment, IPLA, for Piedmont), IZSLER Virology and Epidemiology units collaborating with local Veterinary Officers for Lombardy.

The tasks to be carried out within this initiative were allocated to the named actors (defined as any individual, group, or organization who acts or takes part in the initiative and its context). The entomology centers (or local Veterinary Officers in Lombardy) are in charge of mosquito collection, while hunters with a specific permit and rangers collect the birds. The veterinary health institutions perform surveillance on animals and lab tests on animals and mosquitoes. The public health institutions are in charge of the surveillance in humans and testing of human samples. However, although each involved institution has specific tasks, they act for the common aim to early detect WNV circulation and reduce the risk of infection. The funding is provided by the respective Regional Health Services and, in Piedmont, also by research projects.

The initiative is guided by shared leadership between actors (veterinarians, medical doctors, biologists, and entomologists), who regularly meet in trans-disciplinary groups. Frequent regional (i.e., 3–4/year in Piedmont and Lombardy, 8–10/year in Emilia-Romagna) and plenary meetings are organized to allow actors to provide feedback. Joint activities among regions (i.e., sharing data on entomological traps at regional borders serving for surveillance for neighboring regions since 2016) are necessary for a complete coverage of the surveillance area, but also create team spirit and enhance communication.

Sharing and linking of information in inter-disciplinary groups within each region and communication between regions (meetings, periodic epidemiologic bulletin and updates on IZSLER website, email, phone calls) is well established. As described above, some information (i.e., lab test results on mosquitoes collected through entomological traps at regional borders) is

shared among regions. In addition, in Lombardy, the results of the animal and mosquito surveillance are available online and updated daily.

Stakeholders of the initiative (defined as any individual, group, or organization who may affect, be affected by, or perceive themselves to be affected by the initiative) include human doctors, veterinary practitioners, hospital patients, and the general population. Seminars and educational activities are organized in order to increase the knowledge on the disease and involve stakeholders in surveillance activities, e.g., seminars and courses targeting official veterinarians and practitioners (especially horse veterinarians), medical doctors in hospitals and family doctors. The general population is involved through communication campaigns, websites, and informative leaflets and brochures. Reports of the activities are addressed to hunters and to individuals working with horses.

Drivers and Rationale

The initiative was started by the North Italian regions in response to recurring outbreaks of West Nile Disease and subsequent endemisation. Drivers for the initiative can therefore be assigned to four main categories: economical, emotional/psychological, environmental, and social:

(A) Economical: West Nile neurologic disease causes high healthcare costs for human and equine patients. Moreover, it determines financial damage in the form of DALYs (Disease Adjusted Life Years) for affected humans, in terms of loss of manpower for employers and of investments for owners of commercially used horses. Additionally, a continuous screening of blood donations from previously affected areas during the entire WNV circulation period is costly.
(B) Emotional/psychological: patients (human, horse) affected by neurologic disease are suffering. This suffering extends to the family and friends of the affected patients—especially in fatal cases.
(C) Environmental: possibly due to climate and environmental changes, mosquitoes—including the ones carrying WNV—have a higher chance of survival during winter (overwintering) leading to the establishment of WNV endemic areas in Northern Italy.
(D) Social: there is a lack of knowledge in the general population, regarding mosquito biology, their breeding habitats and their potential to carry disease.

The rationale of the initiative is to use a multi-disciplinary approach to early detect viral circulation in the species targeted by the surveillance activities, and the subsequent reduction of the infection risk in humans. Thanks to this early WNV detection, preventative measures can be applied in a more targeted way. The screening of blood donations from previously affected areas may be reduced to the active transmission season, starting with the first seasonal evidence of virus circulation. Additionally, public awareness campaigns may be intensified for populations at risk, once seasonal WNV transmission is detected.

Theory of Change (TOC) of the Initiative

According to NEOH, the TOC is created for the actors to define the (long-term) goals of their initiative and the building blocks and resulting changes required to achieve these goals.

For the presented initiative, these building blocks, necessary changes, and goals have been described in detail in the previous parts of this document. However, to align with the other manuscripts from this series, a summary, following the more schematic approach of a TOC, and the resulting graphical version of the TOC, the "pathway of change" (**Figure 1**), is provided.

West Nile virus is endemic to Northern Italy, being maintained in a transmission cycle between birds and mosquitoes. Humans and horses are accidental hosts and may suffer from a febrile illness to sometimes fatal neurologic disease. Transmission to humans may occur *via* bites of infected mosquitoes or the reception of infected blood or organ donations. The general population is insufficiently aware of the infection risks and thus poorly educated regarding strategies to prevent infection.

The basis for the initiative is the identification of appropriate actors with knowledge on WNV transmission, and of the stakeholders of the initiative. The funding of actors, including the support of networking infrastructure and other material and personnel, is essential. Additionally, stakeholders have to be compliant and respond to educational campaigns provided by the actors, by taking personal actions to prevent mosquito bites and maybe even by reducing breeding habitat.

The intermediate aim of the initiative is to prevent humans from being bitten by infected mosquitoes and from receiving infected blood transfusions or organ transplants. By preventing an infection, the risk of developing WNV disease will be reduced, and therefore the ultimate aim will be achieved: to decrease suffering and health care costs due to WNV disease.

To achieve these aims, experts from public, animal, and environmental health are working together to early detect seasonal WNV transmission in birds and mosquitoes, and to detect infections in horses and humans. After the first seasonal detection of WNV, blood and organ donations will be routinely screened, to decrease transmission risk. Additionally, educational campaigns for the general population may be carried out timely when seasonal infection risk increases resulting in a better-informed public that may act promptly and on their own initiative to prevent mosquito bites and to reduce breeding habitats.

As the initiative is ongoing, there will be a consolidation of networking among actors and an increase in expert knowledge on WNV transmission and disease, which will both feed back into modifying the approaches to achieve the intermediate and ultimate goals of the initiative. This results in a resilient system which can change over time to adapt to unexpected challenges, and according to the evolution of the epidemiological situation.

An indicator to measure the performance of the initiative may be a reduced annual incidence of human WNV cases. Additionally, an increased knowledge regarding WNV transmission and mosquito biology within the general population, maybe assessed by a questionnaire, could be a measure of successful performance.

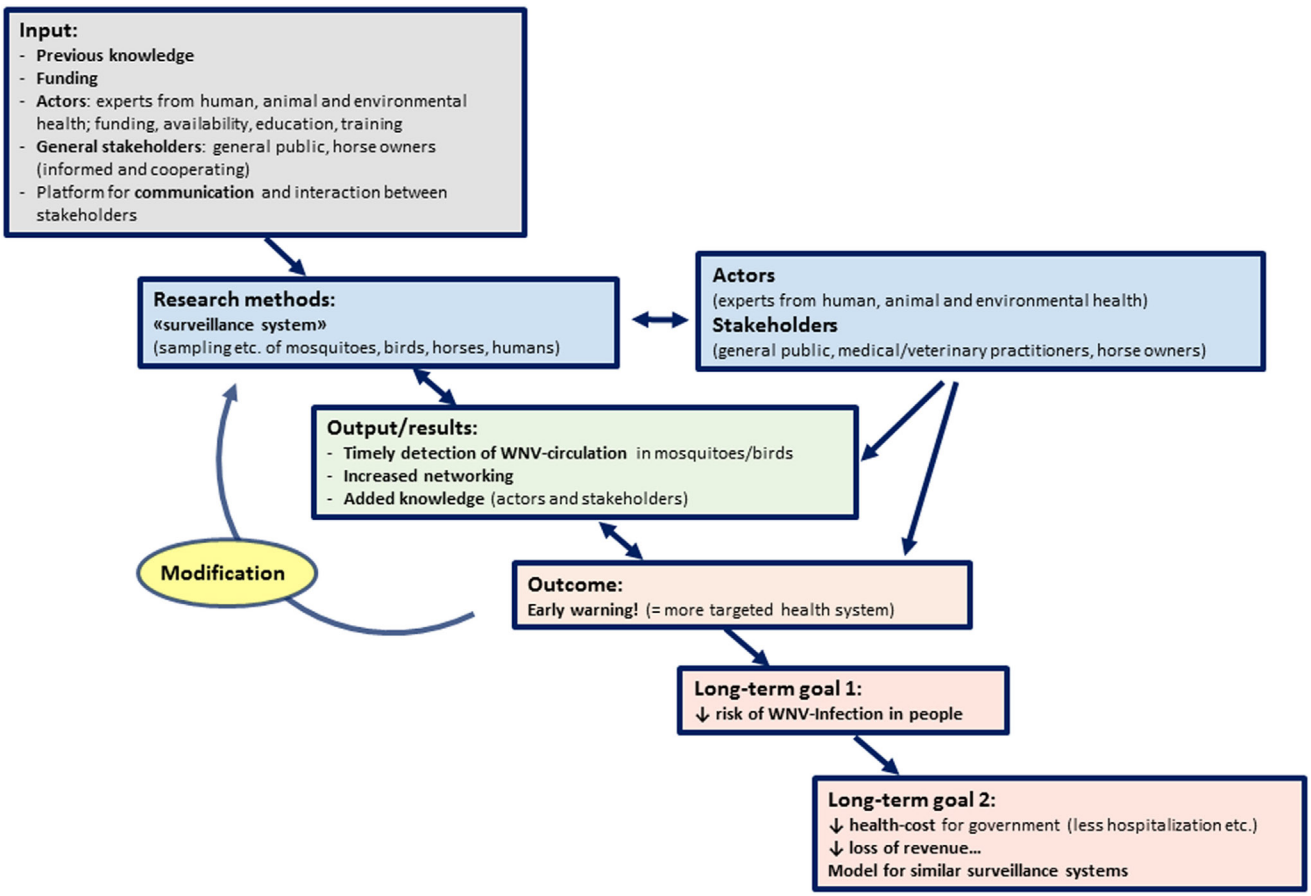

FIGURE 1 | Pathway of Change representing the theory of change applied to the West Nile virus (WNV) surveillance in Northern Italy in 2016: building blocks, goals, and resulting changes required to achieve these goals.

Assessment of the OH-Ness of the Initiative

In accordance with the evaluation protocol developed by NEOH, we first defined and later scored the five different aspects considered to be essential for a perfect OH approach: OH thinking, OH planning, Transdisciplinarity and leadership, OH sharing, and OH learning. Scores ranged from 0 (=no OH approach) to 1 (=perfect OH approach) and were allocated corresponding to the scoring key provided by the respective evaluation tool.

For the evaluation of OH thinking, different OH dimensions, i.e., geographical space and time frame of the initiative, the legislation it is based upon and which it may help to modify, the dimensions of life involved in the surveillance activity and the dimensions of life that the initiative may impact upon, were described. Also, we detailed the knowledge necessary for the creation and running of the initiative and knowledge resulting from it, the management of the initiative, the networking within and between groups and sectors, between actors and stakeholders as well as the influence of the economy upon the initiative (e.g., funding) and the impact of the initiative on the economy (e.g., reduction of health care costs). Scoring was based on different formulas considering the scales (e.g., local, national, global scale for the dimension "space") we attributed to the different dimensions. Formulas for scoring included the relevance (i.e., the effect of the exclusion of the dimension on the initiative, and the effect of the initiative on the dimension itself), the balance among dimensions (i.e., equal weight), the highest scale and the number of scales.

When evaluating OH planning, we described all tasks to be carried out within the initiative and defined the stakeholders and necessary material, including additional personnel and funding. The tasks were further subdivided into responsibilities (e.g., the handling of an animal during blood collection) and matched with the professional skills of the involved personnel. A perfect match between responsibility and professional skill was scored as 1.0.

In the evaluation of Transdisciplinarity and leadership, scores were given according to the involvement of stakeholders, the effective involvement and integration of different disciplines, the collaboration among actors, the flexibility of the initiative, the degree of open-mindedness and presence of hierarchies.

To evaluate and clarify the processes of OH sharing, the different aspects of communication and sharing mechanisms were elucidated. Aspects included the basis on which potential actors were identified at the start of the initiative, how strongly they are

involved in it, to what degree knowledge (data, methods, results) is shared between actors. Additionally, the resilience to change of sharing mechanisms was evaluated.

The evaluation of OH learning was based on multiple-choice questionnaires filled in by the actors of the initiative. Questionnaires were prepared in accordance to the ones provided by NEOH, translated into Italian and distributed to actors representing the different health sections (animal, public, environmental health) in each of the three regions. Scores were given as suggested by NEOH resulting in a mean score for all questionnaires.

RESULTS OF THE EVALUATION

Five assessments were conducted, resulting in a mean score for each OH aspect considered. We reached high scores for OH thinking (0.90) and OH planning (0.89). Lower scores were attributed to OH sharing (0.83), Transdisciplinarity and leadership (0.77), and OH learning (0.67). The results are depicted in a spider diagram (**Figure 2**) with the surface area and shape illustrating the degree of OH implementation and the balance between the operational and the supporting means. We can observe a weakness in the infrastructure and supporting means for the initiative (OH learning and sharing infrastructure), namely critical issues related to communication, and learning gaps. In contrast, the operational aspects (OH thinking and OH planning) of the initiative are its main strengths, indicating a developed transdisciplinary team and comprehensive multi-dimensional approach. The results of the scoring of each OH aspect are detailed below.

The mean score for OH thinking was 0.90. Among the different dimensions assessed, space, knowledge, and networks obtained the highest mean score (=1.0), followed by dimensions of life (0.92), time (0.82), economy (0.80), management (0.77), and legislative dimension (0.72).

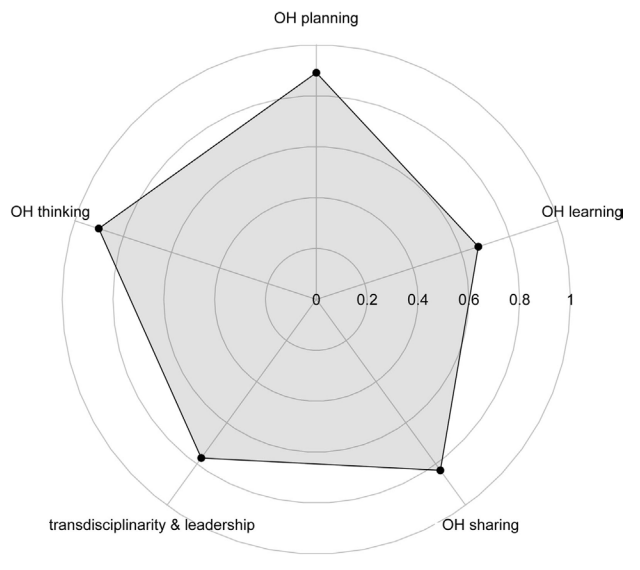

FIGURE 2 | Spider diagram illustrating the degree of One Health (OH) implementation and the balance between the operational and the supporting means of West Nile virus surveillance in Northern Italy in 2016.

The initiative is implemented in a relatively small spatial (local, subnational, national) scale. However, as an operational aspect, the OH thinking of the system is influenced and has an impact both at a local level (e.g., provinces) and at a national level. Local, subnational, and state bounded knowledge is crucial for the creation and running of the initiative. Knowledge resulting from it is broad and can be categorized as local, subnational, and state bounded as well as universal, since it is added to the body of knowledge about WNV and disease surveillance and applies to countries with similar societal and epidemiological characteristics. Networking in the initiative is relatively complex, including interaction within and between work groups, within and between sectors (i.e., the animal and public health sector) and between stakeholders and the general population (trans societal). All scales were thus considered relevant.

Dimensions of life considered in the initiative include the gene, as well as the cell/organ, and population scale. In fact, humans, horses, wild birds, and mosquitoes are the target of the surveillance system (individuals, groups, populations). Samples of the above-named targeted species are tested for antibodies and/or gene sequences of WNV; after a first positive result in any species tested, human blood and organs are screened for WNV.

Time is of paramount importance in the planning of surveillance activities (e.g., organization, funding), therefore, surveillance plans are issued annually. However, the operational thinking required for their design (viral circulation in the geographical area, transmission season, vector and host distribution, etc.) can be independent from the time-frame of the plan implementation (e.g., 2, 5 years, etc.). Concerning the economic dimension, funding of the initiative is partly national (Ministry of Health) and partly regional. Both costs and benefits (e.g., reduction in welfare costs) of the initiative will impact at the regional and national level.

The management of the initiative is strategy-based and therefore rather broad and complex as compared to projects or work packages. Relevant legislation ranges from a rather low scale (operational rules, regional laws) to national and international regulations.

One Health planning was scored 0.89. A perfect match between responsibility and professional skill (score: 1.0) could be allocated to activities regarding the active surveillance on mosquitoes, surveillance of neuroinvasive disease in humans, laboratory tests on horses, wild birds, and mosquitoes, including species identification, laboratory tests on blood and organ donations, and on human suspects (WNND) samples, as well as activities regarding data sharing and communication. Surveillance on wild birds and passive surveillance on horses were considered as more critical and received a lower score, since such activities are partially carried out on a voluntary basis for lack of specific funding (**Table 1**).

Transdisciplinarity and leadership were given an overall score of 0.77. We considered the WNV transmission cycle, including the potential hazards for humans and horses (within this paragraph named the WNV "problem") as well presented to the society (score: 1.0), with all actors and stakeholders involved in the initiative although not all efficiently engaged (0.8). Transdisciplinarity is necessary to solve the problem (1.0), being relevant to the health of people, animals, and environment.

TABLE 1 | One Health (OH) planning.

Task	Match
Positioning of the entomological traps (active surveillance)	1.0
Collecting mosquito traps and transfer to laboratories (active surveillance)	1.0
Wild birds collection (trap/shoot) and transfer to the laboratories (active surveillance)	0.5
Passive surveillance on wild birds found dead	0.8
Passive surveillance in horses: reporting of suspect cases of WND (neurologic symptoms)	0.5
Passive surveillance in horses: sampling of suspect cases of WND (neurologic symptoms)	1.0
Active surveillance on horses	1.0
Laboratory tests on horses, wild birds, and mosquitoes incl. species-ID	1.0
Surveillance of neoroinvasive disease in humans	1.0
Laboratory tests on blood and organ donations, and on human suspects (West Nile neuroinvasive disease) samples	1.0
Data sharing and communication	1.0
Overall score (mean) for OH planning	**0.89**

Description of the different tasks of the West Nile virus surveillance in Northern Italy in 2016. Scores were given for the match between necessary skills, possessed skills, and available personnel, material and/or infrastructure. A perfect match was scored as 1.0.

TABLE 2 | The Network for Evaluation of One Health questionnaire provided to assess transdisciplinarity and leadership was subdivided into different question complexes.

Question complex (no. of questions)	Score
Presentation of the societal problem within One Health (5)	0.94
Assessing broadness to further classify the initiative (3)	0.53
Assessing integration (10)	0.72
Assessing reflection, learning, and adaptation (3)	1.00
Assessing efficiency and effectiveness of the case study's problem solving (2)	1.00
Assessing management, social and leadership skills (5)	0.35
Assessing team structure (well-structured vs. pseudo team) (8)	0.78
Actors and competencies (2)	0.80
Problem formulation, focus, goals, and criteria of success (6)	0.92
Overall score (mean) for transdisciplinarity and leadership	**0.77**

For the West Nile virus surveillance in Northern Italy in 2016, the mean for each question complex was calculated.

Disciplines, methods, and scales of analysis have an intermediate diversity (0.6). The initiative is broad and inter-sectoral (0.9), but there is a low involvement of the non-scientific community (0.1). There is a good balance across different disciplines and they work well together (0.9), however, gender is slightly biased toward male (0.7). Few cultural issues are considered to affect the problem (0.7). Regarding the integration, there is a good degree of interactions among actors of different disciplines (0.9), although this combination of disciplines cannot be considered as innovative (0.5). There is also a lack of formulation of a common OH objective covering all disciplines (0.2), with the initiatives aim being very "human health-oriented," although such common objective could be a basis for knowledge integration. The project design has a very good flexibility at short, mid and long term (1.0). The initiative was considered as effective to contribute in detecting and solving the complex WNV problem (1.0). Although the management structure well supports the initiatives goal, with a good combination of disciplines/fields of expertise (0.9), leadership is task-oriented (0.1) with a limited open-mindedness (0.4) and rather static hierarchies. Different teams are working within the initiative and have a good level of cooperation (1.0) with fair inter-team relationships (0.8). Each team has clear objectives and their work is recognized at the organization level; however, they do not meet to discuss their effectiveness and how it could be improved. Competencies in the teams are appropriate to solve the problem (0.8). The initiative is very relevant to OH (1.0), and the problem is adequately translated to scientific questions (0.8) and has a solid scientific basis (1.0). Methods, collaboration, and integration fit the OH strategy (0.8) (**Table 2**).

We attributed a score of 0.83 to OH sharing. In detail, stakeholders and actors are described in the regional laws, although a specific process of identification is not foreseen by the initiative (0.8). The overall involvement of stakeholders in the initiative, namely the personnel and hunters with a specific permit involved in the surveillance activities and the general population, was scored as good (0.7). Actors of the surveillance systems are highly involved in the initiative (0.9) through regular meetings, emails, reporting/writing of the epidemiological bulletins.

There is a high level of internal information sharing (0.9), with meetings, epidemiological bulletins, and reports available to all actors. Surveillance results are published and an online information sharing platform exists (10). External sharing mechanisms are good (0.7), with the online publication of activities, and surveillance results, and information campaigns during fairs and markets. Data and information sharing are funded within the mandatory activities of the institutions involved, and data sharing agreements are stated in the regional regulations.

Data quality is high (0.9), since data are compiled by dedicated staff/data analysts belonging to the different institutions. Bulletins are revised from all stakeholders. Appropriate (institutional) structures, databases, and backup systems ensure an appropriate data storage (0.9). Data accessibility is good (0.6), especially regarding the internal accessibility to maps and data. However, there is a limited accessibility to the general population, and the way it is made accessible (e.g., websites or brochures) varies by region. There is a good level of data sharing (0.7) and a high level of methods (0.9) and results (0.8) sharing among all actors. Methods, data, and results are continuously stored, resulting in an increased expertise over time (0.9); however, due to financial constraints, trained fixed-term personnel is "lost" in the process of time. Knowledge derived from the initiative is disseminated through congresses, seminars, meetings, and educational activities (0.9).

The level of resilience to change is high (0.9). Data are collected because of public (regional) funding: they are owned by the authority, always accessible and independent from changes to the system (e.g., change of laboratories performing the analysis).

The multiple-choice questionnaires filled in by nine actors involved in the initiative (one entomologist, one veterinarian, and one medical doctor per region) gave a mean score of 0.67 for the OH learning. Entomologists gave a lower mean score (0.60), compared to veterinarians (0.70) and medical doctors (0.71) (**Figure 3**).

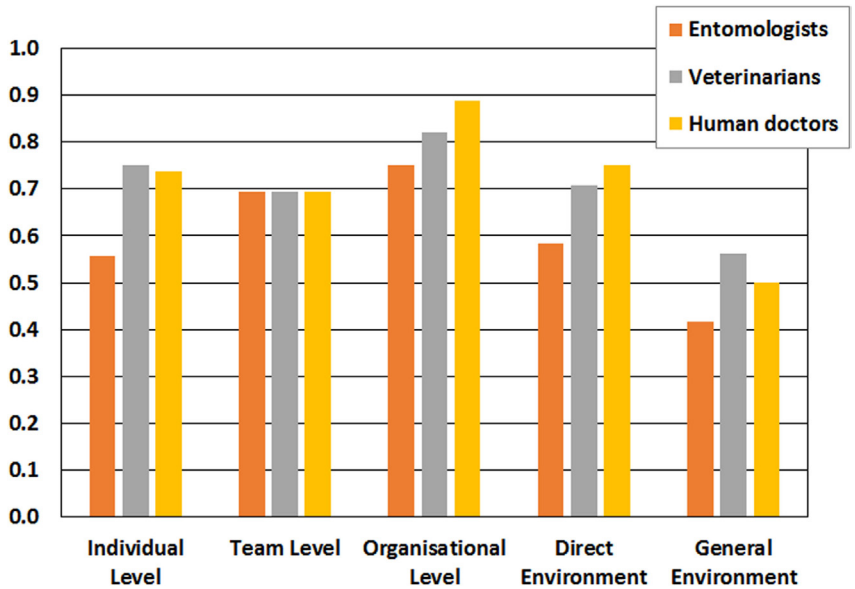

FIGURE 3 | One Health learning of the West Nile virus surveillance in Northern Italy, 2016, considering different levels of learning and the supportiveness of the environment. The Network for Evaluation of One Health questionnaire was compiled by representative actors: an entomologist, a veterinarian, and a human doctor for each considered region. The bar plot states the mean score for each profession.

Although organizational, team, and individual learning levels are interconnected and influence each other, the highest mean score was obtained at the organizational level (0.81), followed by team (0.69) and individual (0.67) levels. Direct and general environments reached a mean score of 0.68 and 0.50, respectively.

These results show that organizations involved in the initiative (i.e., the different public institutions in the three regions) provide a high-level support for individual and team learning, and for their interplay within the context of the initiative. Specifically, this organizational support for learning reflects the existence of different resources to collect, store, and make available all existing information and knowledge to the individuals and teams involved. This enables possible modification of the organization's underlying norms, policies, and objectives, based on the existing and acquired knowledge, providing resilience to the initiative. Differences in the mean scores assigned to organizational learning were observed among the three regions. Actors of Lombardy and Emilia-Romagna gave higher scores (0.73 and 0.72) compared to their colleagues in Piedmont (0.56), highlighting a possible weakness in the resources available for the OH learning in the latter region.

The team level learning was perceived as good (mean score 0.69). The teams participating in the initiative regularly meet for reporting results, and for sharing different perspectives and ideas aiming at obtaining the best view to inform decisions. Therefore, this result indicates a good interaction between the individual and the organizational learning of this initiative.

Individual learning was perceived as good by the actors, obtaining a mean score of 0.67. This score included both adaptive learning (i.e., how much the learning obtained was used to correct and improve existing procedures, competencies, technologies, and paradigms), and generative learning (how much the learning obtained was used to modify the organization's underlying norms).

Finally, the context of the initiative (i.e., direct and general environment) was found to be scarcely supportive for learning. Specifically, the general environment (i.e., non-specific elements of the organization's surroundings that might affect its learning like economic, technological, sociocultural, and others) obtained the lowest score (0.50). This could be due to the fact that society does not perceive governmental authorities as learning-oriented organizations.

FURTHER DEVELOPMENTS: PROCESS EVALUATION

In addition to the quantitative OH-ness evaluation presented in this study, an ongoing qualitative evaluation (process evaluation) will provide data to confront to the OH-ness evaluation results.

The objective of the process evaluation is to detect strengths and weaknesses of how the initiative is planned and implemented using the opinion of "privileged observers" involved. In detail, the process evaluation is investigating (i) how the initiative is conducted, and the importance/sense given to it; (ii) the legal framework of the initiative as shared reference to fully adhere to.

Privileged observers' opinions were collected in three focus groups, one for each region. Privileged observers are individuals having key roles in regional institutions involved in the WNV surveillance (regional Health Services; public health, animal health, and entomology centers). A maximum of eight participants attended each focus group, and they were selected among

the actors involved in the initiative design and planning, and ideally represent the different disciplines involved (human and veterinary medicine, entomology).

Each focus group had a maximum duration of 90 min, was conducted by one moderator and one observer and recorded by an assistant. Specific questions on aspects considered important for the initiative were developed, as well as different documents to facilitate the discussion. These documents included a list of topics that should emerge with the questions, and prompt (solicitations) to make those topics emerge, if not spontaneously triggered by the questions. Fidelity questions were answered by participants using a flip board. Finally, general questions concerning the individual opinion on the initiative were submitted and answered in written form at the end of each focus group, in order not to influence the previous answers.

Preliminary results highlighted differences among Regions, mainly due to the different epidemiological situations (i.e., incidence of the disease in the human population). The critical points identified so far are related to communication and funding.

FINAL CONSIDERATIONS

Considering the complexity of the transmission cycle of WNV (see Identification of the System), a OH approach seems necessary to guarantee the efficacy of any surveillance and control activity. In fact, knowledge on WNV circulation in all the species involved in the transmission cycle, and the subsequent informed decisions for its prevention, would unlikely be obtained through a single-discipline and uni-sectoral approach.

An integrated animal-human-vector approach to face WNV was adopted in several European countries (Austria, France, Greece, Italy, and UK), with activities varying according to the epidemiological scenario. Such approach may improve efficiency and save resources, thanks to the implementation of targeted control measures (11). For example, studies in Italy showed that the integrated surveillance had several advantages, both at national (12) and regional level, i.e., Emilia-Romagna region [(13); Paternoster et al., under review]. These included an increased efficiency in detecting infected blood units, the adoption of evidence-based preventative public health measures, and a reduction in health costs, thanks to a targeted strategy for testing blood units.

The evaluation protocol developed by NEOH and applied in the present study represents an innovative tool to assess the degree of OH implementation of a health-related initiative. To our knowledge, transdisciplinarity, collaboration, and communication aspects have not been specifically addressed in other studies. Researches so far mainly focused on performances or economic aspects of integrated WNV surveillance systems. In example, Kolmenakis et al. (14) performed an economic appraisal of public health management interventions adopted in Central Macedonia, Greece, to tackle the 2010 WNV outbreak. A study in the United States, assessed the cost-effectiveness of alternative WNV blood-screening strategies (15). In the French Mediterranean coast, Faverjon et al. (16) assessed that a multivariate surveillance system, which combines different data sources for WNV syndromic surveillance (e.g., reports of nervous symptoms in horses and wild bird mortality) had a major sensitivity and specificity in detecting outbreaks compared to approaches using data sources separately. Although this study underlines the importance of developing a more collaborative work between existing surveillance networks, no attempt has been made to evaluate the degree of inter-disciplinary collaboration. Similarly, Chaintoutis et al. (17) highlighted the usefulness of the surveillance on pigeons to determine WNV geographical spread and for early warning in Greece but made no specific assessment of the degree of implementation of a OH approach.

Our OH-ness evaluation confirmed the presence of an established multi-disciplinary approach and cross-sectoral collaboration (i.e., OH approach) in Northern Italy (Emilia-Romagna, Piedmont, and Lombardy regions). Surveillance is based on the collaboration between different regional institutions involved in public, animal, and environmental health, both at a regional and inter-regional level (see Results of the Evaluation). Several actors and stakeholders are involved and communicate within a complex operational and institutional network (see Detailed Description of the Initiative and Scientific Background).

The operational aspects (OH thinking and OH planning) are the main strengths of the initiative. Weaknesses were detected in the infrastructure and supporting means (OH learning and sharing infrastructure), namely critical issues related to communication, funding, and learning gaps. These results can be used to modify the system and improving its critical elements. Indeed, the OH-ness evaluation enables the detection of the strength of a multi-disciplinary approach and cross-sectoral collaboration of integrated zoonosis surveillance, providing insights that are useful for its improvement. Moreover, this standardized evaluation can be combined with other evaluations (e.g., process evaluation, cost–benefit evaluation) to measure the impact of the OH approach on the initiative. Further information can arise by comparing the OH-ness assessments of surveillance activities in different geographical areas, socio-economic contexts, or for different vector-borne diseases.

As regards our case-study, an ongoing process evaluation will provide a more detailed analysis of the surveillance planning and implementation. Evaluation results could (i) be the basis for developing shared recommendations, (ii) be used by Animal and Public Health decision makers at national or regional level, and (iii) provide insights on the efficacy of integrated health systems for zoonoses mitigation.

AUTHOR CONTRIBUTIONS

GP, LT, and BV conceived and designed the work and drafted the manuscript. MT, MC, AL, MP, and AP provided part of the data. AF, GB, GP, LT, and BV designed and carried out the process evaluation. All authors contributed to the analysis and interpretation of data, participated in the revision for important intellectual content, and approved the final version to be published. All authors agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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One Health-ness Evaluation of Cysticercosis Surveillance Design in Portugal

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The increasing occurrence of human cysticercosis, a zoonotic neglected disease, is challenging the traditional prevention and control paradigm and calling for One Health (OH) solutions in industrialized countries. OH solutions for health interventions are increasingly being used to capture expected and unexpected outcomes across people, animals, and the environment. The Network for Evaluation of One Health (NEOH) proposes an evidence-based framework, relying on systems and mixed methods approaches to evaluate the One Health-ness. In this case study, this tool is used to evaluate the design of the Observatory of Taeniasis and Cysticercosis, as an example of intersectorial collaboration for surveillance in Portugal. The OH Initiative (drivers and expected outcomes) and its system (boundaries, aim, dimensions, actors, and stakeholders) were described. The different aspects of this Initiative were scored with values from 0 (=no OH approach) to 1 (=perfect OH approach). The OH index was 0.31. Its OH ratio is 1.98. Overall scores were as follows: OH thinking 0.75; OH planning 0.60; OH working 0.60; OH sharing 0.35; OH learning 0.50; and systemic organization 0.50. Operational levels of the Initiative are the main strengths, indicating a comprehensive multidimensional innovative approach and transdisciplinarity. Critical issues in the supporting infrastructure were observed, related to communication, learning and organizational gaps in the project, with the evaluation being conducted as the project is being designed and implemented. The strengths and weaknesses detected may be used to refine the Initiative. This case study therefore exemplifies and supports OH assessment also for ongoing projects, at design and early implementation stages for guiding and guaranteeing an OH-oriented perspective.

Keywords: One Health, case study, cysticercosis, evaluation, surveillance, neglected disease

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INTRODUCTION

In European countries, emerging *Taenia solium* taeniasis and cysticercosis in urban areas is questioning the traditional disease paradigm as a zoonotic disease of developing countries, requesting for integrated approaches and One Health (OH) solutions (1, 2). Human cysticercosis is a preventable fecal–oral transmitted neglected parasitic infection caused by cysticerci of the tapeworm *T. solium*. Neurocysticercosis (NCC), the single major cause of adult onset seizures in endemic

areas, occurs when cysticerci lodge in the central nervous system in humans (3).

In non-endemic settings, imported and autochthonous cysticercosis emergence is plausible, impacting on human, animal, and environmental health and welfare. In Portugal, 357 hospitalized NCC cases were detected during a retrospective study covering the 2006–2013 period (4). In the absence of legal notification or established surveillance system, the Observatory of Taeniasis and Cysticercosis (OTC) was designed.

The OTC aims for an OH-based national disease surveillance system, increasing knowledge and awareness for evidence-based interventions leading to disease control and eradication, based on sustainable solutions impacting on human, animal, environmental, societal, and economic health and welfare. The surveillance design is based on cross-sectorial and transdisciplinary collaboration between human and animal health institutions at local, regional, and national levels, targeting humans and pigs, aiming at detecting, and treating the tapeworm carriers, therefore reducing the risk of infection in the human and pig populations.

The OTC was evaluated using the innovative framework developed by the Network for Evaluation of One Health (NEOH), representing a case study illustrating the application of this methodology and grasping to what extent the underlying integration as a principle and approach is actually contributing to manage the health problem (5, 6).

BACKGROUND AND RATIONALE

In the *T. solium* life cycle and transmission, both pig and humans can be infected by the metacestode larval stages and develop disease. The infection results from the ingestion of *T. solium* eggs, shed in the feces of human tapeworm carriers, through contaminated food and water or by autoinfection: the eggs hatch, migrate, and lodge in the tissues, where they develop into cysticerci. Human become tapeworm carriers by ingesting undercooked pork meat containing viable cysticerci in muscle tissue. Cysticercosis clinical symptoms often appear months/years after the infection. The acute and chronic neurological symptoms/disease in humans determines health-care costs and suffering in the form of disease-adjusted life years.

Human cysticercosis has been primarily associated with rural and peri-urban areas of developing countries where sanitation is poor and pigs roam freely and eat human feces. In industrialized countries, cysticercosis, although rare, is increasingly being diagnosed and has been associated with migration and travel from endemic areas. However, it may occur in individuals with no history of pork consumption or travel to endemic areas (3, 7). Epidemiological studies have demonstrated tight clustering in households and suggest the most common source of infective eggs is an asymptomatic household tapeworm carrier (8).

In Portugal, cysticercosis was considered prevalent before 1975. Thereafter, improved sanitation and industrialized pig production under veterinary control made Portugal officially free of porcine cysticercosis; diagnosed human cases have been considered mainly imported (Statistics Portugal, www.ine.pt). As in most European countries, there is no NCC notification or surveillance. There is scarce and not updated data on human and porcine cysticercosis. While old, mostly rural human cases indicated probable autochthonous infection; nowadays, industrialized pig production in closed systems under veterinary control is rather generalized. Human disease cases tend to occur in 20–64 years age group (55.2%) in urban settings, indicating imported cases or the presence of tapeworm carriers infecting other people, without the presence of infected pig intermediate hosts (4).

Thus far, the disease control model has reflected a rural reality, where free-ranging pigs are raised, sanitation conditions are poor, and sanitary inspection measures are insufficient. Control tools generally include pig-oriented measures, human tapeworm treatments, health education, and sanitary improvements. Environmental contamination with *Taenia* spp. eggs is a key issue in most studies, influencing the presence of *Taenia* spp. antigens in both pigs and humans (9). Soil-related, socioeconomic, and behavioral factors are associated with the emergence of significant clustering of human cysticercosis (8, 9). However, very few studies have been produced in urban environment of developed countries. In this setting, transmission patterns are likely to relate more with behavior, housing conditions, water supply, basic sanitation, schooling and birthplace of the individual or relatives, human migration patterns, and food preparation; the role of free roaming pigs or soil conditions not being as obvious (10).

OTC in Portugal: The OH Initiative

The OTC was designed, aiming at the surveillance of taeniasis and cysticercosis, fostered by human health and animal health national authorities in collaboration, asking for cross-sectorial, inter, and transdisciplinary cooperation and networking at all stages of development and action. It aims to obtain essential information on the burden and epidemiology of cysticercosis in Portugal. Its final aim is sustainable health protection through cysticercosis prevention and control, focusing on human health and welfare without disregarding animal health and the ecosystem.

Main drivers of the Initiative are as follows: (i) the disease occurrence in migrants from endemic areas, whose access to health care may be compromised by legal and economic issues (illegal immigration and poverty) and, rarely, in non-migrants: 45 hospitalizations per year (4, 11–14); (ii) the unawareness of the disease burden due to absence of (systematic) human cysticercosis and pig cysticercosis data; (iii) the non-applicability of the traditional disease prevention and control tools (involving the pig as an intermediate host) to the current disease scenario (human-to-human transmission); and (iv) the fact that the disease can be effectively prevented by tapeworm eradication in human carriers (that is, preventing transmission).

The Initiative comprises the following core surveillance activities:

(1) Baseline characterization and thereafter monitoring of the national epidemiological scenario, by systematically obtaining and analyzing the available disciplinary administrative data, to identify possible geographic hotspots: (a) human health sector: human cysticercosis hospitalizations (Hospital Episodes Statistics); (b) animal health sector: pig cysticercosis diagnosis at slaughterhouses and at non-industrial pig distribution units (less than 100 animals); and (c) human social

sector: Portuguese resident and foreign resident population data (Statistics of Portugal).

(2) In the geographic hotspots, implementing a questionnaire-based surveillance targeting health-care units to detect and monitor new human cysticercosis diagnosis (notification system) associated with an epidemiologic field survey to patients and contacts, exploring human, animal, and environmental factors, identifying possible human tapeworm carriers. It uses the structural resources and communication algorithms already in practice for other reportable diseases (national notifiable disease surveillance system) under the aegis of the public health national authority. It involves hospital and primary care physicians as primary reporting source and public health physicians at the local health department as primary level data recipients and reporting source for the epidemiologic field survey. Secondary level data recipients are national health authority and OTC.

(3) In the geographic hotspots, implementing a questionnaire-based surveillance targeting non-industrial porcine distribution units (less than 100 animals) to detect and monitor new pig cysticercosis diagnosis at slaughterhouses (notification system) associated with an epidemiologic field survey to the pig handlers, exploring human, animal, and environmental factors, identifying possible human tapeworm carriers. It uses the structural resources and communication algorithms already in practice for other reportable diseases under the aegis of animal health and food national authority and establishing a structured communication pathway between animal health and human health sectors in the reporting and surveillance system. It involves slaughterhouse inspectors as primary reporting source and public human health physicians at the local health department as primary level data recipients and reporting source for the epidemiologic field survey. Secondary level data recipients are the national health authority and the OTC.

(4) Biological species diagnosis of tapeworm carriers in the reference laboratory, using *T. solium* taeniasis coproantigen detection test with molecular species confirmation among human cysticercosis cases and human case contacts identified in (2) and (3). Referral for laboratorial diagnosis is done through the local health department, involving primary care/hospital physicians and public health physicians, the reference laboratory also acting as a reporting source in the surveillance system. Secondary level data recipients are the national health authority and the OTC.

(5) Hospital-based treatment for the identified human tapeworm carriers within the local health-care system. Referral for treatment is done upon laboratorial diagnosis through the local health department, involving primary care/hospital physicians and public health physicians.

(6) Monitoring, stewardship and supervision of the reporting process, the field epidemiological surveys, and the referral for laboratorial diagnosis and treatment.

(7) Yearly data management and analysis and report generation and dissemination, complying with the national standards of confidentiality, to the involved actors, stakeholders, and decision-makers.

The Initiative is led by human and animal health sectors in coordination under the aegis of Human and Animal Health Authorities. It fosters trans-sectorial communication and data sharing at different hierarchical and decision levels: human and animal health. Within each sector, the hierarchical channels and structural elements already in use for other purposes, namely, disease notification, are used. Innovation comes from (i) introducing human and pig cysticercosis as a notifiable disease and within the same surveillance process; (ii) triggering active human case detection (human tapeworm carrier) upon the diagnosis of a case of human or pig cysticercosis, active animal case detection in the affected non-industrial pig distribution unit also being also promoted; (iii) promoting detection and correct medical approach of tapeworm carriers, paving the way for control and eradication of human-to-human transmission (NCC disease transmission control); (iv) enforcing laboratorial technology, introducing the use of specific diagnostic tests beyond research purposes; (v) enforcing ongoing transdisciplinary and cross-sectorial networking, feedback, and collaboration; and (vi) harboring academic and field research purposes, through collaboration with postgraduate educational institutions.

The expected consequences of this Initiative are improvements at the level of the disease burden estimates, as well as at the level of the epidemiological and medical approach of each individual case, impacting on human, animal, and environmental health.

Planning surveillance should be an iterative process, requiring the regular reassessment of objectives and methods, to double check if the purposes of the surveillance system are being met. To gather consistent and systematic awareness data and identify the changes related to the organization of services, information systems, and institutional relationships, allowing for a complete outcome-based evaluation, the Initiative needs to be running 5 years minimum.

The Initiative was, however, designed considering OH concerns and approach to surveillance and problem solving. Therefore, OTC design was evaluated for its OH characteristics and One Health-ness (OH-ness).

The adhesion to OH protocol is often praised but not proved. The evaluation of OH-ness is hence an innovation in the OH context and a preliminary step to assess the real advantages of OH in comparison with the traditional approaches to health evaluation.

The evaluation question was the following: is the OTC designed according to OH characteristics and requirements? This evaluation is being conducted as the OTC is being implemented, in a feedback loop that allows for ongoing design and implementation readjustments to ensure effective and efficient OH action, in theory and practice. End users are the Human and Animal Health Directorates and the OTC itself. The Initiative and OH evaluation may provide an example of cross-sectorial and transdisciplinary collaboration at national level on how to manage a non-notifiable neglected zoonosis in a European country.

METHODS

For taeniasis and cysticercosis surveillance design evaluation, the Network for Evaluation of One Health (NEOH) evaluation framework was used (5). It uses a systems approach and aims to relate the OH process characteristics (OH-ness), namely, operational aspects

(thinking, planning, and working) and supporting infrastructure aspects (sharing, learning, and systemic organization). It consists of a mix methods approach, including a descriptive and qualitative assessment with a semiquantitative scoring for the evaluation of the degree and structural balance of OH-ness. The six different aspects for a perfect OH approach of the Initiative were scored using standardized aspect-specific assessment tools: OH thinking, OH planning, OH working, OH sharing, OH learning, and systemic organization. Each one consisted of a series of up 17 questions and an associated scoring system with values between 0 and 1 as well as spider diagrams, with a score of 1 reflecting a full realization of the different OH characteristics (ideal scenario). OH thinking assesses the way actors and stakeholders think in and about the OH Initiative and the system in which it operates (the context) [scoring criteria: dimension coverage and balance; Initiative to environment match; integrative health approach; system features and target; sustainability and social–ecological considerations; perspectives and theory of change (TOC) factors]. OH planning evaluates planning and resource allocations in the Initiative (scoring criteria: common aims; stakeholder and actor engagement; self-assessment and plan revisions; and individual objectives). OH working assesses the interdisciplinary and participatory engagement in OH Initiatives (scoring criteria: broadness; collaboration; transdisciplinary balance; cultural and social balance; and flexibility and adaptation). OH sharing evaluates the extent and methods of information and data sharing infrastructures in OH Initiatives (scoring criteria: general information and awareness sharing; data and information sharing; methods and results sharing; and institutional memory and resilience to change). OH learning evaluates the learning infrastructure of the Initiative (scoring criteria: focus on adaptive and generative individual learning; focus on adaptive and generative team learning; adaptive and generative organizational learning; direct learning environment supportive of adaptive and generative learning; and general learning environment supportive of adaptive and generative learning). System organization assesses the systemic organization of the Initiative, focusing on leadership skills and criteria for effective teamwork (scoring criteria: team structure; social and leadership structures and skills; competence; and focus on innovation). Detailed scoring criteria, metrics, and results can be found in Supplementary Material.

The scores for each assessed OH aspect were plotted on to the spokes of a spider diagram to allow visualization of the overall project integration and balance between operational and infrastructure aspects. These scores were combined into quantitative OH index (OHI) and OH ratio (OHR) for a holistic appreciation. The OHI, reflecting the degree of integration of the operational aspects and infrastructure, was calculated from the area enclosed by the points when plotted onto de spider diagram according to the following equation:

$$\mathrm{OHI} = \frac{\left\{\begin{array}{c}(\mathrm{ScP}\times\mathrm{ScT})+(\mathrm{ScL}\times\mathrm{ScP})+(\mathrm{ScS}\times\mathrm{ScL})+(\mathrm{ScO}\times\mathrm{ScS})\\ +(\mathrm{ScW}\times\mathrm{ScO})+(\mathrm{ScT}\times\mathrm{ScW})\end{array}\right\}}{6}$$

where ScP is the score obtained in OH planning, ScT is the score obtained in OH thinking, ScL is the score obtained in OH learning, ScS is the score obtained in OH Sharing, ScO is the score from systemic organization, and ScW is the score obtained in OH working.

The OHR, reflecting the balance between operations and infrastructure, was calculated dividing the area enclosed by the points associated with OH operations by that associated with OH infrastructure, according to the following equation:

$$\mathrm{OHR} = \frac{\left(\frac{\mathrm{ScO}\times\mathrm{ScW}^2}{\mathrm{ScO}+\mathrm{ScW}}\right)+(\mathrm{ScW}+\mathrm{ScT})+(\mathrm{ScT}+\mathrm{ScP})+\left(\frac{\mathrm{ScP}^2\times\mathrm{ScL}}{\mathrm{ScP}+\mathrm{ScL}}\right)}{\left(\frac{\mathrm{ScP}\times\mathrm{ScL}^2}{\mathrm{ScP}+\mathrm{ScL}}\right)+(\mathrm{ScL}+\mathrm{ScS})+(\mathrm{ScS}+\mathrm{ScO})+\left(\frac{\mathrm{ScO}^2\times\mathrm{ScW}}{\mathrm{ScO}+\mathrm{ScW}}\right)}.$$

The OH-ness evaluation was preceded by the system identification considering the OTC as a subsystem and the outline of the expected outcome based on the TOC of the Initiative, as proposed by the NEOH evaluation framework. The proposed quali-quantitative evaluation of OH-ness, also in combination with other evaluation approaches (e.g., a process evaluation or a cost–benefit evaluation) enables the detection of strengths and weaknesses of the Initiative. The combination of the six OH characteristics in single quantitative OHI and OHR associated with visual images contributes to objectivity when considering two or more OH Initiatives, although an optimal range for OHI, and not a higher value, may be indicative of a "better" OH Initiative (5).

The scope of the evaluation and delimitation of the system are considered pivotal for the outcome of the evaluation. The rationale behind this case study and the application of the evaluation framework were not to ascertain whether an already fully established and implemented Initiative meets OH characteristics, but rather to ensure that a newly started Initiative will achieve this on the longer term, by correcting its design on the way. The evaluation type was process self-evaluation. Three internal evaluators conducted the evaluation, and three external evaluators completed a general review of the evaluation. Data and information gathering relied mainly on focus group discussions and project documents.

RESULTS

Identification of the System and TOC

The system includes the OTC (OH Initiative) as a subsystem operating within the system, aiming at surveillance of taeniasis and cysticercosis, impacting on human, animal, and also environmental health.

System boundaries are determined by the following considerations:

(i) Cysticercosis is emerging in European non-endemic countries, affecting humans, pigs, and environmental surroundings. Unawareness of disease risk, communicability, and costs is recognized. The Initiative is being set at national level, but the results may be valuable at European and International levels. These elements allow the identification of main geographical, life, and knowledge dimensions of the system.

(ii) The disease (NCC) may be asymptomatic for long periods of time and may be associated with long-term sequela and disability. It can be acquired in foreign endemic countries, and human tapeworm carriers are usually asymptomatic,

thus favoring transmission. Any changes within the system will require years, all this allowing the identification of the main time dimension of the system and adding complexity to knowledge, life, and management dimensions.

(iii) The disease is preventable. However, there is no established surveillance for human disease, although it exists for other communicable diseases, and surveillance performs deficiently for animal disease. Hence, the importance legislative dimension of the system. The existing surveillance framework is disciplinary and sectorial in nature, cysticercosis successful surveillance and control requiring networking between actors and stakeholders at different organizational and operational levels. It brings together public health and veterinary authorities, academia, laboratories and hospitals, and medical and veterinary practitioners. These elements allow the identification of legislative and networking dimensions, also reinforcing management dimensions. A possible long-term impact on economy needs to be taken into account (economic dimension).

The actors and stakeholders are Human Health Directorate, Animal and Food Directorate, human and veterinary health academic institutions, public health and health care-providing institutions (hospitals and primary care facilities), practitioners in human and animal health, and laboratories in human and animal health. Stakeholders also include the community, patients, and political decision-makers.

The TOC for this case study is the awareness and knowledge on the epidemiology of cysticercosis in Portugal (**Figure 1**). In European countries, namely, Portugal, where basic sanitation and food chain quality control have long been achieved and consolidated, disease can be controlled and eradicated by efficient and correct identification and treatment of human tapeworm carriers. This can be achieved through an integrated human and animal health surveillance system that combines passive and active surveillance activities. Ecological and environmental variables favoring transmission are considered within these activities and subsequent intervention. The enhanced networking, knowledge, and results will allow greater collaboration with health systems at international level and the adoption of preventive measures, guiding future more informed and productive research and control solutions in a global space. Moreover, it will be of interest for national and European governments and policy makers.

Cysticercosis surveillance being an ongoing process at early implementation, only expected outcomes are outlined.

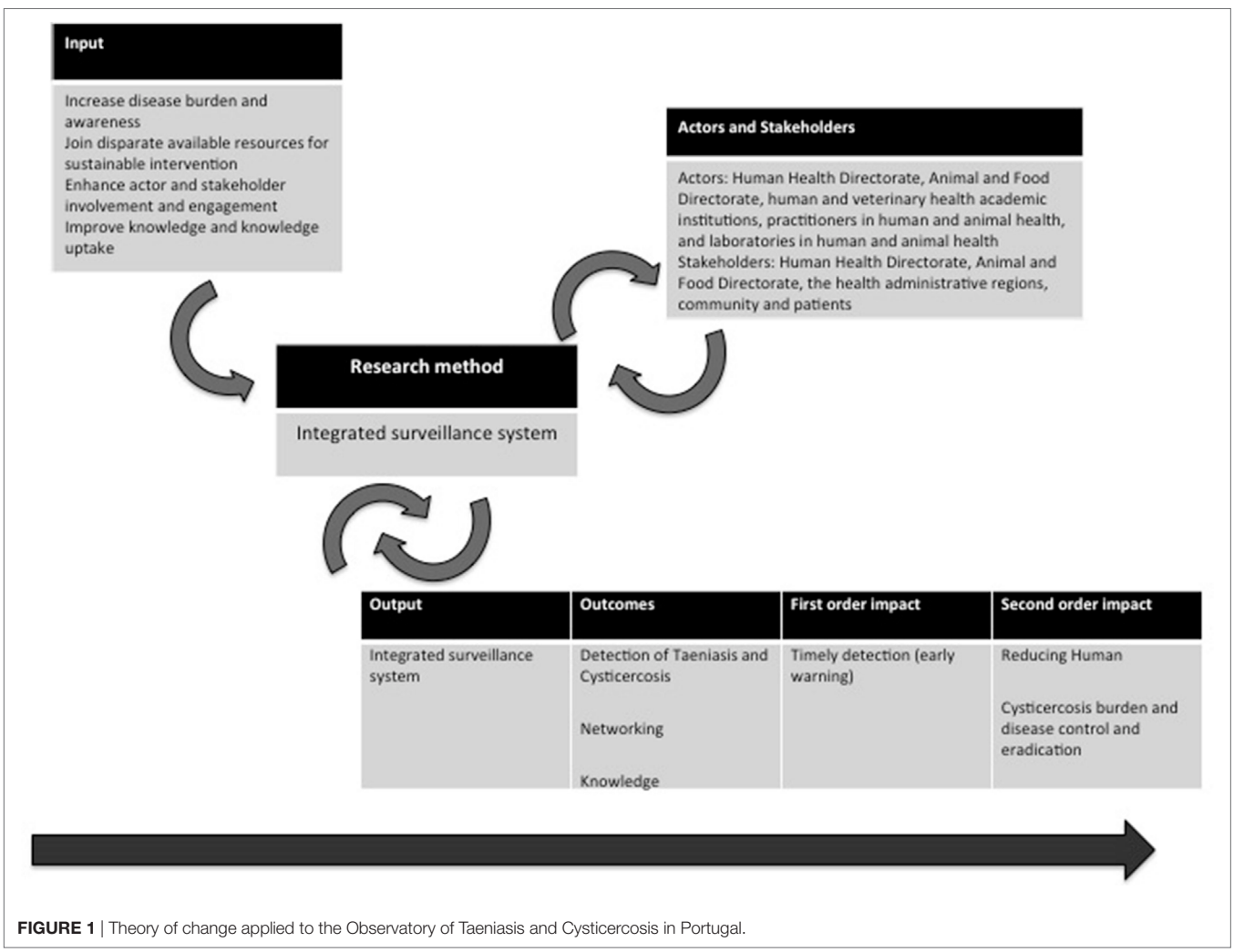

FIGURE 1 | Theory of change applied to the Observatory of Taeniasis and Cysticercosis in Portugal.

Disciplinary outcomes include the following: (i) disease awareness and determinants definition; (ii) disease burden (frequency, severity, health status, etc.); (iii) tapeworm carriers detected; and (iv) effective tapeworm carriers' treatments. Interdisciplinary outcomes are based on the Initiative innovation allowing for reporting practices, generation of new sources of data and networks, also creating a favorable environment for developing new operational projects, research projects, and national and international networking and collaboration. Also, the development of guidelines concerning case diagnosis, epidemiological case contacts' survey, and treatment is an interdisciplinary outcome. The evolving trans-sectorial and transdisciplinary official and non-official collaboration and transparency at different levels and hierarchies within the system as well as the expected increased interest in OH approaches for solving complex health problems are OH outcomes of the Initiative. Moreover, innovation is brought by introducing a new model for control of a neglected disease in European settings, involving changing the disease control paradigm.

OH-ness

The OH index was 0.31. Its OHR is 1.98. The results were depicted in a spider diagram with the surface area and shape illustrating the degree of OH implementation and the balance between the operational and the supporting means (**Figure 2**). The operational levels of the Initiative are the main strengths, namely, OH thinking and OH working, indicating a comprehensive multidimensional approach and transdisciplinarity. On the other hand, weaknesses

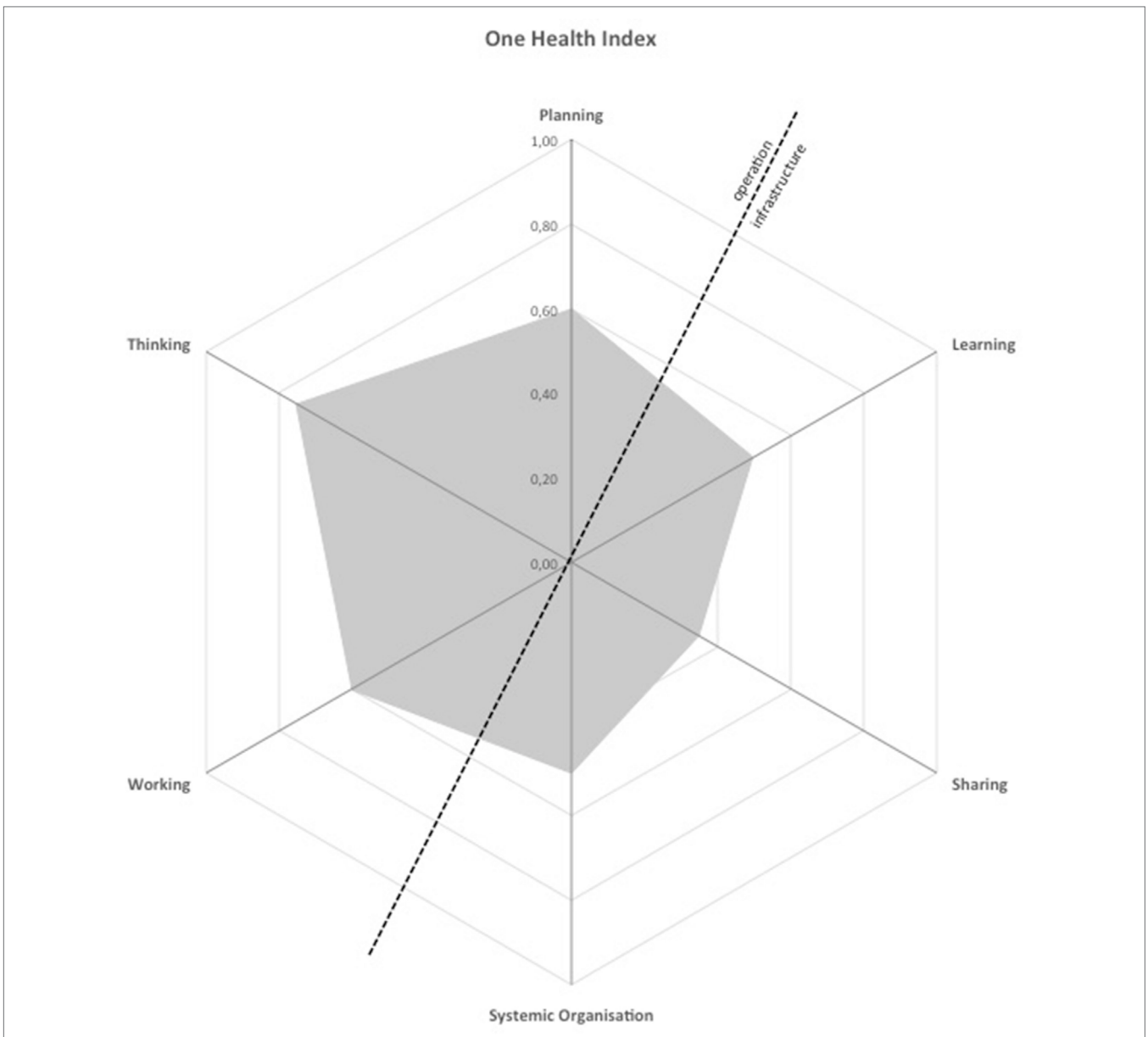

FIGURE 2 | Spider diagram illustrating the degree of One Health implementation and the balance between the operational and the supporting means of the Observatory of Taeniasis and Cysticercosis in Portugal.

in the supporting infrastructure, namely, OH sharing, team structure, and organizational learning were observed.

One Health thinking score was 0.75. Eight different dimensions were considered: space, time, life, knowledge, and network were considered crucial dimensions and obtained the highest score (=1), followed by economy (=0.4), and the passive recognition of management and legislative dimensions (=0.2). The scorings of the considered criteria were as follows: dimension coverage and balance 0.8; Initiative to environment match 0.7; integrative health approach 1.0; system features and target 0.7; sustainability and social–ecological considerations 0.8; and perspectives and TOC factors 0.4.

One Health planning score was 0.60. It was calculated according to the match between tasks, resources, and responsibilities. The scorings of the considered criteria were as follows: common aims 1.0; stakeholder and actor engagement 0.7; self-assessment and plan revisions 0.6; and individual objectives 0.4–1.

One Health working score was 0.60. The scorings of the considered criteria were as follows: broadness of the Initiative 0.8; collaboration 0.6; transdisciplinary balance 0.8; cultural and social balance 0.5; and flexibility and adaptation 0.8.

One Health sharing score was 0.35, reflecting overall data and information sharing infrastructure. The scorings of the considered criteria were as follows: general information and awareness sharing 0.3; data and information sharing 0.4; methods and results sharing 0.8; and institutional memory and resilience to change 0.1.

One Health learning score was 0.50, and it assesses the learning infrastructure. The scorings of the considered criteria were as follows: focus on adaptive and generative individual learning 0.5; focus on adaptive and generative team learning 0.7; adaptive and generative organizational learning 0.4; direct learning environment supportive of adaptive and generative learning 0.4; and general learning environment supportive of adaptive and generative learning 0.5.

Systemic organization score was 0.50, the tool focusing on leadership skills and criteria for effective teamwork. The scorings of the considered criteria were as follows: team structure 0.5; social and leadership structures and skills 0.7; competence 0.5; and focus on innovation 1.0.

DISCUSSION

The establishment of integrated surveillance programs focusing on tapeworm carriers' detection and treatment, for disease control and eradication, as the OTC program, may effectively tackle cysticercosis in industrialized countries. Adhesion to OH standards should guide surveillance program development at all stages. OH evaluation tools may play a role in certifying and guaranteeing adhesion.

In the evaluation performed, operational aspects were the main strengths (OH thinking, OH working, and OH planning) indicating a comprehensive transdisciplinary-integrated health approach, sustainability, and ecological consideration. Weakness in the infrastructure and supporting means for the Initiative (OH learning, OH sharing, and systemic organization) was detected, the most critical being related to information and data sharing and team structures. The six assessments were combined in an OHI of 0.31, reflecting the degree of integration of operational and infrastructure aspects of the Initiative, given by the proportion of the surface of the spider diagram hexagon covered (**Figure 2**). OHR was 1.98, reflecting the balance between operational and infrastructure aspects of the Initiative through its symmetry over the diagonal on the spider diagram (**Figure 2**). The optimal range for OHI and OHR has, however, not been established (5).

Considering the individual aspects assessment, the higher score was obtained for OH thinking (0.75). The Initiative is at designing and early implementation stages, the conceptualization of the Initiative and the thinking in an about the Initiative and the system being comparatively better consolidated. It has a highly integrated approach, covering diverse dimensions at differing scales and incorporating many perspectives. It aims to understand disease patterns and trends, identifying where to intervene to control disease transmission. It addresses mainly human, animal, and environmental concerns also being considered. It impacts on the tree pillars of sustainability (society, environment, and economy) although this cannot yet be captured. The knowledge resulting from the Initiative may apply internationally to countries with similar societal and epidemiological characteristics.

One Health planning aspect (0.60) analysis showed that essential stakeholders and sectorial and disciplinary actors are identified and described, but their full engagement is ongoing. The Initiative is planned to aim at sustainable health outcomes. Participating institutions from human and animal health sectors (national, regional, and local health authorities; health professionals working in human care, animal care and veterinary inspection; and academia and reference laboratory) and the formal and informal communication and networking generated are planned to achieve the aim. Planned formal and informal feedback communication loops and yearly formal reports' discussion with the national health authorities and their disclosing to other stakeholders and actors within the Initiative allow for underway corrections of the planned activities and involvement of new actors and stakeholders as needed. For each of the planned activities, according to the formulated objectives, matching of roles, responsibilities, and competencies was clearly established but resource allocation is ongoing.

One Health working (0.60) assessed the transdisciplinarity and the degree of cross-disciplinary working and leadership enabling an innovative approach to the problem. A flexible coordination between professionals coming from animal health and human health areas was developed, the environmental component being developed within these areas. The Initiative is broad and cross-sectorial, although human health and animal health sectors dominate; disciplines, methods, and scales of analysis are diverse. Disciplines involved include clinical medicine, laboratory and diagnostics, public health, and epidemiology (including field and applied epidemiology) from academic and non-academic, governmental and non-governmental fields in the human and animal health sectors. There is a reasonable degree of interaction between actors from the different disciplines. There are difficulties in enforcing the methodology of the Initiative and in the communication between governmental institutions, the Initiative not being considered a priority. The aim seemed clear to all, there were face-to-face meetings, but part of its implementation still lacks the approval of government institutions. The methodology

has been discussed with the actors and stakeholders, including the health authorities, and it has been adjusted to the work reality of each sector. Being a long-term systematic surveillance project at designing and early implementation phase, the project design can adapt to internal and external changes that may influence its implementation.

The lowest score obtained was in OH sharing (0.35). The Initiative does not yet have official mechanisms to facilitate sharing of information, although regular (annual) reports, newsletters, and workshops are to be implemented. Online and face-to-face meetings occur as deemed necessary. It uses peer-reviewed publications and conferences to share relevant data resulting in new knowledge production (4). Compliance with confidentiality and data protection issues need to be tackled since it may interfere with data sharing and accessibility. Within the Initiative, methods and results are to be discussed and shared. Institutional memory and safeguarding access to data and information in case of change are not yet organized.

Concerning OH learning infrastructure (0.50), the main focus was on adaptive and generative team learning, the team meetings consisting on information sharing, discussion, and analysis, enabling supportive decision-making and corrective approach. The Initiative aims that the stakeholders involved, namely, the health authorities and institutions, be focused on improving procedures and evolving effectively toward new intervention and approach strategies, but there is some inertia to changing more conservative disciplinary paradigms of health surveillance, even when this change is seen as advantageous and appropriate.

Systematic organization (0.50) assessed team structure, leadership, and focus. The Initiative depends on teamwork. Several teams are to be involved at different organizational and operational levels, although some teams' structure and objectives need to be further clarified. The Initiative is organized in interrelated and interdependent working packages, which may involve different sectors and disciplines from different fields of expertise within human and animal health. Disciplinarity and transdisciplinarity are being considered in team constitution that is still ongoing. Task-oriented, relationship-oriented, and change-oriented leaderships are present, although unbalanced: informal connections and face-to-face processes are privileged. The OH challenge, the mainstay of the Initiative, is translated into the scientific and developmental questions of the Initiative and the innovation in relation to the state of the knowledge.

Globally, the evaluation conducted indicates that OTC is being designed complying with OH characteristics. The Initiative introduces methodological innovation to which sectorial health authorities may not be completely receptive in practice even though considering the OH approach highly relevant on theoretical grounds. Considerable obstacles are deemed to occur; they need to be both reasoned beforehand and tackled as they arise. For instance, different governmental institutions have valuable data, potentially useful for surveillance, the data being, however, cumbersome to obtain and lacking transparency. Moreover, cysticercosis is a neglected and infrequent disease in Portugal, which may contribute to the general indifference and non-prioritization by the health authorities. However, the already available data suggest the disease burden and the social, ecological, and economic consequences along with the possibility of disease emergence may not be negligible, moreover, considering globalization and increasing human and animal mobility and trade (4, 15). The scientific community, including CYSTINET (European Network on Taeniasis/Cysticercosis), is actively urging to introduce and improve human and porcine cysticercosis surveillance and control practices in Europe (16). New knowledge concerning the national epidemiologic scenario of cysticercosis has already been produced. It was internally and externally disseminated in communications, conferences, and peer-reviewed international publications. The results produced are steps toward the mobilization and harmonization of working methodologies toward an OH model.

LIMITATIONS

The application of the NEOH evaluation framework to the ongoing design of the OTC proved challenging at times. It illustrates an innovative approach to the evaluation framework, this framework being itself pioneer in the context of OH evaluation. The timing of the evaluation allows for introduction of corrections and adjustments in the Initiative to ensure an OH-oriented implementation. However, NEOH tools require a large amount of specific data, some of it not available or feasible at the time, making the evaluation process laborious and hard to accomplish, especially considering the evaluation perspective in this case study. Information was gathered within the designing and coordinating teams that consist of elements from public health and epidemiology, medicine, and academia within human and animal health sectors. Some operational and structural aspects are still being considered and pushed forward. The engagement of actors and stakeholders is not complete. Some teams need structuring and to have their roles and tasks more clearly defined. The work is done primarily on voluntary basis or linked to other academic and non-academic institutional programs.

The scoring may be influenced by the conflict between what the Initiative will achieve if everything works out as planned and what is already achieved, namely, at infrastructure level. Even though the assessment tools seem *a priori* to be more suited for retrospective evaluation, the results of the evaluation provide a valuable contribution to the corrective action needed in the OH Initiative. The communication pathways and sharing mechanisms, key elements of the Initiative, need to be carefully reconsidered and reinforced before advancing further in the implementation. The same applies to team structuring, role definition, and communication between teams, at different organizational and executive levels. This feeds back into corrective action on the planning aspect, further defining and organizing the resources for each objective. Some items of learning and systemic organization should be more adequately assessed once the Initiative is fully implemented. It would be relevant to repeat full evaluation after at least 5 years of project implementation so that changes related to the organization of services, information systems, and institutional relationship can be identified, deeper knowledge has been produced, mechanisms for data information sharing have been implemented, and learning aspects can be effectively recognized.

The NEOH evaluation framework anchors on the system theory and combines descriptive and qualitative assessment with a semiquantitative scoring for the evaluation of the degree and

structural balance of OH-ness, the individual analysis of the six assessment tools being also valuable. Putting the Initiative into its context, as a subsystem within the system, allowed a more complete understanding of the Initiative, its relevance, and the impact pathways. The completion of the assessment tools may be subject to bias toward the perception of a particular evaluator; furthermore, considering that this was a self-evaluation process. The review of the scoring criteria by several others evaluators, both internal and external and from different disciplines, helped to address this bias. Summarizing the six assessed OH aspects in a single quantitative and visual element, the OHI and OHR, is attractive as an objective evaluation result in itself and for comparing different Initiatives. Its meaning or interpretation, however, is not yet well defined. A higher OHI does not necessarily indicate a better OH Initiative, so it is difficult to draw conclusions of the results of this case study comparing to others (5). However, this case study is one in a group of case studies, providing the first data on OHI and OHR for various contexts and OH Initiatives. Data of the evaluation framework data from this case study will be compared with other case studies during validation of the framework and in creating benchmarks in the future. Complementary to OH evaluation, conventional evaluation models need to be considered, namely, process evaluation and cost–benefit evaluation, and will provide data to confront with OH-ness evaluation and will provide more detailed analysis on the surveillance planning, implementation and cost–benefit.

Considering the case study presented, NEOH evaluation framework comes forth as an interesting tool also to guide the design of OH Initiatives. In this perspective, operational aspects (OH thinking, OH planning, and OH working) are more tangible to assess. However, infrastructure aspects tools, less applicable, may display relevant information that if disregarded will compromise successful implementation of the Initiative, considering the OH goal.

Evaluation results enable redirecting of the Initiative toward a more OH-oriented perspective. Evaluation results can, moreover, contribute to (i) develop shared guidance and recommendations for surveillance, intervention, prevention, and control of cysticercosis; (ii) be used on Animal and Public Health policy and decision at regional and national level; and (iii) provide insight and an example on how to manage a non-notifiable neglected zoonosis in a European country.

CONCLUSION

The taeniasis and cysticercosis health challenge in industrialized countries, namely, Portugal among other European countries, urges OH solutions. This case study explores the reasoning behind the taeniasis- and cysticercosis-integrated surveillance challenge, within the United Nations 2030 agenda, considering the added value of OH for health and welfare in an ecological perspective.

It illustrates the successful application of the NEOH evaluation framework to the ongoing design of OTC in Portugal as a means to ensure adhesion to OH standards. Reflective and corrective action to strengthen team structure, beyond the human health and animal health sector, and communication and information sharing mechanisms is needed, therefore amplifying and clarifying the real scope of the OH concept. Health authorities' increased awareness is needed for the non-negligible health, social, ecological, and economic issues associated with the disease to further fuel effective sectorial collaboration, networking, and transparency. The institutions need reshaping to better facilitate transdisciplinary processes, promoting a health (human, animal, and environmental)-centered approach. The use of the evaluation framework to guide OH Initiatives design requires that those involved in the process are comfortable with systems thinking to approach complex and dynamic structures. Some items of the assessment tools, namely, the infrastructure tools, may not be applicable at designing stages even though the attempt to complete them enforces the feedback loop leading to reconsideration or amendment of planning issues or other operational aspects. In future, this may evolve toward adjustments or adaptation of the framework to different evaluation contexts, or else, an evaluation framework-based comprehensive OH checklist to guide project development. Further context-specific research will help to clarify and better understand the strengths and weaknesses of the tool in the different settings.

In conclusion, the case study highlights and supports OH assessment also prospectively, that is, guiding and guaranteeing its planning, designing, and implementation in an OH-oriented perspective. Focusing on a systems approach, the use of this tool for prospective and retrospective evaluation and monitoring may prove a valuable addition in future health programs, strategies, and policies.

AUTHOR CONTRIBUTIONS

AF and MV conceived and designed the work and drafted the manuscript. AF, MV, and JT carried out the evaluation. AC, DM, and SG contributed to revising the evaluation. All the authors contributed to the analysis and interpretation of data, participated in the revision for important intellectual content, approved the final version to be published, and agreed to be accountable for the content of the work.

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SUPPLEMENTARY MATERIAL

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A One Health Evaluation of the Southern African Centre for Infectious Disease Surveillance

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Rooted in the recognition that emerging infectious diseases occur at the interface of human, animal, and ecosystem health, the Southern African Centre for Infectious Disease Surveillance (SACIDS) initiative aims to promote a trans-sectoral approach to address better infectious disease risk management in five countries of the Southern African Development Community. Nine years after SACIDS' inception, this study aimed to evaluate the program by applying a One Health (OH) evaluation framework developed by the Network for Evaluation of One Health (NEOH). The evaluation included a description of the context and the initiative, illustration of the theory of change, identification of outputs and outcomes, and assessment of the One Healthness. The latter is the sum of characteristics that defines an integrated approach and includes OH thinking, OH planning, OH working, sharing infrastructure, learning infrastructure, and systemic organization. The protocols made available by NEOH were used to develop data collection protocols and identify the study design. The framework relies on a mixed methods approach by combining a descriptive and qualitative assessment with a semi-quantitative evaluation (scoring). Data for the analysis were gathered during a document review, in group and individual interviews and in an online survey. Operational aspects (i.e., OH thinking, planning, and working) were found to be balanced overall with the highest score in the planning dimension, whereas the infrastructure (learning infrastructure, systemic organization, and sharing infrastructure) was high for the first two dimensions, but low for sharing. The OH index calculated was 0.359, and the OH ratio calculated was 1.495. The program was praised for its great innovative energy in a difficult landscape dominated by poor infrastructure and its ability to create awareness for OH and enthuse people for the concept; training of people and networking. Shortcomings were identified regarding the balance of contributions, funds and activities across member countries in the South, lack of data sharing, unequal allocation of resources, top-down management structures, and limited horizontal collaboration. Despite these challenges, SACIDS is perceived to be an effective agent in tackling infectious diseases in an integrated manner.

Keywords: Southern African Centre for Infectious Disease Surveillance, One Health, evaluation, capacity, surveillance

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Abbreviations: CoP, community of practice; ICT, information and communication technologies; NEOH, Network for Evaluation of One Health; OH, One Health; OHAE, One Health Analytical Epidemiology; OHMB, One Health Molecular Biology; RGMA, Research Governance, Management, and Administration; SADC, Southern African Development Community; SACIDS, Southern African Centre for Infectious Disease Surveillance.

INTRODUCTION

Emerging infectious diseases have always been, and are still today, a major burden for human populations (1). This burden is particularly high in low- and middle-income countries (2), and Africa is considered the continent to suffer the most from infectious diseases (3) and to have the least capacities to control them. More than 60% of human emerging infectious diseases are zoonotic, meaning they can be transmitted from animals to humans or *vice versa* (4). Our modern societies and new ways of life are changing the dynamics of zoonotic diseases transmission (5). Deforestation, international trade, hunting, or ecotourism are all factors that increase the likelihood of contacts between humans and wildlife facilitating potential spillovers of zoonotic pathogens from a wildlife reservoir to humans (6, 7). In addition, pathogens' and vectors' transmission cycles and ability to spread and adapt depend on the environment in which they evolve. Tackling emerging infectious diseases requires the study of environmental factors that lead to the modification of ecosystems, such as climate change, biodiversity loss, or other anthropogenic causes (1, 8).

Rooted in this understanding that emerging infectious diseases occur at the interface of human health, animal health, and ecosystem health (4), the Southern African Centre for Infectious Disease Surveillance (SACIDS) initiative aims to promote a trans-sectoral approach to address better infectious disease risk management in Southern African countries. SACIDS' vision was outlined in 2008 after a series of meetings and workshops held between five Southern African Development Community (SADC) countries and international partners. As defined at the inception of the initiative, SACIDS' mission is to "harness innovation in science and technology to improve Southern Africa's capacity (including human, financial, and physical) to detect, identify, and monitor infectious diseases of humans, animals, plants, and their interactions to better manage the risk posed by them" (9). The creation of SACIDS was in line with the gradual recognition of the One Health (OH) concept, which gained momentum at the beginning of the twenty-first century following the highly pathogenic avian influenza outbreaks (10, 11). Although it is hard to reduce this transdisciplinary approach to one definition, the description made by the Food and Agriculture Organization of the United Nations gives a good idea of the OH principles: "A collaborative, international, cross-sectorial, multidisciplinary mechanism to address threats and reduce risks of detrimental infectious diseases at the animal–human–ecosystem interface" (11).

Nine years after its establishment, the SACIDS program benefited from an external evaluation. The added value arising from integration and its transdisciplinary approach was highlighted in the evaluation report (12). However, OH is still a relatively new concept, and few studies have been implemented to evaluate systematically OH initiatives (13). The Cooperation on Science and Technology Action Network for Evaluation of One Health (NEOH, http://neoh.onehealthglobal.net/, accessed April 17, 2017), is working toward the establishment of a science-based evaluation protocol to enable quantitative and qualitative evaluation of various OH activities. This protocol aims to provide an assessment of the strength of an OH initiative by confronting the OH process characteristics of operations (thinking, planning, and working) and supporting infrastructure (systemic organization, learning, and sharing) with achieved changes and comparing it to outcomes generated by the initiative (14).

With a focus on the surveillance of infectious diseases, this study aimed to evaluate the OH capacity building program SACIDS by using the framework developed by NEOH. The data used for the evaluation were collected from different SACIDS stakeholders and actors in Tanzania, Zambia, Mozambique, Democratic Republic of Congo (DRC), and the UK using different data collection approaches. We present the context in which SACIDS evolves, describe the theory of change and the outcomes of the initiative and the assessment of the different OH dimensions of SACIDS.

METHODS

General Overview

The evaluation questions for this study were as follows: *What is the context within which SACIDS operates and how does it link to this context? What is the SACIDS theory of change? What are the outputs and impact achieved? How can the different OH dimensions in SACIDS be characterized? Which elements were particularly strong and which could be improved to ensure that longer-term impacts can be realized?*

The Southern African Centre for Infectious Disease Surveillance was interested in supporting this evaluation to get an assessment of its OH dimensions and to understand which elements were working well and which ones could potentially be improved in the future. To achieve this, we conducted a process evaluation that was based on the One Healthness (OHness) framework from NEOH (14) and described the outcomes achieved by the program.

The protocols made available by NEOH (14) were used to develop data collection protocols and identify the study design. The NEOH framework relies on a mixed methods approach by combining a descriptive and qualitative assessment with a semi-quantitative evaluation (scoring) for the evaluation of OHness with an OH index (OHI), while including conventional metrics on the outcomes' side. The descriptive part is based on systems thinking.

Data Collection

The data collection methods included a document review, face-to-face group and individual interviews, phone interviews, and an online survey. Data were collected between March and July 2017 during visits to Zambia and Tanzania as well as interviews conducted from the UK.

Documents for the document review were requested and obtained from SACIDS Executive Director and secretariat. They were asked to share any documentation including proposals, reports, presentations, peer-reviewed and lay publications that described the SACIDS program and journey from its inception to the end of the Phase 1 funding (i.e., 2008–2017).

Following the document review, two questionnaires were developed to gather insights and perspectives from SACIDS members. The first one was a questionnaire to be administered

in face-to-face interviews to collect data on OH data sharing infrastructures, OH planning, and OH working components of SACIDS. The main goal of this questionnaire was to enable discussion between the participants and to capture the main issues on which people agreed or disagreed. The detailed question guide can be found in Table S1 in Supplementary Material. Target respondents were SACIDS members from all SACIDS active countries (i.e., Tanzania, Zambia, the DRC, Mozambique, South Africa, and the UK) with long-standing SACIDS experience, i.e., people who had been part of the program for at least 4 years. Moreover, different levels of seniority were aimed for with invited participants spanning postgraduate students, postdocs, community of practice (CoP) leaders, initiators, advisors, and management board members. The questionnaire was used in two group interviews in Morogoro, Tanzania with five SACIDS members, and in Lusaka, Zambia, with six SACIDS members. Moreover, individual interviews were conducted with the SACIDS Executive Director and a SACIDS smart partner in the UK (smart partnerships in SACIDS are partnerships with institutions that can provide specific input and expertise to the program) plus a representative from Mozambique. No partner from South Africa was interviewed due to resource constraints. The decision to interview people in either group or individual interviews, respectively, was made solely on practical considerations and the availability of people. People who could not be met personally were interviewed using the online application Skype 7.52; one person in the DRC and one person in the UK were interviewed in this way. The complete question guide for the personal interviews was too long to apply in the same detail to all respondents. Consequently, the interviewers allowed more time for the questions that the respondents seemed to be most knowledgeable about. Some of the questions on the management of SACIDS were skipped when participants (mostly MSc or PhD students) claimed that they did not know how exactly SACIDS was managed. When there was an unresolved disagreement in a group interview, the interviewer noted down both opinions.

The second questionnaire was an online survey in the software Google Forms to collect data on the dimensions of OH learning and OH thinking (Table S2 in Supplementary Material). The survey was widely distributed in the SACIDS community based on an email list shared by the SACIDS secretariat and followed-up by two personal reminders by email. The target respondents were the same as for the personal interviews. Apart from the online approach, the same questionnaire was used with individual SACIDS members, namely, four in Tanzania, eight in Zambia, and one in the UK.

All face-to-face interviews were held in English by the first and last author, respectively. Written notes were taken during the interviews and summarized afterward. Ethical approval for the interviews and the online survey was sought from the Royal Veterinary College (RVC) and was granted by its Social Sciences Research Ethical Review Board, number URN SR2017-1002.

Data Analysis

The context, the description of the initiative, and the theory of change were derived from the document review and refined based on information gathered during the interviews with SACIDS members. Outputs and outcomes were identified during the document review and complemented by information shared by respondents during the interview and surveys. The assessment of the outputs and outcomes was descriptive only.

After the data collection was completed, the extent of the OHness was assessed by following the recommendations developed in the NEOH tools (14); all dimensions, the information collected for each element, and the scoring can be found in Table S3 in Supplementary Material. The OHness is a sum of characteristics that defines an integrated approach and includes OH thinking, OH planning, OH working, sharing infrastructure, learning infrastructure, and systemic organization (14). The understanding and capacity to use the tools was enhanced by training future evaluators in July 2016, organized by NEOH.

Metrics are described and detailed in the NEOH tools (14), and a short summary of each element is provided below. Every question was scored based on a detailed explanation of the arguments gathered during the various interviews, and the reasoning for the score was presented. Each OH characteristic was described by a final score, summarizing the question-specific scores. In the end, an OH spider diagram was constructed, and an OHI and OH ratio (OHR) calculated using the equations presented in Ref. (14).

The data collection and assessment were mainly conducted by the first and last author, respectively, based on information shared by SACIDS members and the documents reviewed. Where there was a difference in the scoring, they discussed the discrepancy, presented their arguments, and agreed on a score. A general review of the evaluation was completed by the coauthors, all external to SACIDS, but with the Tanzanian coauthor closely collaborating with the initiative.

OH Thinking

Based on the assumption that the integration of human, animal, and ecosystem health requires systems thinking and the consideration of multiple dimensions, feedback loops, and interconnectedness (14), the questions probing for system thinking relied on the match between the dimensions of the initiative and its context as well as key elements of systems thinking. Particular attention was given to the scales in different dimensions, and that the initiative reflects the context in which it operates. The score given for the quantitative evaluation of SACIDS OH thinking resulted from the mean of six different categories: (1) the balance of consideration of the different dimensions by the initiative, (2) the match between the initiative and its context, (3) the initiative's integrated approach to health, (4) the system features targeted by the initiative, (5) the initiative's considerations of sustainability and socioecological factors, and (6) the consideration of different perspectives and factors that impact on the theory of change.

OH Planning

The planning score is built on the assumption that careful planning of tasks and activities in line with the initiative's objectives and goals in an OH way necessitates careful and balanced allocation of resources to all tasks and objectives under consideration of the integrated nature of the program. Consequently, this score includes the description of (1) common aims, (2) stakeholder and actor engagement, (3) self-assessment and plan revisions; and (4) matching of planning and resources for all objectives.

OH Working

Interdisciplinary collaboration brings together people with different skills, expertise, experience, backgrounds, and often from varying epistemologies with the aim to tackle complex problems with a high societal stake that require an understanding of the human behavior (15–17). In OH, interdisciplinarity has merged with a participatory approach in the form of transdisciplinarity (17), which relies on appropriate leadership and management that is visionary, supportive, and engaging (17, 18) to create a strategic dialog, shared decision-making, and non-hierarchical relationships and allows for self-reflection, flexibility, and recursiveness (17, 19–21). These considerations were the basis for the OH working assessment, which considered (1) the breadth of the initiative, (2) collaboration, (3) transdisciplinary balance, (4) cultural and social balance, and (5) flexibility and adaptation.

Sharing Infrastructure

In a broad sense, data and information sharing is a science catalyzer (22). However, data and shared information can also stimulate progress in both mandatory and voluntary interventions, surveillance and control programs, e.g., when used for certification, open-access reporting opportunities or surveillance, and benchmarking (23). A central benefit of data sharing stems from analyzing data more comprehensively and developing further knowledge and information. In the NEOH sharing tool, the following elements were considered: (1) general information and awareness of sharing, (2) data and information sharing, (3) methods and results sharing, and (4) institutional memory/resilience.

Learning

Learning, a change in cognition, potential behavior, or actual behavior through better knowledge and understanding, can be achieved at the individual, group, and organizational levels (24), strongly influenced by the interplay between them (25). In other words, they work together and influence each other (26). The assessment of learning was done using the individual questionnaires. Five categories were evaluated, each one being composed of two to three questions: (1) adaptive and generative individual learning, (2) adaptive and generative team learning, (3) adaptive and generative organizational learning, (4) direct learning environment supportive of adaptive and generative learning, and (5) general learning environment supportive of adaptive and generative learning. For each of the 13 questions, the score given was the mean of the answers obtained in the individual questionnaires. Then, within a category, each question was weighted depending on its importance (questions relating to generative learning had more weight than questions relating to adaptive learning, which had more weights than the ones relating to basic learning).

Systemic Organization

In many complex settings, change-oriented leadership can overcome rigid conventions, norms, and traditions by targeting leverage points in systems to modify behavior. In OH, there is also the challenge that collaboration may be dominated by one discipline, which can reduce commitment, interest, and motivation. A solution is shared/distributed leadership and governance (27) to promote engagement of all disciplines and unlock creative potential, competence, and innovation. Consequently, the selection of questions for the scoring of the systemic organization of OH initiatives involved (1) team structures, (2) social and leaderships structures and skills, (3) competence, and (4) focus and innovation.

OHI and OHR

Once all scores for the six dimensions were available, the six assessments were illustrated in a spider diagram, in which each assessment was represented by a spoke. The diagram depicts the operational aspects "OH thinking," "OH planning," and "OH working" opposed to the infrastructure for "learning," "sharing," and "systemic organization." Based on this, the OHI is computed by calculating the proportion of the surface of the hexagon covered, while the OHR is the relation of the surface covered in the top left of the diagonal to the one in the lower right (14).

EVALUATION RESULTS

Definition of the Context and the Initiative

General Overview

The Southern African Centre for Infectious Disease Surveillance is a regional consortium established and operating in Tanzania, Zambia, Mozambique, DRC, and South Africa. In addition to these five countries, SACIDS also engaged smart partnerships with institutions in Kenya and in the UK.

Several drivers motivated the creation of SACIDS and the willingness to adopt an OH approach. The main argument behind SACIDS inception was the understanding that zoonotic diseases increase both the human health burden and losses of animal production. The synergy of the health and economic consequences of such diseases, amplified by the poor governance systems and civil instabilities, the lack of participatory health policies, of personnel and of resources and the need for adequate leadership, exacerbates poverty (3, 28, 29). All of these factors call for a syndemic approach to tackle infectious diseases (30) through better collaboration between human health, animal health, environmental health, and socioeconomic sectors.

In each African participating country, several institutions from the academic, government, or research sectors participate in SACIDS activities and engage various actors with human health or animal health backgrounds. Following an OH approach, the main objectives of SACIDS are to enhance institutional capacities for African-led research, to promote collaboration between veterinary, medical, and other sectors involved, and to enable better sharing of information and resources between individuals and institutions at a national, regional, and international level. To reach these objectives, SACIDS' strategy is concentrated on five pillars, described as follows: (1) to enhance the capacity of institutions for the detection, identification, and monitoring of infectious diseases

of both humans and animals, in a "one medicine" framework, (2) to enhance biosafety and quality management (BQM), (3) to enhance skills through taught and distance-learning programs, (4) to enhance information and communication technologies (ICT) to support learning and disease surveillance systems, and (5) to enhance skills through research. By promoting joint efforts in education, communication, research, and disease surveillance, SACIDS is a pioneer initiative in the adoption and application of OH principles for the surveillance of infectious diseases in Southern Africa.

Description and Visual Representation of the Context

The Southern African Centre for Infectious Disease Surveillance is an initiative that exists in five countries of the SADC,[1] which has been working toward the establishment of "economic development, peace and security, and growth" since the 1980s and aimed to "enhance the standard and quality of life of the people of Southern Africa and support the socially disadvantaged through regional integration" (31). Before the establishment of SACIDS, the SADC had already promoted some linkages and network building at a regional level, which was one of the reasons to select only SADC countries to build SACIDS.

The political context in which SACIDS evolves is a legacy of the post-colonial era. The whole process of political change in Africa took decades from the 1950s to the 1990s, and Southern African countries were late in this transition. This has been an obstacle to the implementation of disease control programs in these countries. Political instabilities remain a challenge to long term policy planning, as in the DRC where the rapid turnover of governments makes it difficult to create solid links between individuals or institutions. Regarding capacity for the surveillance of infectious diseases, only South Africa had adequate tools and expertise to monitor and control human and animal emerging infectious diseases. The country had the ability, the infrastructures, and the capacity to guide the other countries that were too weak to match globally agreed standards.

Figure 1 gives an overview of the context within which SACIDS was developed. This provides a general impression of the interactions happening at a national level in the participating countries between human health, animal health, and environmental sectors and between governmental and academic institutions. Although each country has its own specificities, the overall academic and government structures used to shape SACIDS at the national level were found to be similar: a ministry of health, a ministry of agriculture/livestock, a government structure for the environment and/or the wildlife, national institutes for research in human and animal health, and universities with both schools of human medicine and veterinary medicine. Tanzania and Zambia already had some postgraduate programs at their universities and had started to create some connections between veterinarians and human doctors. In Mozambique and DRC, a crucial lack of institutional capacity was noted, with no scientific PhD programs in place in Mozambique and no veterinary school in Kinshasa, the capital city of DRC.

[1] The SADC comprises 15 countries: Angola, Botswana, DRC, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Swaziland, United Republic of Tanzania, Zambia, and Zimbabwe.

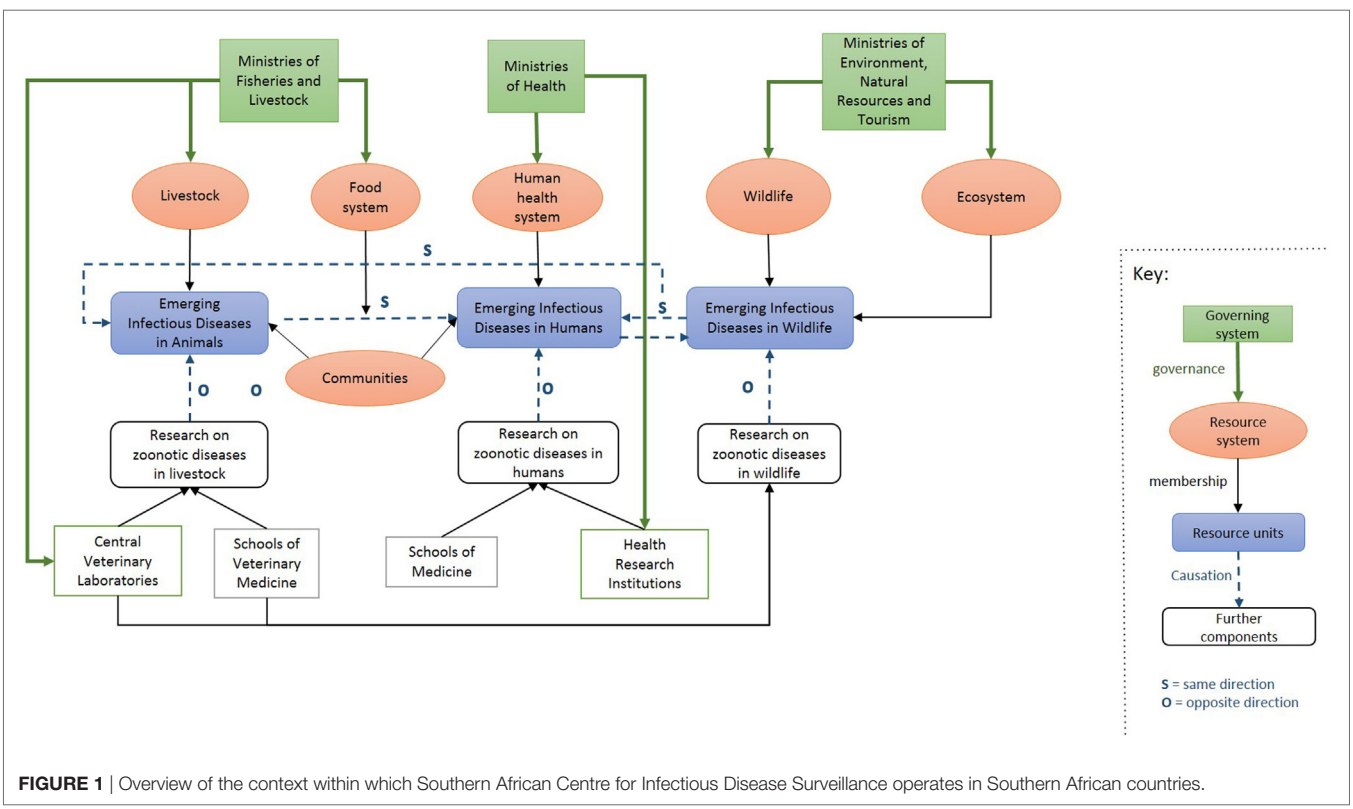

FIGURE 1 | Overview of the context within which Southern African Centre for Infectious Disease Surveillance operates in Southern African countries.

Description of the OH Initiative in Relation to Its Context

The Southern African Centre for Infectious Disease Surveillance was created as a consortium in 2008 under the guidance of its present Executive Director. It was guided by two international foresight studies that called for action against infectious diseases (32, 33). Hence, it arose from the recognition that a majority of emerging infectious diseases were zoonotic, and that joint efforts from the human health and animal health sectors were necessary to control them effectively. As described in the first evaluation report of SACIDS, the initiative's main goal is "to enhance institutional capacities for intersectoral research approaches to tackling infectious disease priorities through 'One-Health' approaches in both universities and research institutes across southern Africa" (34).

From 2008 to 2016, SACIDS received funding from different organizations including the Wellcome Trust foundation, Google, the Rockefeller Foundation, the African Development Bank, and the International Research Centre. SACIDS was selected by the Wellcome Trust to be one of the seven consortiums that constitute the African Institutions Initiatives, which aim to improve research capacity and African-led research through networked approaches in 18 African countries and 51 institutions. SACIDS resulted in the partnership of five Southern African countries: Tanzania, Zambia, DRC, Mozambique, and South Africa. In total, 18 institutions engaged with SACIDS from the beginning, namely, in Tanzania: Sokoine University of Agriculture (SUA) in Morogoro, Muhimbili University of Health and Allied Sciences in Dar es Salaam, National Institute for Medical Research in Dar es Salaam, and Tanzania Veterinary Laboratory Agency in Dar es Salaam; Mozambique: Eduardo Mondlane University (UEM) in Maputo, Institute of Agricultural Research (Ministry of Agriculture) in Maputo, and National Health Institute (Ministry of Health) in Maputo; DRC: University of Kinshasa, Central Veterinary Laboratory in Kinshasa, and University of Lubumbashi; Zambia: University of Zambia (UNZA) in Lusaka, Central Veterinary Research Institute in Lusaka, and Tropical Diseases Research Institute in Ndola; and South Africa: National Institute for Communicable Diseases in Johannesburg, Veterinary Institute of the Agricultural Research Council in Pretoria, University of Pretoria, and Stellenbosch University. Each country therefore had at least one university, one human health, and one animal health institute engaged with SACIDS, which reflected the consortium's aim to encourage collaboration between human and animal health sectors and to promote scientific training at a postgraduate level.

The Southern African Centre for Infectious Disease Surveillance also engaged with external partner institutions that are not directly part of SACIDS but which collaborated on some specific research projects, helped on the establishment of training courses and gave external advice to the initiative over time. The main partners are the International Livestock Research Institute, Nairobi, Kenya; the RVC, London, UK; the London School of Hygiene and Tropical Medicine (LSHTM), London, UK; and the London International Development Centre (LIDC), London, UK.

Figure 2 shows the effect of the SACIDS program within its context. Through the establishment of coordinating structures at the national level, SACIDS created channels of communication between institutions from different sectors and enabled better collaboration between them. SACIDS aimed to tackle the existing silo structure and to create horizontal links between sectors both at the government and academic level. SACIDS also launched postgraduate training classes and encouraged research on emerging and vector-borne diseases, bacterial diseases (including food-borne diseases and antimicrobial resistance), viral diseases of food security importance, and cross-cutting OH sciences, which should not only have a positive effect on the control of emerging infectious diseases in Southern Africa but also create interdisciplinary networks among students—an important foundation for future collaboration between sectors. SACIDS' secretariat, based in Tanzania, acts as the principal coordinator between the participating countries and with SACIDS' external partners.

At the regional level, SACIDS' management structure is established according to inter-institutional agreements. At the beginning, SACIDS had an Executive Director assisted by two Deputy Directors of which one was responsible for animal health (from Tanzania) and another responsible for human health (from South Africa). Since 2016, through World Bank funding, SACIDS has been running two African Centres of Excellence (ACEs), namely, one in Tanzania at SUA and one in Zambia at the UNZA. Both ACEs report to SACIDS through the SACIDS Governing Board. Each ACE is led by a Centre Leader with a deputy. The Deputy Centre Leader in Tanzania is the same person as the SACIDS Executive Director. Moreover, SACIDS has a secretariat, composed (apart from the Executive Director) of a program operation manager, a "training and research support officer" and a finance unit (**Figure 3**). The coordination at the academic level is operated by three people: one in charge of the "training and research" section and two in charge of "innovation and technology development." To promote transdisciplinary research and capacity building at the regional scale, SACIDS created CoPs that encourage collaboration between institutions within or between member countries. Each CoP is led by two people, one from the medical side and one from the veterinary side, with the two leaders coming from different institutions and sometimes from different countries. The CoPs are organized around six research themes: (i) diseases of economic and food security importance, e.g., foot and mouth disease; (ii) emerging viral diseases, e.g., Ebola; (iii) bacterial zoonoses including food-borne diseases, e.g., tuberculosis; (iv) climate-dependent, vector-borne diseases, e.g., Rift Valley Fever; (v) bacterial rare diseases, e.g., plague; and (vi) cross-cutting OH issues, e.g., surveillance (which often require integrating different sciences). These communities of practice are composed of supervisors and mentors, postdocs, PhDs, and MSc students. Through research, everyone within a CoP should have the opportunity to interact and exchange with the other people of the CoP, to learn from them and to be a mentor for someone else.

At the national level, national coordination bodies are in place to ensure communication between the secretariat of SACIDS and the member institutions in the country (**Figure 4**). These structures, called the "NatCIDS," are composed of at least two people, one with an animal health background and the other with a human health background. These NatCIDS are the relay to enable

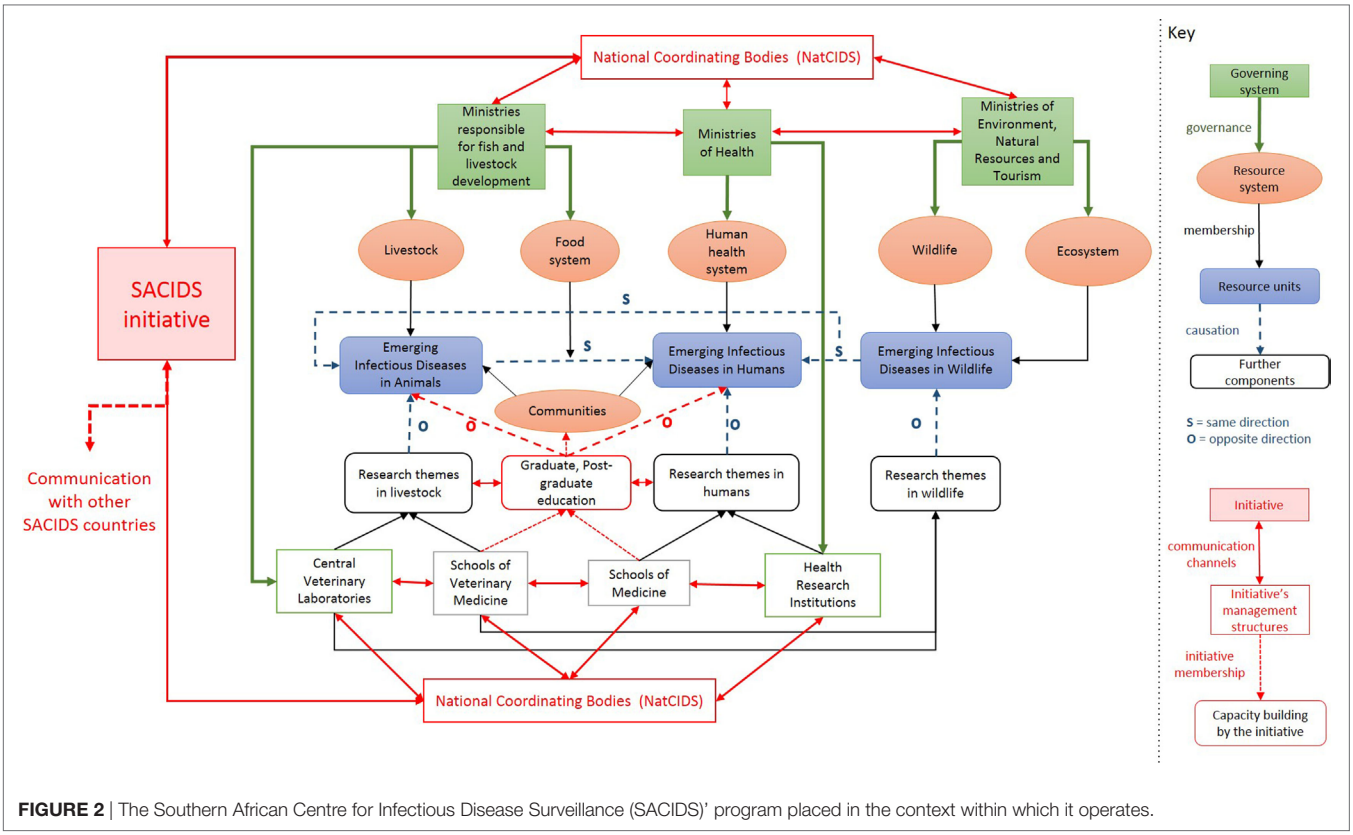

FIGURE 2 | The Southern African Centre for Infectious Disease Surveillance (SACIDS)' program placed in the context within which it operates.

discussions between SACIDS and national stakeholders, which can facilitate the application of government decisions where necessary. They also have an important role in the communication between SACIDS countries, to facilitate the exchange of students for attending an MSc, PhD, or postdoc in another country.

Different funders provide funding at the level of the SACIDS secretariat for core functions for forum, coordination, communication, advocacy, and resource mobilization, among others. Each CoP is expected to mobilize their own resources and pay into the secretariat; in exchange they receive administration support from the SACIDS secretariat.

Theory of Change and Outcomes of the Initiative

Theory of Change

In the first years of SACIDS, a model for a theory of change was elaborated. Building a theory of change is valuable for the implementation of long-term projects as it helps planning, implementing, and monitoring the required steps to reach the desired outcomes. SACIDS theory of change's diagram, presented in **Figure 5** [designed from Ref. (34)], shows the initial inputs received by the initiative in terms of funding, infrastructures, institutional expertise, management structure, and program strategy.

The process phase reveals the tools that SACIDS planned to use to create change in the African research and academic setting in which it evolves. This involved mainly network promotion, creation of communities of practice and teaching courses, and improvement of infrastructures and governance for research. The OH outputs that should arise from this process are core components to shape a compliant environment to conduce high-quality research at a regional level. From these, outputs should result in short-term expected outcomes, mainly structured in three categories: *Expected Scientific Skills* outcomes, *Expected Research Governance, Management, and Administration* outcomes, and *Expected Infrastructures* outcomes. In the long term, other outcomes and impacts on the socioeconomic sphere are expected to result from the SACIDS initiative. In the future, SACIDS initiative aims to lead to sustainable, well-funded, and well-managed African-led research, strong international scientific collaboration, as well as better consideration for research findings in policy adoption. However, these outcomes and impacts are for the moment only foreseen, and, at the time of the evaluation, SACIDS was still in the process of implementing changes at the institutional level and produce concrete outputs in the participating countries.

Measured or Estimated Outputs of SACIDS

At the time of this evaluation, SACIDS was still in early stages of program development; it has a long-term planning horizon and wants to continue building capacity for many years to come. Consequently, the timeframe to achieve outcomes and socioeconomic impacts as illustrated in **Figure 5** do not fall within this first phase of SACIDS but remain open to achievements in the future. Nevertheless, SACIDS produced a broad range of

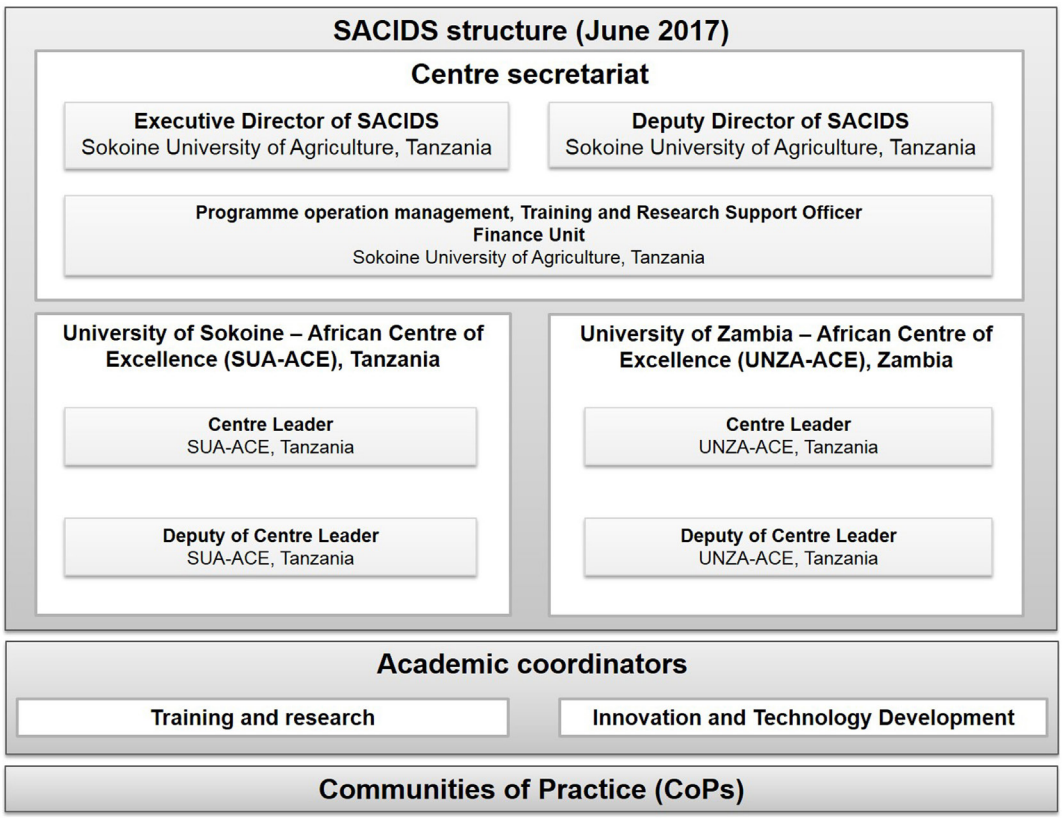

FIGURE 3 | Southern African Centre for Infectious Disease Surveillance (SACIDS)' structural organization at the regional level.

outputs over the past 9 years. The key milestones put in place by SACIDS are presented for the main SACIDS' objectives (**Table 1**), namely, enhancing BQM, enhancing ICT to support learning and disease surveillance systems, enhancing skills through taught and distance-learning programs, and enhancing skills through taught and distance-learning programs. The data used for developing **Table 1** were extracted from yearly progress reports produced by SACIDS for the Wellcome Trust foundation.

Evaluation of the OHness of SACIDS

OH Thinking

The overall OH thinking score was 0.56 with a wide diversity of scores for the different aspects, ranging from 0.4 for system features and targets as well as perspectives and TOC factors, to 1 for its perceived integrated approach of health (**Figure 6**).

OH Planning

The overall OH planning score was 0.8 with some variation across scores for the different aspects, ranging from 0.4 for Objective 2, i.e., *enhance BQM*, to 1 for Objective 5, i.e., *enhance skills through research apprenticeships* (**Figure 7**). Objective 1 was not scored because of a lack of information for this objective.

OH Working

The overall OH working score was 0.6 with some variation across scores for the different aspects, ranging from 0.4 for broadness of initiative and collaboration, respectively, to 0.7 for cultural and social balance as well as transdisciplinary balance (**Figure 8**).

Sharing Infrastructure

The overall score for sharing information and data was 0.2 with little variation across scores for the different aspects, ranging from 0.2 for institutional memory/resilience to 0.4 for methods and results sharing (**Figure 9**).

Learning Infrastructure

The overall OH learning score was 0.74 with very balanced scores of either 0.7 or 0.8 for all aspects considered (**Figure 10**).

Systemic Organization

The overall score for the systemic organization in SACIDS was 0.8 with some variation across scores for the different aspects, ranging from 0.7 for social and leadership structures and skills as well as competence, to 1 for focus and innovation (**Figure 11**).

OH Index

Figure 12 depicts OH thinking, planning, and working opposed to learning infrastructures, sharing infrastructure, and systemic organization. The operational aspects on the left of the diagonal are opposed to the infrastructure on the right. Apart from a low

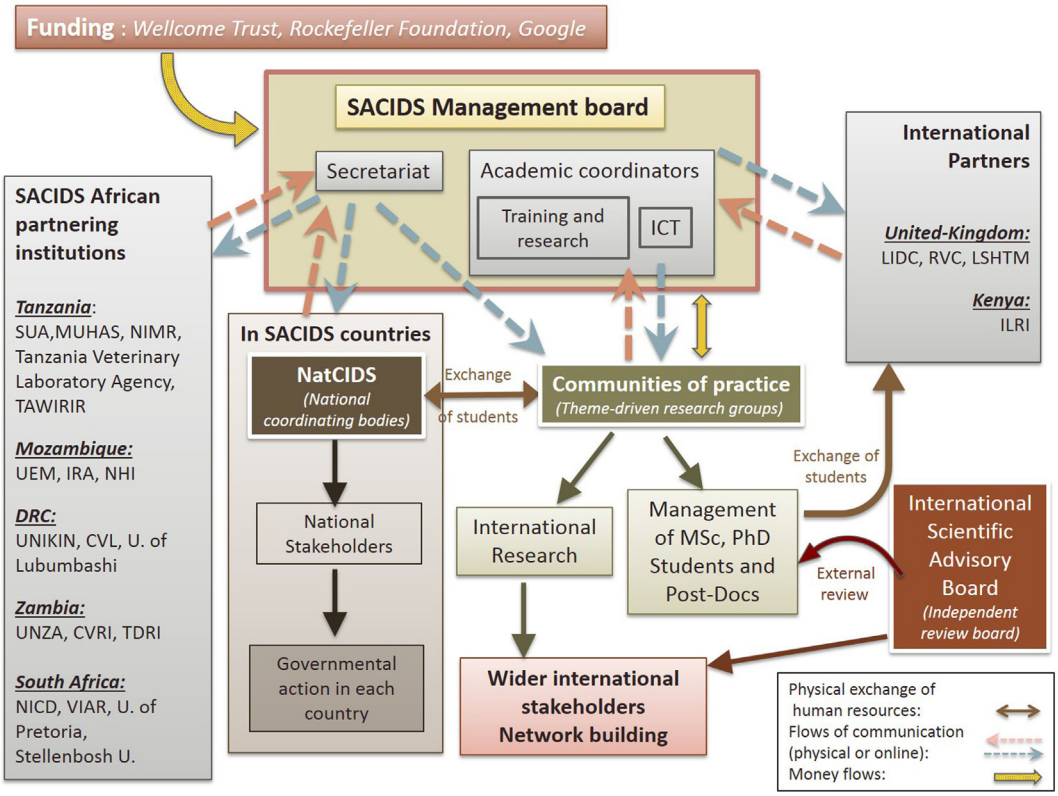

FIGURE 4 | Interactions between Southern African Centre for Infectious Disease Surveillance (SACIDS)' internal and external bodies. Abbreviations: SUA, Sokoine University of Agriculture; MUHAS, Muhimbili University of Health and Allied Sciences; NIMR, National Institute for Medical Research; TAWIRI, Tanzania Wildlife Research Institute; UEM, Eduardo Mondlane University; IRA, Institute of Agricultural Research; NHI, National Health Institute; UNIKIN, University of Kinshasa; CVL, Central Veterinary Laboratory; UNZA, University of Zambia; CVRI, Central Veterinary Research Institute; TDRI, Tropical Disease Research Institute; NICD, National Institute for Communicable Diseases; VIAR, Veterinary Institute of the Agricultural Research Council; LIDC, London International Development Centre; RVC, Royal Veterinary College; LSHTM, London School of Hygiene and Tropical Medicine; ILRI, International Livestock Research Institute; U., University.

sharing score, the two sides appear to be quite balanced. The OHI calculated was 0.359, and the OHR was 1.495.

Pros and Cons in the Implementation of the Initiative

Southern African Centre for Infectious Disease Surveillance program participants stated that the main advantage of the program was its great innovative energy in a difficult landscape dominated by poor infrastructure and its ability to create awareness for OH and enthuse people for the concept. Another major positive observation was SACIDS ability to train a range of people in OH thinking and working who can be local enablers and have the skills to facilitate progress and development. They were described to be the people who understand that changes are necessary and can act as local champions to drive OH research, capacity building, and development considering the important pillars of OH.

The main shortcoming described by various SACIDS members was the imbalance across the countries involved in the South. Several people commented on the success of SACIDS in Tanzania and to some extent in Zambia and South Africa, but the DRC and Mozambique seemed to have been left behind in the process and struggled to make the same progress as other countries. Other points of criticisms raised related to a lack of data sharing, unequal allocation of resources, top-down management structures, and limited horizontal collaboration.

DISCUSSION

Discussion of Evaluation Methodology

The evaluation and data collection process were well received by SACIDS participants. Both the SACIDS management and the secretariat were forthcoming in the engagement of respondents and supportive of the evaluation. All participants interviewed shared information, feedback, and opinions generously and appeared to answer questions honestly and trustfully. However, it was difficult to engage with more junior researchers in SACIDS, as they were busy with their projects or did not fulfill the inclusion criteria. The support of the SACIDS Executive Director was crucial in engaging SACIDS members and maximizing participation. Thus, the study has benefited from good representation of opinions across all SACIDS countries, apart from South Africa

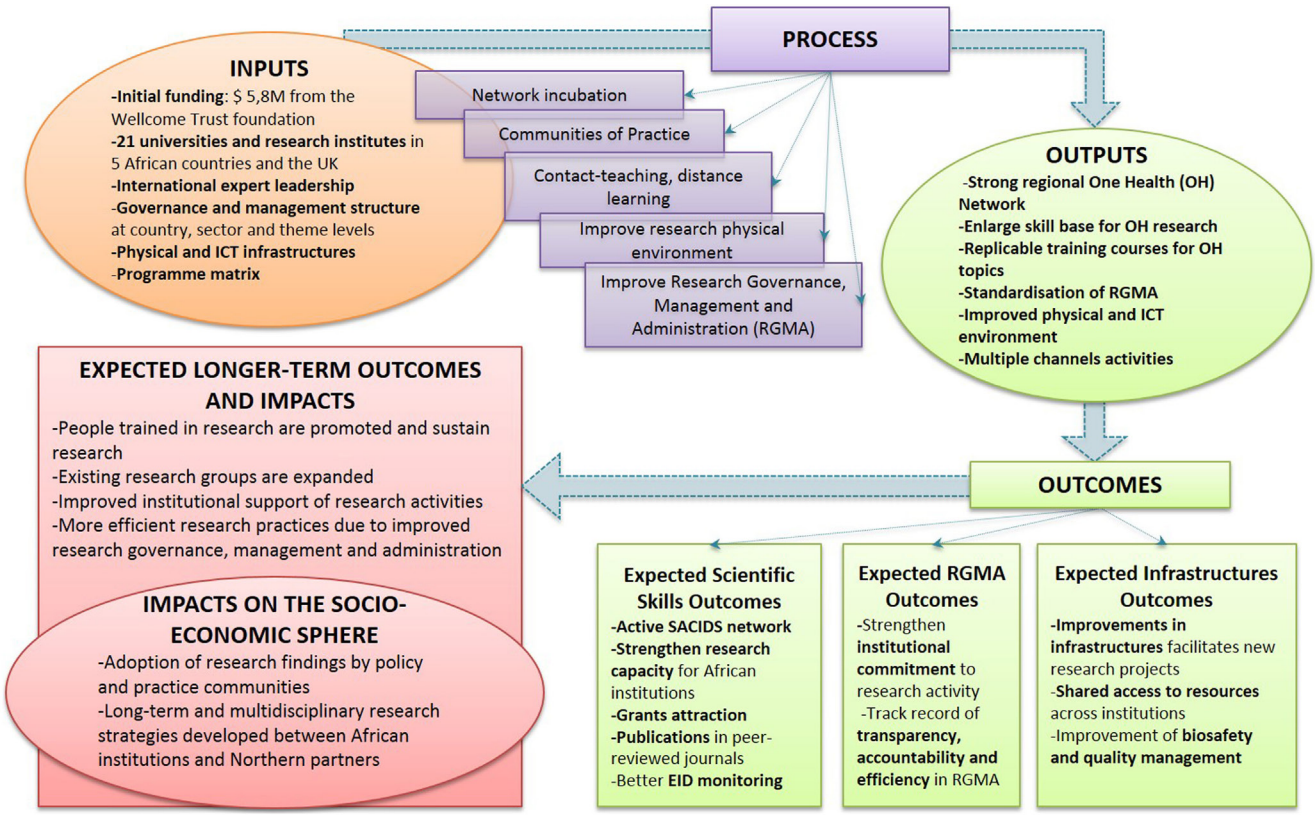

FIGURE 5 | Theory of change of the Southern African Centre for Infectious Disease Surveillance.

for which we were not able to arrange an interview within the available time frame.

Given that this was an external evaluation, the collation of documents, document review, preparation of questionnaires, and interviews were time-consuming activities. The complete question guide for the personal interviews was too long and too detailed to apply in full for all respondents. The interviewers therefore needed some flexibility in the way the questions were selected and asked, according to the specific circumstances (in particular background, knowledge, and expertise) of the interviewee. If respondents did not have enough knowledge on a specific topic, the interviewers moved on to the next question. Where respondents had ample in-depth insights and knowledge, the interviewers allowed more time for their answers. Consequently, there was an imbalance in the time spent on individual questions per interview, but the interviewers made an effort to achieve an overall balance across all interviewees.

The systematic approach developed by NEOH allowed insights into a wide range of aspects in a structured way, which may otherwise have been missed. Interviewees volunteered a broad range of information to open questions, often reflecting on what was asked before providing in-depth answers. Often, people gave lengthy and detailed answers demonstrating their own experience, self-reflection, and opinion of the program. The semi-structured interview format was thus perceived to be beneficial, as it allowed the gathering of data that could not have been predetermined.

The evaluation was conducted primarily by the first and last authors, both of whom were external to SACIDS, although one assessor had collaborated with a SACIDS project previously. Consequently, there was no conflict of interest, and the assessors were able to conduct the study in an unbiased manner. The information shared was often based on personal experience and subjective impressions, but the approach to include a broad range of representatives from across SACIDS allowed to gain a comprehensive picture and a good understanding of the global functioning and processes of SACIDS. However, an even more detailed understanding of the theory of change, the SACIDS operations and some of the individual concerns reported could have been gained by using participatory approaches with representatives from all SACIDS institutions. Due to time and budgetary constraints, this was not feasible but would have provided further information on commonalities and differences in the vision and the implementation of SACIDS. The collection of such data could be considered during one of the SACIDS annual meetings in the future.

Finally, it was observed that the evaluation at the program level may not have captured some of the more integrated and transdisciplinary endeavors of single research projects. This indicates a methodological shortcoming of the NEOH framework for the

TABLE 1 | Southern African Centre for Infectious Disease Surveillance (SACIDS)' outputs by objective and year.

	Enhance biosafety and quality management (BQM)	Enhance information and communication technologies to support learning	Enhance skills through taught and distance-learning programs	Enhance skills through research apprenticeships
2010		SACIDS website developed and running as www.sacids.org (accessed April 17, 2017)		
2011	Gap analysis of BQM at the participating university faculties/departments was conducted through quality auditing visits to participating institutions to establish their status, gaps, needs, and requirements for implementation of BQM systems	Linking of SACIDS Secretariat to the host institution's financial system A website and a Facebook page were created to improve the consortium's web presence	Launching MSc in One Health Molecular Biology (OHMB) took place with an intake of 8 SACIDS sponsored students (2 from Democratic Republic of Congo (DRC), 2 from Zambia, and 4 from Tanzania) First One Health (OH) Conference in Africa took place on the 14th and 15th July 2011 at the National Institute for Communicable Diseases (NICD)-NHLS, Johannesburg, South Africa	All Postdoctoral Research Fellows have been appointed to work on the following (disease) themes: Filoviruses, FMD, Plague, RVF, and TB
2012	Nomination of biosafety focal points for participating universities in the four countries (DRC, Mozambique, Tanzania, and Zambia)	Setup of videoconference equipment at Sokoine University of Agriculture (SUA), to facilitate online lectures Setup of high availability server environment for hosting e-learning software Deployment of a Google App implementation to assist students and SACIDS staff in document sharing and other online activities	Launching of the MSc One Health Analytical Epidemiology (OHAE) at UNZA was done. Twelve students were admitted by the University to the course OH curriculum workshop between the Royal Veterinary College, London School of Hygiene and Tropical Medicine (LSHTM) and SACIDS was held at the London International Development Centre (LIDC) on second April 2012 The First SACIDS Summer School 20–24th August 2012, SUA. This was the first One Health Summer School in Africa was jointly organized by SACIDS and LIDC	
2013		Two pilot e-learning systems were designed and deployed; custom made and open source (Moodle) Design, development, and deployment of a secretariat wide Intranet system as a tool to facilitate communication between and/or within the secretariat to improve data sharing capabilities and overall knowledge base	Second SACIDS Summer School Report of 20–24th August 2013, SUA	Research apprentices and their African and UK supervisors met on 14 April 2013 in Arusha for progress review, assessment of protocols and work plan development Six PhD students attended various transferable skill courses from 9th January to 8th February 2013 at the LSHTM
2014	Three mobile BSL-3 units for DRC (University of Kinshasa), Mozambique (Eduardo Mondlane University) and Tanzania (SUA) have been purchased to enhance biosafety for the diagnosis of and research on highly infectious diseases	Deployment of videoconference facility that assists students and research apprenticeships to virtual interaction with the supervisors and attend courses	Course modularization: modularization of MSc OHAE, modules for 7 courses have been written and finalized Third One Health Summer School August 25–30th 2014, SUA	The SACIDS community of practice (CoP) Leaders Meeting was held at the National Institute of Communicable Diseases of the National Health Laboratory Service (NICD-NHLS), Johannesburg, South Africa from 30th to 31st January 2014
2015			The modularization of OHMB Course at SUA has been completed	The molecular biology platform at SUA is in place Novel FMDV genotypes/topotypes have been identified Development of monoclonal antibody based lateral flow diagnostics for Ebola and Marburg diseases Discovery of two lineages of Peste des Petits Ruminants (PPR) Virus and of African swine fever co-circulating Discovery of novel topotype of *Mycobacteria bovis* in Serengeti ecosystem Finding of increasing AMR prevalence in southern and East Africa

(*Continued*)

TABLE 1 | Continued

	Enhance biosafety and quality management (BQM)	Enhance information and communication technologies to support learning	Enhance skills through taught and distance-learning programs	Enhance skills through research apprenticeships
2016		A new data collection tool (AfyaData) has been developed under a leveraged project funded project by Skoll Global Threat Fund, which is being used as disease surveillance tool. This tool is an improved version of previous tools and will also be used for data collection for various research activities	OHMB: a total of 36 students were enrolled for MSc OHMB since year 2010. Out of the 36 students, 3 were discontinued from their studies OHAE: a total of 26 students were enrolled for MSc OHAE since year 2011. Only two OHAE have not graduated	A total of 13 postdocs were recruited since 2010. Eight have completed their Postdoctoral Research and five are in their final stages of research work A total of 10 Res MSc were recruited. Seven have graduated

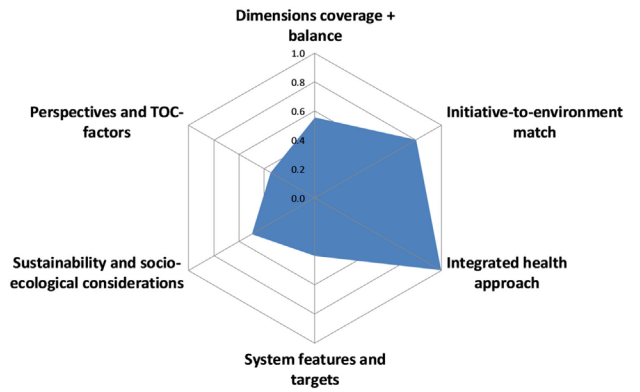

FIGURE 6 | Assessment of One Health thinking in the Southern African Centre for Infectious Disease Surveillance.

evaluation of a large program aimed at capacity building. One of the respondents mentioned that there are fewer divisions between the different disciplines in Africa driven by "living in a disease rich environment, the economics, the malnutrition, the poverty and tough life in general" (respondent observation). Thus, researchers often have advanced skills working within communities, know alternatives to conventional medicine, and are more flexible to adapt to changing circumstances. These issues were poorly captured during the data collection for this evaluation.

Because of resource limitations, this study only listed outputs in relation to the theory of change but did not investigate outcomes achieved and their classification into disciplinary, interdisciplinary, or OH outcomes. At the level of the output, the OH concept is difficult to distil; interdisciplinarity is more likely to be noticeable at the level of the outcomes. In future research, efforts should be placed on the assessment of the outcomes achieved and the impact they may provoke.

Discussion of Results

This part refers to the OHness scores reported in the results section and the associated information and justification in Table S3 in Supplementary Material. SACIDS was a very ambitious and visionary program driven by the need to fill existing gaps in surveillance capacity of endemic, exotic, and emerging diseases in Southern African countries. Coordinating a program across different countries, sectors, and disciplines with different cultures and context comes with many challenges. The program planning was based on a needs assessment of surveillance capacity, and the acknowledgment that an integrated approach to health was called for. From the outset, SACIDS aimed to be an African-led initiative that would produce capacity to address issues of societal, environmental, economic, and health concerns through an interdisciplinary, OH approach. The program was complimented by many respondents for its ambition, the changes achieved and the effectiveness in bringing together disciplines and sectors in a shared program.

This evaluation was conducted at the level of the SACIDS program and not the individual projects. Consequently, the results do not report on the finer detail related to diseases, associated technical capacities, and field work that would be found at the level of research projects within the CoPs.

For most OHness dimensions, apart from information and data sharing infrastructure, SACIDS scored between 0.6 and 0.8.

With regards to OH working, SACIDS presented an effective and productive management structure that clearly addressed issues in the context it operates tackling underlying disconnect and silos among different sectors. Its setup spans different countries, sectors, and various types of institutions with the aim to build capacity in an integrated manner. An external feedback mechanism from the International Review Board promotes reflection and action for change when needed. SACIDS actors have proven to be flexible in their working and are able to react to changing circumstances, as observed by one interviewee: *The director is able to change his thinking and his staff seem able to do the same*. Despite the flexibility observed, there were some shortcomings in that the working was perceived to be rather hierarchical with little engagement of junior people in decision-making and no perceptible involvement of grass-root organization or communities in the coordination and management of the program.

While the teams were described to work very well within the CoPs, they existed as clear units within institutional teams with little interaction with other disciplines, although increasing interaction between the human and veterinary teams was reported to be developing. Increased interaction could be nurtured by having more dedicated staff members that would actively link members and encourage exchange and team building in an integrated way. Currently, there is only one person

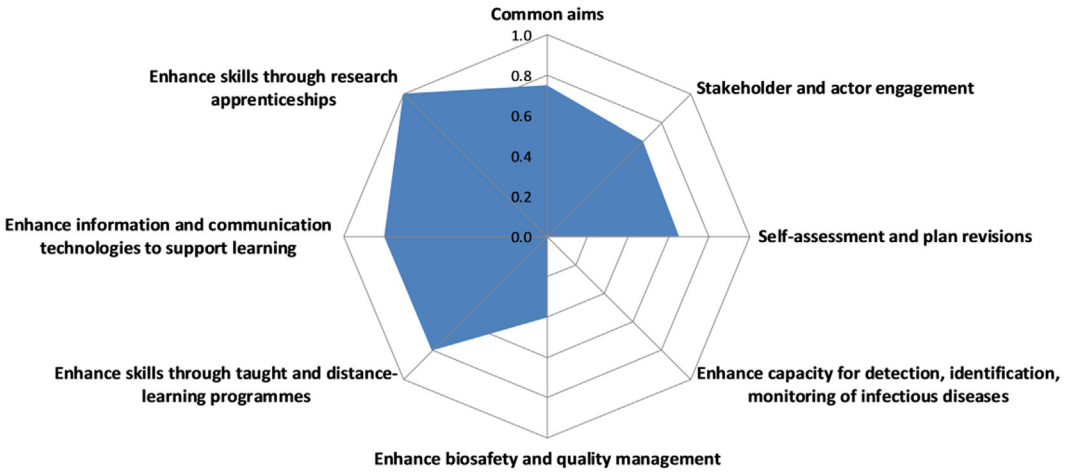

FIGURE 7 | Assessment of One Health planning in the Southern African Centre for Infectious Disease Surveillance.

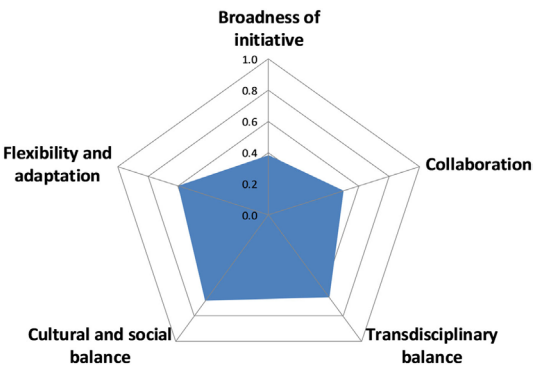

FIGURE 8 | Assessment of One Health working in the Southern African Centre for Infectious Disease Surveillance.

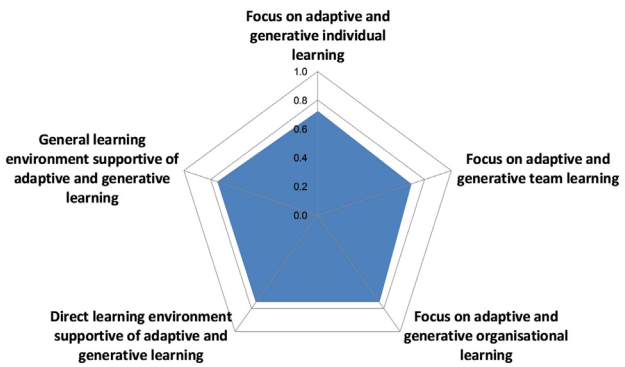

FIGURE 10 | Assessment of learning infrastructure in the Southern African Centre for Infectious Disease Surveillance.

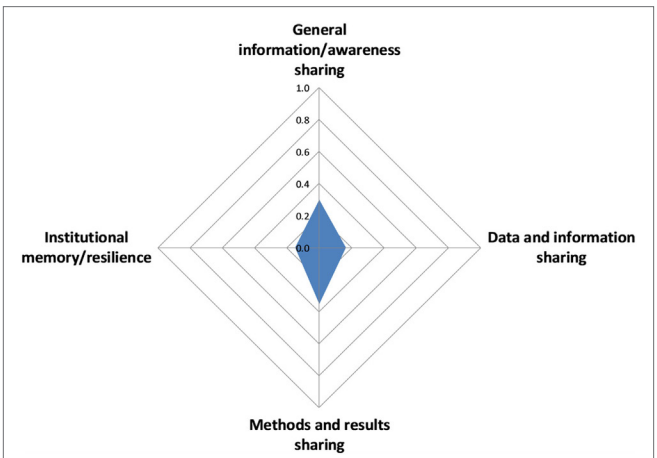

FIGURE 9 | Assessment of information and data sharing in the Southern African Centre for Infectious Disease Surveillance.

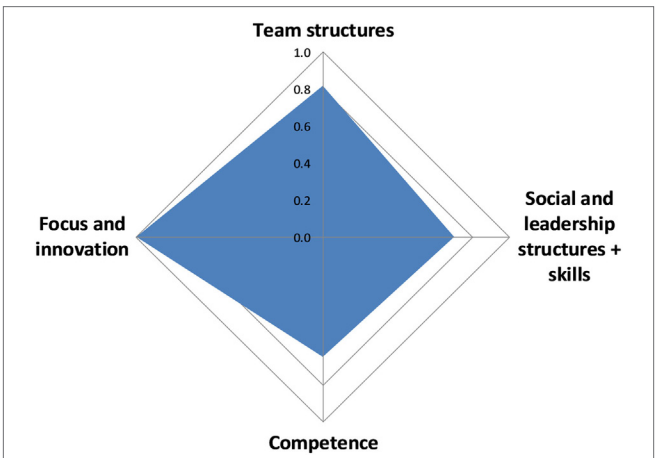

FIGURE 11 | Assessment of systemic organization in the Southern African Centre for Infectious Disease Surveillance.

FIGURE 12 | One Health Index of the Southern African Centre for Infectious Disease Surveillance.

acting as the main coordinator between SACIDS and consortium partners. This role could also extend to linking more effectively with Northern partners and promoting a professional collaboration based on equality. The current partnership was perceived by some to be unbalanced with behavior of superiority instead of equality. Nonetheless, the model of joint supervision with input from Northern partners was highly appreciated and perceived to be effective and beneficial.

The Southern African Centre for Infectious Disease Surveillance earned praise for its recruitment process of high academic quality postgraduate students. It was suggested to use a similar recruitment process within other SACIDS functions with the aim to increase the breadth of people from different countries, cultures, and expertise. In addition, this would enhance the transdisciplinary skills in the program (or as one respondent put it: *allow SACIDS to have a cocktail of ideas and understandings*) and reduce the bias toward selection from Tanzania. This could be achieved by promoting self-reflection and feedback in SACIDS. The current structures were found to be well established and working well with regards the implementation of the program and the technical considerations, but there seemed to be little input into management and organizational structures across all SACIDS members. Because transdisciplinarity is based on broad engagement of actors and stakeholders, such a move could help to create more ownership and networking. The respondents made several useful recommendations during the interviews on how the SACIDS organization could be improved. They included expanding of SACIDS to allow new institutions and people to join the program; a more communicative, engaging, and disseminative secretariat that would actively link all partners; a clear definition of roles and responsibilities for everybody involved; and promotion of a more participatory approach that would help establish consensus from a broad range of participants including people on the ground (as mentioned by one respondent *We need to get a degree of democracy within SACIDS. The ownership has to go to the people*). These examples show that there are several suggestions for change available in the consortium, and the program may benefit from harvesting the creative potential in a participatory way.

The lowest score overall was recorded for information and data sharing (score of 0.2). Several concerns were voiced relating to this issue. Although one of SACIDS' primary aims was to create a trans-national network to enable transdisciplinary collaboration between actors engaged in the control of infectious diseases, there is a lack of resources attributed to information and data sharing and the creation of institutional memory. Each CoP team is in charge of data quality, with combined responsibility from the supervisor and the team. To date, there is no student induction program, which means that the supervisor's research experience is relied on to ensure data quality, rather than a systematic approach, which can lead to variability in data quality between students and between projects. While there are some structured internal sharing mechanisms and established ways of communication between CoPs, SACIDS lacks a platform where data could be shared and made available among project partners in a standardized format that would reduce risks of duplication. In addition, there are no formal institutional arrangements that would support data and information sharing in a systematic way. Consequently, there is real risk that institutional memory may be lost if knowledgeable SACIDS members move to new jobs without passing on their knowledge to others. Currently, the program only has a repository for results (e.g., theses, publications) but could benefit from a common database or documentation that stipulates how data must be checked, prepared, and presented for sharing purposes. While the establishment of such a database can be resource and time consuming, the establishment of a shared archive may be more achievable. With such a resource, all SACIDS partners would have access to the outputs and would not need to go through the secretariat if they wanted to access certain information. A "read-only" database would minimize the risk of mistakenly deleting items from the repository or changing them. A benefit of such a database could be to make educational materials more widely available so that partners could use them for teaching and training purposes. Some respondents observed that SACIDS had contributed greatly to sharing of information between individuals or groups by enabling better cooperation and collaboration between them, but that there was large individual variability and many people or institutions were still reluctant to share data with others. This may be an indication of the tensions that may exist between individual interests for (academic) progress and a need to share information and data for the purpose of a common good, which should be an underlying principle of a program like SACIDS. Given the importance of data and information sharing in transdisciplinary programs and the efficiency loss associated with insufficient institutional memory, SACIDS may want to consider making an investment into formalizing and promoting such processes.

At the regional management level, certain processes were reportedly sluggish because of delays in implementation, substandard logistical processes, and unclear lines of command. Consequently, this affected the performance of researchers and projects, being unable to proceed due to delays in accessing the required materials. Previous evaluations of SACIDS already reported challenges related to the distribution of resources (12). Coupled with the perception that there is a bias in funds, staffing, and activity toward Tanzania, some participants suggested decentralizing some of the secretariat's activities and funding, to allow some national level management and facilitate resource allocation at country level. Because SACIDS only pays the secretariat and the Executive Director, some of the other SACIDS participants with in-kind contributions feel that they are undervalued for the time invested. Consequently, there was a call to generate more funding and create more paid positions across all SACIDS countries in a transparent way with the aim to institutionalize the program and reduce bureaucratic burden on SACIDS members.

The unequal success in the implementation of postgraduate programs across SACIDS countries can partly be explained by different institutional capacities at the start of the program. Unlike Zambia and Tanzania, DRC and Mozambique did not have any PhD programs in place before the start of SACIDS, and the implementation of such courses required more time and effort than in the other countries. In addition, Zambia and Tanzania institutions benefit from being designated as "African Centres of Excellence" by the World Bank, which reflects the high quality of research and educational programs in place in these countries. SACIDS seems aware of the necessity to address the need for better capacity building in DRC and Mozambique and is prioritizing this issue as a major objective for the next phase of the program.

Because this evaluation was conducted at a stage, where the program development had mainly focused on its establishment (e.g., network, training and capacity building, development of infrastructure and processes), there is currently a disconnect between the rationale and motivation for SACIDS and actual outcomes and impact. Consequently, there is no assessment of improvements in attributes that define infectious disease surveillance, such as performance or functional attributes of surveillance or their OH integration. To facilitate future program success and achievement of outcomes and impact, it is recommended that SACIDS develops measurable indicators in line with their theory of change and implements relevant data collection and evaluation activities. Such information will not only be important for the management of SACIDS but also enhance credibility among (future) funders.

Across the board, people perceived SACIDS to be a very positive and effective African-led initiative that helps bring together the disciplines of OH and allows important issues in the region to be addressed and to bridge funding gaps. Nowadays, there is a common understanding that we need both a quantitative and qualitative approach to understand, prevent, and control infectious diseases. This cannot be done with classical veterinary interventions alone, such as vaccination or other technical measures, but it is important to consider other perspectives as well in a systems approach. The focus of SACIDS has been primarily on technical capacity building and the shortcomings relating to environmental disciplines and the social sciences, which it aims to address, are acknowledged and will be addressed in the next phase of the program. SACIDS' vision and mission are important endeavors for capacity building in the region and its approach has the potential to promote progress and development. However, this evaluation has identified several issues in management, delivery, and OH integration that the program may want to address to promote success in the long term and realize the outcomes and impact envisaged in an efficient and effective manner. It is recommend that SACIDS continues to look at how the technical progress can be embedded in social aspects, local communities' practices and behaviors. Consequently, it may be important to look at other measures that may lead to changes in infrastructure, such as sewage and water systems, land management policies, and education. A prioritization approach based on participatory engagement with a wider representation of sectors and disciplines from all strata of society could inform a process of discussing strategic directions and grant applications for the future.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the ethics committee of the Royal Veterinary College with written or oral informed consent from all subjects. All subjects gave informed consent in accordance with the Declaration of Helsinki. Ethical approval for the interviews and the online survey was sought from the Royal Veterinary College and was granted by its Social Sciences Research Ethical Review Board, number URN SR2017-1002.

AUTHOR CONTRIBUTIONS

MH and BH conceptualized the study with guidance from SR and SS. MH, KQ and BH were responsible for data collection with EK facilitating access to data, reports, and networks. MH and BH had primary responsibility for data analysis and manuscript writing with all coauthors giving feedback and input.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at http://www.frontiersin.org/articles/10.3389/fvets.2018.00033/full#supplementary-material.

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Control of Cattle Ticks and Tick-Borne Diseases by Acaricide in Southern Province of Zambia: A Retrospective Evaluation of Animal Health Measures According to Current One Health Concepts

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One health thinking for health interventions is increasingly being used to capture previously unseen stakeholders and impacts across people, animals, and the environment. The Network for One Health Evaluation (NEOH) proposes a systems-based framework to quantitatively assess integration and highlight the added value (theory of change) that this approach will bring to a project. This case study will retrospectively evaluate the pioneering use of a One Health (OH) approach during an international collaboration (satellite project to tackle production losses due to tick-borne disease in cattle in Southern Zambia in late 1980s). The objective of the evaluation is twofold: retrospective evaluation the OH-ness of the satellite project and identification of costs and benefits. Data for evaluation was recovered from publications, project documents, and witness interviews. A mixed qualitative and quantitative evaluation was undertaken. In this case study, a transdisciplinary approach allowed for the identification of a serious public health risk arising from the unexpected reuse of chemical containers by the local public against advice. Should this pioneering project not have been completed then it is assumed this behavior could have had a large impact on public wellbeing and ultimately reduced regional productivity and compromised welfare. From the economic evaluation, the costs of implementing this OH approach, helping to avoid harm, were small in comparison to overall project costs. The overall OH Index was 0.34. The satellite project demonstrated good OH operations by managing to incorporate the input across multiple dimensions but was slightly weaker on OH infrastructures (OH Ratio = 1.20). These quantitative results can be used in the initial validation and benchmarking of this novel framework. Limitations of the evaluation were mainly a lack of data due to the length of time since project completion and a lack of formal monitoring of program impact. In future health strategy development and execution, routine monitoring and evaluation from an OH perspective (by utilizing the framework proposed by NEOH), could prove valuable or used as a tool for retrospective evaluation of existing policies.

Keywords: public health, environmental impact, economic evaluation, OH index, one health

INTRODUCTION

Within global health, there is a move toward more integrated planning and delivery approaches that can yield more efficient, effective, and equal outcomes than traditionally siloed approaches to health challenges. The use of One Health thinking to identify stakeholders and capture impacts across people, plants, animals, and the environment has the potential to avoid harm and identify benefits otherwise unseen. The Network for One Health Evaluation (NEOH) proposes a novel evidence-based framework to quantitatively assess integration and highlight the unique benefits (theory of change) that this approach will bring to a project (1, 2).

In 1987, Italian development and research institutions (Ministry of Foreign Affairs, Development Cooperation Office and the *Istituto Superiore di Sanità*, Roma: ISS, Rome) responded to an emergency call of the Zambian government (Ministry of Agriculture, Department of Veterinary Services) for help to control deaths and production losses in cattle caused by *Theileria parva* infection, also known as Malignant Theileriosis, transmitted by *Rhipicephalus appendiculatus* ticks. This Animal Health Programme (AHP) took place in the Southern Province of the country and continued until 1992, but here we concentrate on a 2-year (1988–1989) satellite project (One Health Initiative, OHI). The OHI assessed the implications of the AHP for other stakeholders and implemented public health education and risk mitigation activities in support of the main project. The information and data reported in this paper, concerning the activities of the AHP and OHI are based on the following publications and project reports by Ghirotti et al. (3, 4), De Meneghi et al. (5–7), Camoni et al. (8), Scorziello et al. (9), and to which reference will be made throughout the text.

The Animal Health Programme

The expected outcome of the AHP was to reduce tick-borne diseases (TBD) in cattle, in particular Theileriosis, to avoid losses and increase cattle productivity. The expected impact was to increase animal welfare and stabilize or increase farmers' income. The AHP was conceived as a typical animal health intervention meaning that animal health was the focus of the emergency project with no other initial considerations made for other dimensions of the intervention (**Figure 1**).

The AHP required farmers to attend communal dipping tanks (DTs) with their cattle on a weekly basis during peak tick season (i.e., November–May, 7 months), according to a strategic dipping regime. Approximately 530,000 cattle (45% of the national herd) attended 130 communal dip-tanks in Southern Province over the study period. Cattle would approach the dip-tank in single file along a race and make a small jump into the tank so that head and body would be briefly but completely submerged in an acaricide solution. Cattle would exit into a draining area where excess fluid would drain back into the tank. The dipping liquid contained an organophosphate (OP; in this case, chlorphenfinvos) as the active ingredient against ticks. The dipping process thus required transport, stocking, and handling of OP by dip-tank operators (DTOs). Stocks of concentrated dip fluid were stored in a main central storehouse, and in small buildings at each Veterinary

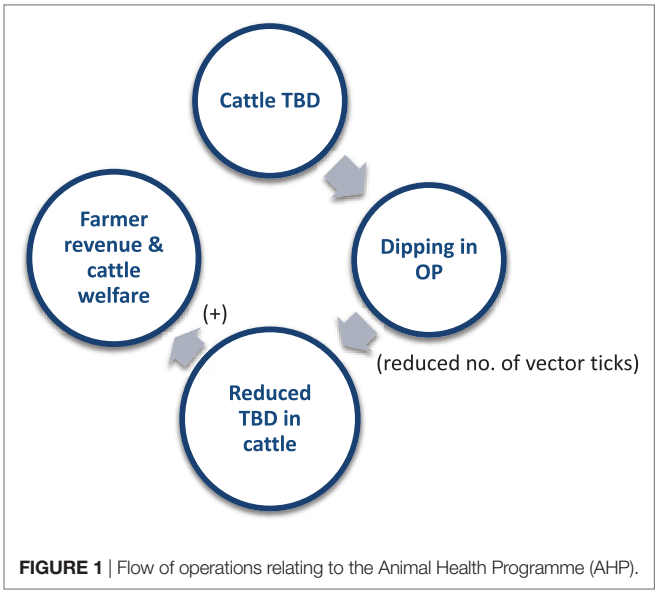

FIGURE 1 | Flow of operations relating to the Animal Health Programme (AHP).

District Office in Southern Province, and transported in 5 l canisters from district storage points to the dip-tanks. Often this was by hand, bicycle, or motorbike. In order to prepare the fluid for the dip-tank, concentrated fluid from the canister had to be diluted with water according to the manufacturer's instructions. At the end of each season the dip-tanks were emptied of fluid (and occasionally this was also performed during the season if the tank became too contaminated). Existing disposal procedures were to discard fluid directly onto fallow land or *via* a decantation pit (where available) to allow degradation of active ingredients. Operation and maintenance of dip-tanks, preparation of dip-tank fluid, and provision of DTOs fell under the responsibility of the Zambian authorities. All staffing, testing, and transport costs associated with the satellite project were covered by Italian sources. Farmers paid a small fee toward cost of treating their cattle on a cost-recovery basis (approximately Zambian Kwacha 50 cents per dip, 0.04 USD in 1988).

The Acaricide Active Ingredient and Potential Health Risks

The OP based acaricide used in the AHP was Steladone 300 EC (Ciba-Geigy) and provided by the Italian Cooperation Programme, who also offered technical assistance. OPs have been successfully used to control vectors of animal disease and plant pests elsewhere. The active ingredient used, Chlorfenvinphos, acts as a cholinesterase inhibitor in ticks but this also occurs in humans, affecting both the peripheral and central nervous system. Toxicity may occur following direct contact, ingestion, or inhalation of fumes (10). The use of this and other OPs in developing countries worldwide had been associated with 3 million acute poisoning cases per year (at the time of the original study), including 220,000 yearly fatalities (11). Risks associated with long-term exposure to small doses are also expected to have some human health impacts but there is little existing literature and risks are largely un-quantified in developing nations (12).

Residues of OPs are expected in soils, water, and animal products such as milk, and maximum limits for residues have been set by the Codex Alimentarius (13). Signs of acute toxicity can range from mild to severe. Severe intoxication can result in generalized convulsions and death through respiratory or cardiac failure but mild intoxication may be difficult to diagnose. Signs of mild intoxication include nausea, headache, miosis, vomiting, weakness, and giddiness (10).

The highest risk of toxicity occurred when staff were handling concentrated acaricide fluid or during storage in poorly ventilated facilities. There was also a smaller risk associated with exposure to the diluted dip-tank solution, especially as the dipping process often results in large amounts of displaced fluid around the tank onto surrounding staff or from the risk of staff accidentally falling into the tank. Reducing the risk of intoxication was achieved through limiting direct contact, inhalation or ingestion of concentrated acaricide by the use of personal protective equipment (PPE), and practice of safe operating procedures for DTOs. An antidote (atropine) can be administered for incidents of acute poisoning, and this was distributed by the satellite project (OHI) to the district veterinary offices, local health-care centers, and district hospitals. There were two recorded incidences where people fell into dip-tanks during the study period, but swift action to clean the acaricide off prevented illness (9).

The Satellite Project (One Health Intervention: OHI)

The implementation of the AHP had effects beyond those directly expected from the dipping of cattle in OPs. As mentioned above, the dipping process requires that fluids used to treat animals be normally disposed onto fallow land at the end of the dipping period, but OPs can persist in soil for up to 30 weeks. Thus, it was assumed the disposal method adopted in the dipping process negatively impacted environmental health and could potentially be a source of contamination of ground water, agriculture, or wildlife. The OHI provided instructions to DTO and stakeholders to implement a decantation pit step in the disposal procedure where toxic substances could degrade before disposal onto fallow land (7, 9).

A second aspect concerned the disposal of OP canisters. The initial agreement with DTOs was to give empty canisters to the district offices. However, local community members were permitted to reuse the canisters to store fuel (i.e., kerosene, petrol, lubricant oil). In spite of recommendations, it was noted that containers were sometimes being used also to store consumables. Toxicology testing showed that even after repeated washing, consumables such as water stored in the canisters, had unsafe residue limits and may be putting the public at risk of acute toxicity. The reuse of these canisters for consumables was an unexpected outcome of the AHP.

Additionally, instructions to farmers not to use milk produced by cattle for at least 12 h after dipping were commonly disregarded. Milk testing showed unsafe residue limits for human consumption until 18–24 h post-dipping and withdrawal times for milk for animal consumption, mainly suckling calves, were only deemed safe 5 h post-dipping (8).

Finally, it was noted by the dipping process managers that people (DTOs and farmers) view the risk to their personal health from exposure to acaricide as low. This was suggested to arise from the perception that the acaricide is a form of "medicine" and that the causal pathway between exposure and illness is not always obvious. Alongside a lack of awareness of the risks from exposure, the (initial) unavailability of PPE was also thought to be a barrier for practice of safe behaviors by DTOs.

Education campaign messages used a variety of multimedia materials, including leaflets, community meetings and radio and TV programs, in particular a radio drama aiming to raise awareness of exposure risks from post-dipping milk consumption and acaricide canister reuse. Means were adapted for use in local, regional, and national education campaigns.

This case study aims to demonstrate how typical intervention strategies for animal health may result in unexpected social impacts due to the insufficient or poor consideration of intervention complexity in the specific social context, e.g., local cultural attitudes to the acaricide and canister reuse, exposing local operators, people, and the environment to increased risk of poisoning and pollution. In this respect, an *ex post* re-consideration of the satellite project may show features of the current OH approach, that we want to evaluate.

The objective of the evaluation is twofold:

(a) retrospective evaluation of the OH-ness of the satellite project
(b) identification of the costs and benefits of the satellite project, and their quantification, where possible with the data available.

This will be a mixed qualitative and quantitative evaluation, based on the reconstruction of the cost of the satellite project and a quantitative consideration of the benefits for the population and the on-site health management system.

The objective of the evaluation can be structured according to the following evaluation questions:

a. what is the degree of OH-ness of the satellite project according to the main components of OH outlined in the NEOH framework?
b. did the use of an OH approach to an animal health and a veterinary public health intervention prove valuable over a siloed disciplinary approach (theory of change)?
c. what were the costs of the satellite project?
d. what were the benefits?

MATERIALS AND METHODS

OH-ness Evaluation: Systems Map, One Health Index, and One Health Ratio (OHR)

The evaluation method follows guidelines outlined in the journal's introductory paper (1). The first aspect for the evaluation was the identification of the system, its dimensions, boundaries, and potentially relevant interacting or independent components. In this case study, the system includes the AHP and satellite project as a subsystem (including their functional links). The system also defines stakeholders as "any individual, group or

organization who may affect, be affected by, or perceive themselves to be affected by a decision or activity" and then a subgroup of actors "who act or take part" in the system. The dimensions characterize the system and may take place at different scales (e.g., the geographical dimension includes various levels of scale, from local to international). Dimensions also take account of the social context in which they operate (people, society, institutions) and their behavior in the context of OP use (including the related structure, infrastructure, and equipment). The sequence of inputs, outputs, outcomes, and impact pathways were plotted graphically in a logical framework. Outcome mapping was used in building the logical framework, grouping outcomes as disciplinary or interdisciplinary and sequential impacts as first or second order. The contribution of the OHI will be compared to the three pillars of sustainability: society, environment, and economy, such as interspecies equity, human welfare, and efficiency in this example. A theory of change was described from the added value the OHI contributed in the system.

Recovery of data from the satellite project for OH-ness evaluation was through publications, project documents still available, and witness interviews including contributions by one of the coauthors (Daniele De Meneghi) and colleagues formerly working in the AHP. These data were analyzed during the evaluation process in accordance with the recommendations and tools set out in the NEOH handbook.[1] Briefly, process evaluation was through semi-quantitative assessment under six major themes, split into operational aspects (thinking, planning, working) and infrastructure (learning, sharing, systemic organization). OH thinking explores the dimensions and scales within the system and the context-specific suitability of the OHI in matching these. OH planning assesses resource allocation and appropriateness and adaptability of plans to address the objectives of a transdisciplinary project. OH working focuses on the disciplinary diversity and placement of appropriate leadership and management to promote non-hierarchical relationships and transdisciplinary working within the team and for project outputs. In a similar line, systemic organization looks at the implementation of shared leadership and governance involving all stakeholders and engaging those from all to avoid a silo mentality. Evaluation of learning examines knowledge exchange infrastructure and how this supports learning within the system and in the broader environment. Finally, evaluation of sharing infrastructure looks to reward projects where there is facilitation for good quality data sharing, for example, where data are presented with recognition of potential bias; in a suitable format to allow merging of data from multiple sectors; and with appropriate measures to uphold confidentiality.

Scores were allocated following review of criteria relevant to each theme and compared to a context-specific benchmark as determined by the evaluator as appropriate to the project under review; where full realization of the ideal scenario was worth 1.0. The scores for each theme were plotted onto the spokes of a spider diagram to allow visualization of overall project integration and the balance between operational and infrastructure elements. As outlined in the introductory article by Rüegg at al., a quantitative overall One Health Index was calculated as a ratio of the area enclosed by the points when plotted onto the spider diagram to the area enclosed if all spokes were equal to 1, according to the following formula:

$$\text{OH Index} = \frac{\left[\begin{array}{c}(\text{ScP}\times\text{ScT})+(\text{ScL}\times\text{ScP})+(\text{ScL}\times\text{ScS})\\+(\text{ScO}\times\text{ScS})+(\text{ScW}\times\text{ScO})+(\text{ScT}\times\text{ScW})\end{array}\right]}{6},$$

where ScP is the score obtained in OH planning, ScL is the score obtained in learning infrastructure, ScS is the score from sharing infrastructure, ScO is the score from systemic organization, ScW is the score from OH working, and ScT is the score from OH thinking.

A comparison between the OH operations and infrastructure was made by dividing the area enclosed by the points associated with OH operations by that for the infrastructure, which gives the OHR:

$$\text{OHR}=\frac{\left(\frac{\text{ScO}\times\text{ScW}^2}{\text{ScO}+\text{ScW}}\right)+\left(\text{ScW}\times\text{ScT}\right)+\left(\text{ScT}\times\text{ScP}\right)+\left(\frac{\text{ScP}^2\times\text{ScL}}{\text{ScP}+\text{ScL}}\right)}{\left(\frac{\text{ScP}\times\text{ScL}^2}{\text{ScP}+\text{ScL}}\right)+\left(\text{ScL}\times\text{ScS}\right)+\left(\text{ScS}\times\text{ScO}\right)+\left(\frac{\text{ScO}^2\times\text{ScW}}{\text{ScO}+\text{ScW}}\right)}.$$

An external evaluator (Gabrielle Laing) consulted with the internal evaluator (Daniele De Meneghi) to compile the information for evaluation with guidance from Maurizio Aragrande and Massimo Canali. Stakeholders Dr. Maria Scorziello Biocca (MD, formerly at Ministry of Health as public health specialist seconded to the ISS Rome) and Dr. Prof. Silvana Diverio (DVM, former grantee of the *Istituto Italo-Africano*, now at the University of Perugia), assisted in data recovery and contributed to OH-ness scoring. Evaluation criteria were described by Gabrielle Laing and scoring for each question reviewed by Daniele De Meneghi, Maurizio Aragrande, and Massimo Canali. A fourth external evaluator (Sara Savic) was asked to review the scoring and criteria based on only the information presented in this paper.

Economic Evaluation

In order to measure interdisciplinary outcomes and translate evaluation findings in a transdisciplinary way (i.e., between disciplines and societal fields such as the private and public sector), it is desirable to use a common metric. In this instance, an economic evaluation was selected.

According to a consolidated and widely accepted definition, the full economic evaluation of an intervention requires the identification of its costs and outcomes and the comparison with the costs and outcomes of one or more alternative actions (being the situation without any intervention one of the possible alternatives). Partial economic evaluations are performed when one of those conditions is not fulfilled, i.e., only costs or only outcomes can be evaluated, or alternative solutions are not examined [about the distinction between full and partial economic evaluations, see Ref. (14–21)].

[1] Rüegg S, Häsler B, Zinsstag J. *A Handbook for Evaluation of One Health – Draft Version, November 2016.* (unpublished/under preparation).

For the satellite project, it was only possible to retrieve data on the expenditure of the intervention from the archives of the institutions concerned and from documentation provided by experts who participated in the project planning and implementation at different levels. Available data on the outcomes are incomplete as an *ex post* evaluation was not planned for this OHI, partly because of the emergency nature of the main AHP project and partly because it was not an ordinary practice for this type of project at that time. The time elapsed and the poor follow-up of the project also hindered the identification of such data within the framework of the current evaluation. This makes a comparison with costs and outcomes of alternative actions impossible.

This evaluation, therefore, reports the description of the expenditure and outputs of the satellite project, identifying the benefits to the population of the beneficiary country, based on the information presented and on estimations about acaricide use in the targeted DT stations.

RESULTS

Systems Map and Theory of Change

A systems map for the AHP and OHI, based on the elements outlined in the Section "Introduction" and in particular

- the technological specification of the dipping process and its aim,
- the social and physical environment of the process,
- the objective risks related to OP use,
- the practices actually adopted by the operators and the local population linked to DTs operations and OP handling and related material and facilities (storage facilities, empty canisters, the environment, etc.)

were used to draw the series of consequences (impact pathway) started by the AHP and shown by the logical framework in **Figure 2**.

The system includes both the AHP and the satellite project as the former involved or induced the latter, in the sense that the existence of the satellite project strictly depends on the implementation of the AHP, its limits, and unexpected consequences. System boundaries are determined by the considerations below:

(i) The fact that the AHP was targeted to a specific region of Zambia (Southern province) by a technical and political decision, exogenously established a geographical limit of the system. This decision formed an initial assumption for the next steps of the system identification process. Together with the dimension of the cattle herds treated (traditional livestock breeding system), these elements allowed for the identification of the main geographical, social, and physical dimensions (boundaries) of the system.

(ii) The dipping process was implemented within these boundaries, allowing for the identification of technological specifications and organization (e.g., the number of risk animals to be treated, the number, dimension, and location of DTs, period and frequency of treatment, dipping routine, use of inputs, etc.). DTs are the technological devices at the core of a process. They imply the use of inputs, the production of outputs, and a flow of actions and consequences (see above AHP process description), and they can be considered basic units of a system characterized by strategy (reducing or eliminating Theileriosis in cattle) and aims (increasing cattle productivity and farmers' revenue). Starting from these elementary units, risk factors can be analyzed for people directly involved in the dipping process.

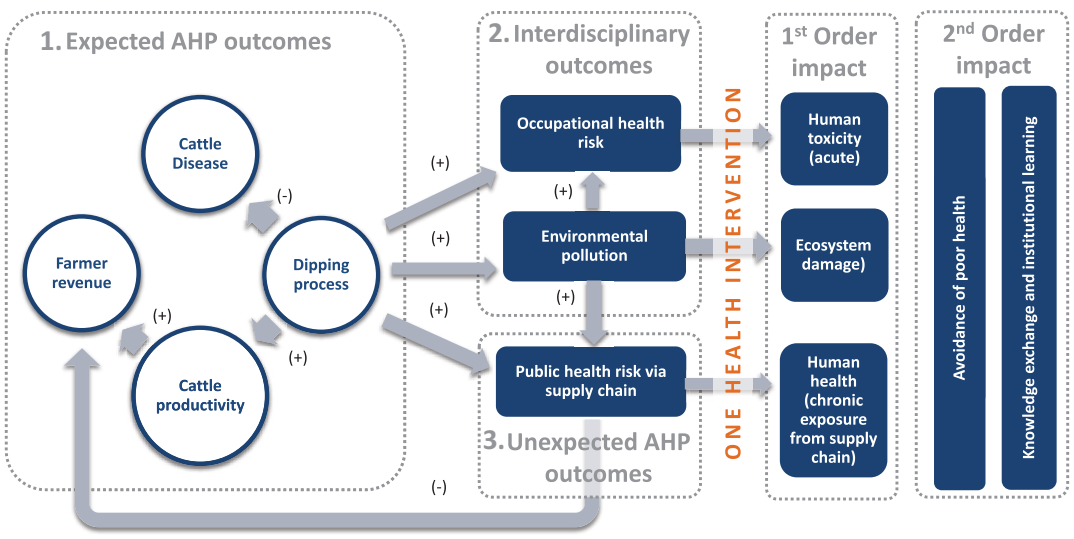

FIGURE 2 | Logical framework showing Impact Pathways describing interactions between inputs, outputs, outcomes, and impact of the system of the Animal Health Programme (AHP) and OHI. The system relating to the primary AHP (Box 1) showing the "theory of change," i.e., interdisciplinary outcomes arising from the AHP (Box 2) and highlighting the impact pathways on which the One Health Initiative acts with both first order and second order impacts assumed. The figure also shows where unexpected outcomes (Box 3) were captured through the adoption of the transdisciplinary approach used in this case.

(iii) The observation of social behaviors related to the dipping process (as described in Section "Introduction") allowed for the identification of current and potential risk originating from the AHP but affecting greater dimensions. This expanded the complexity of the system also including other relevant local social units (mainly consumers of milk from treated cows, users of disposed canisters to store food, farmers, and villagers in general) beyond the DTOs, who were identified as the people at highest risk. The observation of the real dipping process development in different treatment sites allowed for the identification of actions, behaviors, and consequences according to a model which can be conceptualized using a systems-based approach.

The satellite project (OHI) is the initiative operating within the system shown in **Figure 2** and described in **Table 1**. The OHI aimed to reduce or eliminate exposure to the risks of OP use, which were interdisciplinary alongside any unexpected impacts of the dipping process in the context of the AHP. The main stakeholders were the DTOs, the population of Southern province, and the local ecosystem.

The theory of change for this case study is the avoidance of harm to people, plants, animals, or environment that may have arisen if an animal health driven programme of dipping cattle in OPs was implemented alone. The OHI helped to increase the sustainability of the AHP, alongside improved efficacy and efficiency for the Zambian Government looking to increase productivity in the agricultural sector. This was in addition to greater interspecies equity and better health and welfare of people, plants, animals, and the environment through the avoidance of harm and the poor welfare and financial implications such harm could have inflicted. It was also of interest to the national government and potentially international policy makers as results may be suitable for extrapolation to other countries.

TABLE 1 | Main characteristics of the system and impact pathways for the animal health programme (AHP) and satellite project (OHI)—(+) indicates a positive or additive interaction and (–) indicates a negative or inhibitory interaction direction.

	AHP	Satellite project (OHI)
Drivers	Cattle disease	Avoid AHP unexpected outcomes
Means, measures	(+) Dipping process (traditional sectoral approach)	(+) Integrated approach (inter- and transdisciplinary, OH precursor)
1° order outcomes	(–) Cattle disease	(+) Establishment of good practices
2° order outcomes	(+) Cattle productivity and welfare (+) Farmers revenue	(+) Public health (–) Environment pollution
System outcomes	n.a.	(–) Insufficient follow-up from local institutions
Unexpected outcomes	(+) Occupational risk (+) Environmental pollution (–) Public health (chronic and acute disease)	(+) Knowledge exchange (+) Institutional learning (+) Health policy effectiveness

OH-ness Evaluation, OH Index, and OH ratio

The system was scored on the six elements as set out in the NEOH framework. The spider diagram (**Figure 3**) demonstrates the scores for assessment of the One Health operations and infrastructure present in the initiative. The point on each spoke of the spider diagram is set from a score for OH thinking (0.63), OH planning (0.60), OH working (0.55), OH learning (0.50), OH sharing (0.55), and systemic organization (0.60) for the satellite project. Scores were allocated out of 1.0, where a high score was perfect OH criteria achieved and 0.0 was no OH criteria achieved. Scoring criteria are outlined in Tables S2a–g in Supplementary Material.

The mean score for OH thinking (0.63), as established by qualitative questionnaire review (Table S2a in Supplementary Material), was moderately high for this satellite project. The initiative had a highly integrated health approach, covering a variety of dimensions at differing scales and incorporating many perspectives. However, there was a weaker match of initiative aimed at the environment. The geographical dimension of the project targeted a global health challenge, enacted by those from multiple countries, but conducted across a short timescale.

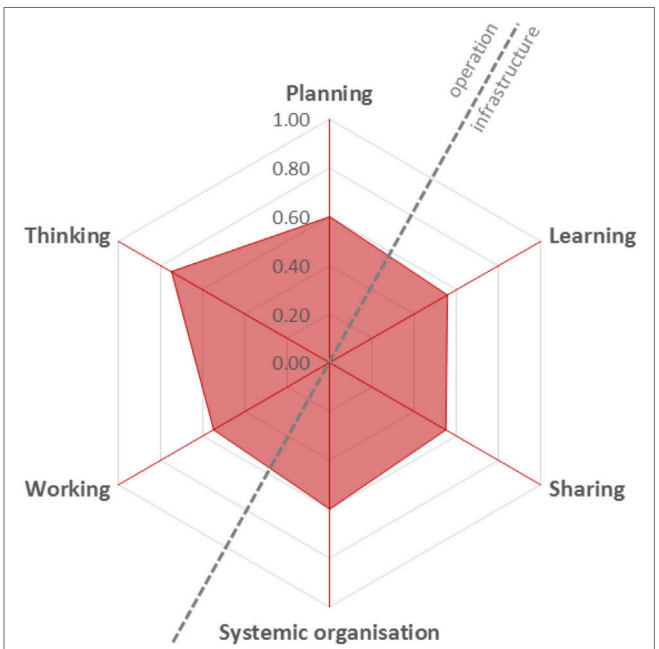

FIGURE 3 | Spider diagram showing the One Health (OH) Index scores assigned for the different elements of the One Health-ness evaluation. The overall OH Index calculated from the area enclosed (shown in red) = 0.34. The hexagon is made up from the scores allocated to the OH operations (thinking = 0.63, planning = 0.60, working = 0.60) and OH infrastructures (learning = 0.55, sharing = 0.50, systematic organization = 0.60). The scores were compared to the ideal scenario (score 1.0). The One Health Ratio is calculated as a comparison of operational scores against infrastructure scores and is 1.20.

Despite the initiative impacting on whole ecosystems, these impacts were not captured. The results of this satellite project could have international economic consequences but were only utilized to inform national protocols.

An extended initiative timescale and more balanced perspective could have captured long-term impacts important for public health and other wider impacts, thereby better serving the global context of OP use to control TBD in cattle.

The mean score for OH planning (0.60) was calculated according to the match between tasks, resources and responsibilities as shown in Table S2b in Supplementary Material. Many specialist staff were utilized effectively in their areas of expertise, for example the toxicologist testing residue samples and the translation of safety advice into broadcast materials by media experts. However, there were many roles completed by those with expertise in animal health that could be more suited to human health experts or social scientists. It was noted, however, that veterinarians held a great deal of professional respect in the communities where they were operating, meaning that it was generally accepted that they had authority to deliver safety information for animal products and treatments and one veterinarian had further training in human and occupational health. A bottom-up approach to the project was utilized with stakeholders actively involved in identifying risks (interviews, etc.) and developing solutions (educational material content and discussions for lack of behavior change following delivery of education). Interaction with local medical centers was only through veterinary staff and there was a lack of follow-up so numbers of possible patients associated with OP use were unknown. However, accident-at-work reporting from the dip-tanks was monitored and captured direct exposure and inhalation toxicities. The project also aimed to build an intersectoral network.

One health working assessed the transdisciplinarity (0.60) and measured the extent to which there was cross-disciplinary working and leadership that enabled an innovative approach to the challenges in this case. The initiative was broad and flexible but suffered from an imbalance of actors. There were a larger number of those from animal health throughout but these contributors came from across multiple dimensions and scales, from local to international, with successful collaboration. Table S2c in Supplementary Material shows how stakeholders worked in an interdisciplinary way across these different dimensions to address issues impacting people, plants, animals, and the environment. There were innovative outcomes arising from the transdisciplinarity of the project through the collaboration with media and communication experts in the production of education materials for a community safety campaign. However, the satellite project may have suffered from a lack of representatives from social science and Zambian public health expertise. The initiative did, however, receive crucial input in the planning phase from an Italian doctor of public health, trained in public health promotion techniques. Despite there being warning labels for harmful exposure routes on the acaricide canisters, the identification of risk behavior and interventions to reduce it, required the involvement of a range of stakeholders and transdisciplinary working. Given the time when the satellite project was performed (late 1980s), a high level of leadership was required to both conceive of, and get accepted by both national governments, such a pioneering project. It also demonstrated adaptability by responding to results as they emerged, allowing unexpected outcomes to be captured while building a network and culture of cooperation through annual conferences.

One health learning infrastructures (0.50) scored moderately compared to the ideal adaptive and generative learning that could occur. It was more favorable at individual level with some adaptive learning, but the application of learned knowledge at individual, team, and organization level was limited (Table S2e in Supplementary Material). Feedback from end-users was readily received during several community "meetings under the tree" allowing for adaptation but was not applied during the initiative. Multimedia educational material received participation from experts and local stakeholders. There was established a yearly seminar for the provincial veterinary staff in Zambia, which also included local experts to disseminate information. Peer-to-peer learning was carried out between the Zambian animal health workers but facilitated by the Italian Institute. Institutional learning also occurred for the Italian vets working mostly for the first time in Zambia under field conditions, meaning exposure to novel challenges. Following the satellite project and AHP any continued collaboration was not formally recorded and thought to be only on a personal level. Up-dates on the present disease extent and on the methods to control Theileriosis, implemented after the termination of the Italian project, were obtained through publications, reports by FAO and Belgian Cooperation projects, and *via* personal communications with veterinary consultants who used to work in the Country. Feedback was gathered at the time of the project during face-to-face meetings, and a final handing-over project report but it has not been taken since the project ended (7).

Another moderately scored aspect of this case study was OH sharing (0.55) as outlined in Table S2d in Supplementary Material. There was good appreciation of the potential stakeholders to be involved in the project but, as previously discussed, those from human health could have played a greater role to enhance the outcomes of the project further. Data quality was variable, with some elements of the OHI being published in peer-reviewed journals (e.g., toxicology data and public health promotion activities) but in other areas there were qualitative risk assessments with no baseline case numbers for harm arising from the AHP. The full impact of the OHI was not captured adequately with only anecdotal evidence collected. However, resources were provided to allow wider sharing of risk behavior data and methods for risk mitigation both internally and externally with staff and regional animal health workers. Frequent and routine meetings were held between Zambian field staff, with provincial Zambian staff invited to a biannual meeting with national Zambian staff. There were also yearly expert missions from ISS Rome that included laboratory technicians, development cooperation, and administrative staff. Findings were used to inform a radio and television program to share findings with the public with the aim of reducing risk behavior but it is unknown if these resource intensive outputs were used after the conclusion of the project.

Systemic organization (0.60) assessed team structure, leadership and focus as outlined in Table S2f in Supplementary Material.

There were multiple teams acting in the initiative with fairly clear objectives; however, some teams were of limited size and lacked formal structure for inter-team relations. The bias toward animal health sector actors was a limiting factor but despite this, the initiative was successful in utilizing an integrated system and yielded interdisciplinary outcomes.

The overall OH Index = 0.34 was calculated from the area enclosed by the points of the spider diagram (**Figure 3**; Table S2g in Supplementary Material). The OHI demonstrated moderate success in most areas of One Health integration. A comparison of the satellite project's OH operations to infrastructure elements showed slightly better operational scores by managing to incorporate the input across multiple dimensions. The ratio of OH operations and infrastructure was estimated by the OHR = 1.20.

Economic Evaluation

Table 2 shows the breakdown of the total expenditure supported by financing organizations for the satellite project, by type of activity and relevance.

Educational and training activities covered 57.2% of the total satellite project's expenditure; the evaluation, monitoring, and prevention of intoxication risk 39.4%; and the other type of expenditure 3.5%. Total expenditure equaled about 2% of the overall budget for the AHP.

The identification of the project benefits for local communities was preceded by estimations on the acaricide use during the AHP implantation in the 90 DT stations initially targeted. According to technical data provided by project experts, in the two years of AHP and OHI operation it can be calculated that 10,035 kg of acaricide active ingredient were used, resulting in the disposal of 6,690 empty canisters and 2,430,000 l of end-of-season DT fluid containing approximately 1,020 kg of active ingredient (see Annexe A1).

TABLE 2 | Breakdown of the expenditure supported by financing organizations for the implementation of the satellite project by type of activity.

Activities	USD[a]	%
Educational and training activities (sub-total)	30,559	57.2%
– *Training activities and conferences*	*11,971*	*22.4%*
– *Radio program concept and development*	*4,448*	*8.3%*
– *Radio program production and broadcast*	*4,818*	*9.0%*
– *Production of dip-tank operator procedural manual*	*4,138*	*7.7%*
– *4-month fellowship by Istituto Italo-Africano for veterinarian counseling to the radio program production*	*3,569*	*6.7%*
– *Production of educational leaflets*	*1,615*	*3.0%*
Evaluation, monitoring and prevention of intoxication risks (sub-total)	21,041	39.4%
– *Residue testing and analysis*	*8,911*	*16.7%*
– *Assessment of occupational hazards*	*7,485*	*14.0%*
– *Provision of personal protective equipment*	*4,487*	*8.4%*
– *Provision and distribution of atropine to hospitals*	*159*	*0.3%*
Other (sub-total)	1,859	3.5%
– *Staff support at ISS Rome and WHO/FAO collaborating center*	*1,859*	*3.5%*
Total expenditure	53,460	100.0%

[a]*Original values in old Zambian Kwacha (ZMK) were converted into US Dollars: average exchange rate from January 1, 1988, to December 21, 1989, 1 USD = 11.8679 ZMK (source: www.fxtop.com, accessed on September 23, 2017).*

The project output included production of educational activities and training materials, laboratory services, hazard assessment, and the provision of protective equipment and antidotes. This contributed to reduce the cases of OP poisoning and the environmental hazard arising from the implementation of the AHP and other similar initiatives, as well as from the general use of pesticides in the impacted area (see Annexe A2).

Annexe A3 summarizes the economic benefits of the project for the population of the beneficiary country consisting of the incomes directly and indirectly generated by employment of local staff and local purchases of goods and services, the willingness to pay of local population for the avoided cases of OP poisoning in humans and the related resource savings for the public health system, the patients and their families, and the willingness to pay of local population for the reduction of health and environmental hazards (see Annexe A3).

Due to a scarcity of data, it has not been possible to appraise the monetary value of such benefits within this study. The estimation of the incomes generated for the local population, beyond the information from the project's technical and financial reporting, would have required other evaluations based on macroeconomic statistics of the benefited country regarding foreign trade and intermediate and final consumption of goods and services at that time (22, 23). A quantification of the prevented OP poisoning cases and an assessment of the reduced health and environmental impacts would have opened the possibility to evaluate, through the available methodologies, both: the willingness to pay of the impacted population for such benefits and the saving of resources obtained (16, 24, 25).

DISCUSSION

Application of this newly described framework for evaluation of integrated health projects has shown the added benefits (theory of change) from taking this pioneering approach in an earlier animal health intervention. The OHI in this case study achieved moderate success in all six evaluation themes, but failed to demonstrate long-term change or continued learning beyond its own system. As highlighted in the introductory chapter by Ruegg et al., a higher OH index does not necessarily indicate a "better" OH initiative, so it is difficult to draw comparisons of results of this case study with others at this time. However, data from this case study can and will be compared to others during further verification of the framework and in creating benchmarks in the future. Despite limited resources allocated to the completion and data collection for evaluation and the long time elapsed since project completion, it is hoped that the qualitative evaluation approach utilized here proves important in understanding short-comings and strengths of initiatives in a context-specific way.

The case study highlights clearly the wider impacts and unintended consequences that even a simple and well-established technology, such as applied for animal health here, may have on other aspects of society. The introduction of an animal health strategy in this local context (dipping and, in particular, acaricide products) did not consider relevant cultural aspects of the society such as perceptions the local population held on the level of potential risks when using an acaricide. Cultural determinants are relevant

aspects of the system as they determine credence, behaviors, and material practices. This emphasizes the need to put health measures in their social context before implementation, i.e., taking a One Health approach to risk analysis and impact assessment. In this case study, AHP managers and local and national authorities were obliged to intervene due to the unexpected consequences (i.e., reuse of acaricide canisters) emerging from the AHP. It was not possible to quantitatively assess the benefits of the satellite project for the reasons already outlined. However, based on the national incidence of signs arising from the misuse of OP and related facilities, it makes sense to affirm that consequences might occur if no measures (the satellite project) were adopted. A lesson that seems still appropriate today.

The evaluation was made challenging by a lack of monitoring data to assess impacts arising from the One Health initiative. Evidence for harm arising from exposure to OPs is widely recognized in the medical literature and thus a logical model of harmful impacts was assumed based on areas where exposure was a risk. Although an integrated approach was not necessary for these harms to be predicted, the identification of risk behavior within the system would have been limited by a siloed disciplinary approach. In this case study, researchers were mostly from the animal health sector but had suitable understanding to allow detection of risks. These initial risk assessments were then supported through transdisciplinary working to develop and deliver intervention strategies.

The OHI was seemingly successful in transfer of knowledge but local stakeholder attitudes to the risks identified and communicated were "rather unmodified." However, this was based on personal observations only. It was generally acknowledged that there was free provision of protective equipment for DTOs but its uptake was not formally recorded or successful on 100% of observations. There was also no formal recording on container reuse following modified advice, but this was sporadically observed (at least 4–5 times) suggesting a <100% success in adhering to warning messages.

The retrospective nature of the OH evaluation limited the potential impact of results. If the OH approach had been taken earlier in the intervention then it may have aided the decision-making in the planning stages, for example, taking into consideration costs or benefits arising from economical, social, and sustainability perspectives in a final decision as to the interventions viability or ethical conflicts.

The imminent health risk multiplier related to the acaricide was identified due to a mostly effective collaboration in an international, multi-disciplinary and multi-institutional team. After the implementation of the satellite project, no trace of this experience reportedly remained encoded in a structured model of institutional cooperation to ensure a similar integrated approach may be used for other problems. This underlines some relevant aspect of OH: (i) interdisciplinary and institutional cooperation is fundamental to get the advantages of OH operation; (ii) individual cooperation does not necessarily translate into institutional structures suitable for facing new problems in an effective way.

The evaluation framework according to the NEOH handbook (see text footnote 1) was applied retrospectively in this case study. This required a great deal of specific data for what was a delayed evaluation (more than 25 years after project implementation) of an informally monitored initiative. This proved challenging at times and limited the involvement of stakeholders to just a few. However, information and data were gathered for the evaluation by way of review of published and gray literature, original documentation from the initiative and semi-structured interview. Attempts to contact other stakeholders and to measure long-term impacts were unsuccessful, but the delay in evaluation in this case study is likely exceptional. It is, therefore, not suggested that this is a failing of the framework.

The AHP and the satellite project were not shaped and managed in order to provide data and information to perform current OH-ness or economic evaluation. Some data about cost were available but benefits can only be assessed in a qualitative and hypothetical way. Organizational and institutional settings adopted for the management of the satellite project are relevant for the assessment of OH-ness. They have been reconstructed through interviews with the people involved with project implementation and most of them could not be reached after approximately 25 years. Available information was compiled independently from the completion of questionnaire tools in the first instance. This allowed a more complete understanding of the initiative but this approach was time consuming and a targeted plan for information gathering to occur throughout the initiative may be desirable. The completion of the evaluation questionnaire by an external evaluator helped to reduce bias but could be vulnerable to misinterpretation on the part of the evaluator. The review of evaluation scoring criteria by multiple other evaluators, both internal and external and from differing disciplines, helped to address any bias toward the perspective of a particular evaluator. This approach proved feasible and practical for the geographically isolated evaluators in this case study. It is proposed that completion of similar evaluations could be done by external evaluators in isolation from stakeholders (thereby reducing resources required), if there existed good processes for information gathering in planning and completion of the initiative. A retrospective evaluation in this instance, therefore, proved limiting. The process of system mapping as an initial stage of evaluation lends itself well to the review of One Health initiatives. In this example, little specific data were available to map a broad system, but the mapping process allowed for assumed impact pathways (based on existing knowledge) to be used to better illustrate the context surrounding the initiative.

CONCLUSION

The satellite project used a pioneering *ante-litteram* OH approach many years before the present OH definition was set and a more structured OH approach was implemented. This case study highlights the risk of implementing health interventions without consideration of the wider context and potential impacts for indirect stakeholders. The avoidance of harm and improved species equity achieved when using a One Health approach is achieved through effective transdisciplinary collaboration. In this case study, the costs of implementing such an approach were small in comparison to overall project costs, but are proposed to have

had large potential impacts. This supports the implementation of One Health assessments as part of larger health programs as good value. It is recommended, however, that there be greater attention paid to determining the system, processes for monitoring and effective influence points in the planning stages to take the greatest benefit of such an approach. Routine monitoring and evaluation from a One Health perspective by utilizing the framework proposed by NEOH, could prove a valuable addition in future health strategies and as a tool for retrospective evaluation of existing policies.

ETHICS STATEMENT

No personal information was used in this evaluation and methods used retrospective evaluation only meaning no ethical consent was sought/required for completion.

AUTHOR CONTRIBUTIONS

DM: general contribution in the study design; providing all background info and data concerning the AHP and the OHI activities which he carried out as (former) project consultant in Zambia; contribution in attributing the OH-ness scores; collaboration in revising, editing the manuscript; GL: primary external OH-ness and economic evaluator; SS: tertiary external OH-ness evaluator; MC: secondary external OH-ness evaluator; co-responsible of the section on "Economic evaluation"; MA: secondary external OH-ness evaluator; co-responsible of the section on "Economic evaluation"; contributor to the section "System map and Theory of Change"; all authors: drafting, editing, and reviewing the final version of the manuscript.

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SUPPLEMENTARY MATERIAL

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX

ANNEXE A1 | Technical data and estimations on acaricide use in the DT stations targeted by the satellite project.

- 90 DTs, mean number of operational DTS/each dipping season (average volume 16,000 l) for about 2 million cattle dips/year;
- DT fluid removed by dipping = 2.5 l per each cattle dip;
- DT replenishment after 1,000 dips = 2,500 l of DT fluid/replenishment;
- Total number of DT replenishments = (2 million cattle dips per year/1.000 dips) − 90 first charging = 1,910 replenishments per year;
- Acaricide dilution in DT fluid: 1 l acaricide/600 l of water for initial DT charging; 3 l acaricide/1,000 l of water for DT replenishments;
- Total acaricide utilized = (16,000 × 90 × 1/600) l + (2,500 × 1,910 × 3/1,000) l = 16,725 l per year (containing 5,017.5 kg of active principle);
- Acaricide canisters (5 l volume) to be disposed = 16,170/5 = 3,345canisters per year;
- End-of-season disposal of DT fluid by using decantation pits before dispersal on fallow land = (16,000 − 2,500) l × 90 DTs = 1,215,000 l per year (containing about 610 kg of active principle).

Source, Ref. (3–7) and own evaluations.

ANNEXE A2 | Output description of the satellite project.

(B) Output description of the satellite project

1. Staff trained: 95 operators of the 90 targeted DT stations, 20 Veterinary assistants, 5 laboratory assistants;
2. Two national seminars organized for veterinarians and livestock officers;
3. One radio program produced and broadcasted twice;
4. Procedure manual for DT operators produced and 250 copies printed;
5. Educational leaflets produced and 300 copies printed;
6. Project report produced and 150 copies printed;
7. Residues analysis in milk samples from 10 cows × 4 subsequent samplings after dipping, plus testing residues in empty canisters used to transport water and other food stuffs
8. Assessment of occupational hazards in DT stations
9. Personal protection equipment provided to the DTOs at the operational DTS;
10. Atropine distributed to vet offices, health centers and hospitals in the 5 District under the AHP assistance
11. Potential avoidance of OP poisoning cases due to implementation of the AHP and similar interventions, and more generally for pesticide use in the impacted area.
12. Potential reduction of health and environmental risks:
    - 12.1. Reduction of the risk of acute and chronic intoxication of DT stations' staff caused by mishandling and bad practices in DT operations (handling of about 9,700 kg of acaricide active principle during the 2-year project period in the 90 targeted DT stations);
    - 12.2. Reduction of the risk of acute and chronic intoxication of herders and local population caused by utilization of empty acaricide canisters for transportation and storage of water, milk, and other liquids for food and domestic uses (about 6,690 empty canisters to be disposed during the 2-year project period in the 90 targeted DT stations);

(*Continued*)

ANNEXE A2 | Continued

- 12.3. Reduction of the risks of acute and chronic intoxication of herders caused by cattle cares and operations practiced within 5 h after DT dipping;
- 12.4. Reduction of the risks of acute and chronic intoxication of herders and local population caused by human consumption of milk produced within 24 h after DT dipping;
- 12.5. Reduction of the risks of active principle dispersion in the environment caused by direct disposal of end-of-season DT fluid into fallow land without previous decantation (25,430 hl of DT fluid containing about 1,020 kg of active principle during the 2-year project period in the 90 targeted DT stations);
- 12.6. Improved skills of DT stations' staff and awareness of local herders and population reduced the general risks of active principle dispersion in the environment (10,035 kg of acaricide active principle were used during the 2-year project period in the 90 targeted DT stations);
- 12.7. Improved skills of DT stations' staff and awareness of local herders and population permanently reduced the risks listed from point *Error! Reference source not found*. to point *Error! Reference source not found.* for similar initiatives undertaken after the end of the project and more generally for pesticide use and handling in the impacted area.

Source Ref. (7–9), and own elaborations.

ANNEXE A3 | Summary of the satellite project's benefits for the population of the beneficiary country.

(i) Incomes generated by the project:
- salaries and other incomes of local staff directly employed by the project;
- incomes generated to local population by project's purchases of goods and services in the territory of the beneficiary communities;
- income generated to local population by project's foreign staff personal purchases of goods and services in the territory of the beneficiary communities;
- increased income derived by the reduced cattle mortality and increased productivity

(ii) Willingness to pay for improvements in the health state of the population consequent to implementation of the AHP and more generally to TBD control practices and pesticide use:
- potentially avoided cases of acute and chronic OP poisoning in humans related to the AHP and to similar interventions;

(iii) Resource saved from potentially avoided cases of acute and chronic OP poisoning in humans:
- resource saved in the public health care sector;
- resource saved by patients and their households;
- avoided productivity losses.

(iv) Willingness to pay for reduced environmental and health hazards consequent to implementation of the AHP:
- reduced risks of acute and chronic OP poisoning in humans;
- reduced risks of OP dispersion in the environment;

(v) Willingness to pay for reduced environmental and health hazards consequent to TBD control practices and pesticide use beyond the AHP:
- reduced environmental and health hazards from general improvement of local skills and awareness regarding TBD control practices and pesticide use.

Source: Own elaborations.

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A One Health Evaluation of the University of Copenhagen Research Centre for Control of Antibiotic Resistance

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We applied the evaluation framework developed by the EU COST Action "Network of Evaluation of One Health" (NEOH) to assess the operations, supporting infrastructures and outcomes of a research consortium "University of Copenhagen Research Centre for Control of Antibiotic Resistance" (UC-CARE). This 4-year research project was a One Health (OH) initiative with participants from 14 departments over four faculties as well as stakeholders from industry and health authorities aiming to produce new knowledge to reduce the development of antimicrobial resistance (AMR). This was a case study focusing on assessing beneficial and counter-productive characteristics that could affect the OH outcomes. The study was also used to provide feedback to NEOH about the evaluation framework. The framework and evaluation tools are described in the introduction paper of this special journal issue. Data for the evaluation were extracted from the funding research proposal, the mid-term UC-CARE project evaluation report and supplemented with opinions elicited from project participants and stakeholders. Here, we describe the underlying system, theory of change behind the initiative and adapted questions from the NEOH tools that we used for semi-open interviews with consortium members throughout the evaluation process. An online survey was used to obtain information from stakeholders. The NEOH evaluation tools were then used for the qualitative and quantitative evaluation of the OH characteristics of UC-CARE. Senior UC-CARE researchers were interested and willing to be interviewed. Young scientists were more difficult to engage in interviews, and only 25% of stakeholders answered the online survey. Interviewees mentioned that the main benefit of UC-CARE was an increased awareness and general understanding of AMR issues. All interviewees stated that the adopted OH approach was relevant given the complexity of AMR. However, some questioned the applicability, and identified potentially counter-productive issues mainly related to the information sharing, collaboration and working methods across the consortium. A more integrated project organization, more stakeholder involvement and time for the project, flexibility in planning and a dedicated OH coordinator were suggested to allow for more knowledge exchange, potentially leading to a higher societal impact.

Keywords: One Health, evaluation, AMR-research, theory of change, outcomes

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INTRODUCTION

Antibiotics are used to treat domesticated terrestrial and aquatic animals, plants, and humans from bacterial infections, but their lack of effectiveness on some resistant bacteria has resulted in deaths and the increased suffering of people and animals (1, 2). Antimicrobial resistance (AMR) is a global issue concerning human and animal health, and several actions are being taken at national and international levels to slow down and reduce this trend (3). In the context of a growing human population, with greater domesticated animal populations, healthcare systems relying on antibiotics for their effectiveness, and international travel and trade, there is an increasing need for the improved management and use of antimicrobials and the pursuit of alternatives to existing antimicrobial compounds (1, 4).

A One Health (OH) approach is recommended by the scientific community and international organizations to solve complex situations and new issues such as AMR (2, 5–7). Researchers from different disciplines need to collaborate and seek support and involvement across multiple sectors. OH approaches have been implemented in diverse fields and the benefit has been demonstrated in different studies (8). Among the numerous examples of OH approaches (9, 10) are those relating to the surveillance of zoonotic or food-borne diseases (11–14), effective disease control policies (15) and implementation of control measures (16–19) and research (20–22).

The "University of Copenhagen Research Centre for Control of Antibiotic Resistance" (UC-CARE) was a collaborative effort across a number of disciplines. It adopted an OH approach as the central theme of the consortium, launching a large 4-year research project in 2013 (23). UC-CARE aimed to provide knowledge to combat AMR through inter-sectorial collaboration between the human and animal health sectors. It involved 14 departments across four faculties of the University of Copenhagen and engaged the Danish livestock farming and pharmaceutical industries and national health authorities as the main stakeholders. The research project had six research work packages (WPs) with specific objectives and varying numbers of researchers (WP leaders, PhD fellows, Post-docs and Assistant/Associate Professors), one WP dedicated to dissemination and education, and one management WP with a management board, stakeholder board and scientific advisory board. The initial budget in the project proposal was 34.7 million DKK, including salaries for 636 man-months (53 years) of research and 54 man-months of technical and administrative support. The initiative therefore constituted a significant OH effort, funded mainly by the university itself.

A mid-term evaluation of the UC-CARE project was conducted in May 2016 by external researchers, and a final evaluation was planned after completion of the project. However, commonly used frameworks for research project evaluations do not cover all the aspects of OH initiatives that are relevant to the outcomes and societal impacts that such initiatives are aimed toward (24). Rather, OH initiatives should be evaluated using methods targeting the transdisciplinarity of the initiative and the potential added value of choosing that approach over a less integrated approach. For this reason, a "Network for Evaluation of One Health" (NEOH) (25) was created in 2014, supported by a European Corporation in Science & Technology (EU COST) action to develop evidence-based guidelines and tools for the qualitative and quantitative assessment of OH initiatives. The developed framework and evaluation tools have been presented in detail by NEOH consortium members in the Frontiers journal research topic[1] (26). In short, it consists of four elements: (i) a description of the underlying system and the OH initiative in relation to the system; (ii) the theory of change behind the initiative, including expected outcomes; (iii) the evaluation process supported by evaluation tools that summarize the qualitative and quantitative evaluation of operations and supporting infrastructures in the initiative (referred to as "the One Health-ness" of the initiative); (iv) a comparison of the One Health-ness and the outcomes of the initiative. The elements are described in more detail in sections Materials and Methods and The Resulting Evaluation of UC-CARE below.

During 2016 and 2017, case studies were carried out by NEOH consortium members on real life OH initiatives to assess the usefulness and present the application of the NEOH framework. Two objectives of the case study were presented: (1) to evaluate the transdisciplinarity and outcomes of the UC-CARE consortium and research project using the NEOH evaluation framework and tools, and (2) to assess the usefulness of the NEOH framework and tools for further refinement. As we decided to illustrate the results of the UC-CARE evaluation using the amended and published NEOH framework resulting from the case study feedback, the following report will focus on the first objective.

MATERIALS AND METHODS

Methods for the Evaluation of UC-CARE

The evaluation mainly took place in November and December 2016 and was fully supported by the management board of UC-CARE. In October 2016, the principal investigator (PI) encouraged all actors in the consortium to agree to an interview with the external evaluator.

Defining and agreeing upon an evaluation question is important, and in this case study, the question was: which elements of UC-CARE were particularly productive and efficient, and which elements could be improved to ensure that the expected intermediary outcomes (i.e., high research quality and substantial output) will ultimately lead to a positive impact on human, animal, and environmental health, given the available resources in the consortium?

To answer the evaluation question, it is necessary for the evaluator to first develop a thorough understanding of the structures, boundaries, and dynamics of the initiative, as well as an overview of the actors involved and stakeholders affected by or interacting with the initiative. The initiative should be seen in relation to the underlying system for which it is intended have an impact (i.e., the context). This constitutes the first evaluation element in the NEOH framework (26).

[1] https://www.frontiersin.org/research-topics/5479/concepts-and-experiences-in-framing-integration-and-evaluation-of-one-health-and-ecohealth.

The second element in the evaluation is to describe the theory of change (TOC), which is an outcome-oriented approach to describing the logics and reasoning behind the design of the initiative, including the identification of expected outputs and outcomes, arising within and between disciplines, and the resulting expected impacts on the underlying system. The TOC was defined by Rüegg et al. (26): "The TOC explains all the different pathways that might lead to the desired effect of an initiative. It not only shows the outputs, outcomes, and impact of an initiative, but also requires outlining (and explaining) the causal linkages. Each effect is shown in a logical relationship to all the others." For the UC-CARE case study, information about the initiative and the expected impact on the underlying system as well as the TOC were obtained from the original research proposal and the mid-way evaluation report in which the consortium design, aims, outcomes and expected societal impacts were partly described, supplemented with interviews with the principle investigators and work-package (WP) leaders, who knew more about the process of the development of the consortium (we refer to section Data Collection and Methods for Assessing OH Outcomes and Outputs below for more information).

The third element is the evaluation process, supported by tools to summarize the qualitative and quantitative evaluation of operations and supporting infrastructures in the initiative (26). This is also referred to as "the OH-ness" of the initiative, and the method used is described in section Methods for Assessing the OH-ness of the Initiative below.

Finally, the fourth element is a comparison of "the OH-ness" with the outcomes of the initiative. For this particular study, this could only be addressed in a qualitative and descriptive way in the discussion of the results (section Discussion). Future comparison across multiple case studies may lead to a better understanding of the optimal attributes of OH initiatives, but this is beyond the scope of this paper.

Data Collection

Data collection was conducted over 3 weeks in November 2016. It was based on (i) face-to-face interviews with consortium partners, (ii) an online survey for stakeholders and external partners, and (iii) internal documentation of UC-CARE (i.e., the initial proposal, mid-term evaluation). The data were collected by the first author, who was the external evaluator of the UC-CARE consortium.

No ethical approval was required for this study in accordance with the national and institutional requirements. All interviewees and stakeholders participated voluntarily and remain anonymous.

Face-to-Face Interviews Among the Consortium

One-hour long, semi-open interviews were conducted with consortium partners selected according to their role and commitment to the project. Three PIs and deputies, six research WP leaders, 20 young researchers (PhD and Post-doc students) and four other selected key people in the consortium were all targeted for interview. The WPs are described in relation to the system in section The OH Initiative UC-CARE Within the System. The constitution of each WP varied depending on available funding over the project period. The last author contacted the targeted interviewees by email to present the evaluation purpose and introduce the interviewer. Thereafter, the first author contacted them personally to schedule the interview.

The interview questions were adapted from the identified information developed in the NEOH tools (26). At the end of every interview, participants were also asked to go back to the original proposal and provide feedback about their results and their perception of progress in the efforts against AMR. The questionnaire was pre-tested through one pilot interview to minimize question ambiguity and generally refine the process. The questionnaire is available in Annex 1 (**Supplementary Material**).

All interviews were recorded with a simple voice recorder, stored as MP4 audio files and then transcribed by the first author after each interview in order to have access to all valuable information provided by the interviewees.

Online Survey for Stakeholders and External Partners

All 27 people on the UC-CARE mailing list for external partners, as well as members of the scientific advisory board and stakeholder board were contacted by personal email to take part in the survey by answering the online questionnaire.

The questionnaire was designed using Google Forms, and included 19 questions that took around 15–20 min to answer. The interview questions were adapted from the identified information developed in the NEOH tools (26). The questionnaire is available in Annex 2 (**Supplementary Material**). The questionnaire was pre-tested through two pilot interviews to minimize question ambiguity and generally refine the process.

Methods for Assessing the OH-ness of the Initiative

After the data and information were collected, the OH-ness of UC-CARE was assessed by following the format developed in the NEOH tools, which was provided in the form of Microsoft Excel spreadsheets with explanations, guidelines and pre-defined calculation formulae for overall measures (26). The OH-ness is the sum of several characteristics that define integrated approaches and transdisciplinarity, including the operations: OH thinking, OH planning, and OH working, and the supporting infrastructures: OH sharing, OH learning, and systemic organization (26). A training session for future evaluators was organized by the NEOH consortium in July 2016 to promote an understanding of the tools and how to use them.

While evaluating OH thinking, we assess how well and how much the dimensions (hierarchical orders of systems' organization) covered by the initiative fit with the real context of the research topic. It therefore helps to understand whether the initiative addresses appropriate aspects of the context so as to have the desired impact on the identified health challenge. The OH planning characteristics concern the organization of tasks in relation to the resources and responsibilities needed to complete the defined tasks and objectives over the duration of the initiative. Some of the questions must be defined in the planning

tool, and can therefore differ among initiatives. Evaluation of OH working characteristics focuses on the broadness of the initiative in relation to disciplines and societal involvement, collaboration and the flexibility to adjust to changing conditions during the working phase of the initiative. When assessing OH sharing, evaluators must investigate the exchange of data and information across the initiative and with stakeholders. OH learning includes knowledge and understanding of the context and the initiative outputs at individual, group and organizational level. Systemic organization is evaluated in terms of the alignment of goals, actors and competencies, as well as relevant leadership skills and behavior.

For each OH characteristic, the identified metrics to support the evaluation were organized into a framework and phrased as a question (Annex 3 in **Supplementary Material**). Every question was scored based on a detailed explanation with arguments for the score. Each OH characteristic was assessed by a final score, which summarized the question-specific scores. All OH characteristics are depicted on a scale from 0 to 1 as a spoke of a diagram found in the sheet named "OH diagram" (26). The diagram surface of the initiative was then calculated relative to the maximum surface attainable, thus referring to the degree of OH integration in the initiative (i.e., the OH index, which is a number between 0 and 1). The balance between operational and supporting means was extrapolated from this (i.e., the OH ratio).

The qualitative and quantitative assessment was mainly conducted by the first and last author. A general review of the evaluation and interpretation of results was completed by the two other authors. Preliminary results were also presented to the UC-CARE consortium during the last annual meeting. Comments from the audience were then integrated into the final version of the evaluation, which was sent to the UC-CARE management board for comment and to check potential misunderstandings before submission of the manuscript for publication.

Methods for Assessing OH Outcomes and Outputs

A TOC was derived from the UC-CARE proposal to support the identification of outcomes and outputs and illustrated in a diagram (26). Realized outputs and outcomes were identified from the online survey, interviews, internal UC-CARE documents, and comments from the PI upon the final evaluation check. Since outputs and outcomes continue to result from the UC-CARE consortium, it is worth noting that those included here were realized by July 2017.

Considered outputs and outcomes were categorized as: disciplinary, interdisciplinary, OH, and unexpected. The analysis of outputs/outcomes was based on overall numeric and textual methods. However, it was not possible to count the exact number of research publications originating from the consortium after the mid-term report, as these were not collected in a central place and due to a lack of response from many consortium participants. This highlights the information-sharing issues in UC-CARE, as discussed below.

THE RESULTING EVALUATION OF UC-CARE

This section summarizes the full evaluation with regard to the four evaluation elements in the NEOH framework, i.e., the description of (i) the initiative within its identified context, (ii) the TOC, (iii) the OH-ness assessment and (iv) outcomes of the initiative.

In total, 18 consortium partners were interviewed: 10 individual interviews, two group interviews (each with two early-career researchers) and one group interview with four actors. At least one person was interviewed from each WP. It was difficult to count the number of partners in the consortium because this changed over time. However, there were 26 PhD and Post-doc fellows involved, and approximately the same number of more senior researchers and technical administrative personnel. The size of the WPs varied according to the available funding.

In addition, of the 27 stakeholders and external partners that were contacted, eight answered the online questionnaire. Five had OH project experience over the previous 10 years, one had short-term experience (between 1 and 5 years) and two had no prior experience in OH before UC-CARE.

Stakeholders and external partners stated they were mainly contacted by the PI at the beginning of the project and five of the eight declared they had provided direct scientific input to the project.

Evaluation Element 1: Identification of the Relevant Context for the Initiative

Description of the Context

The UC-CARE consortium operated within the overall context presented in **Figure 1**.

The overall **aim** of the system is to protect human and animal health in terms of AMR infections, as there has been an increase in deaths attributed to AMR worldwide (27, 28). Denmark has a highly organized and integrated surveillance, prevention and control system to minimize the AMR burdens in humans and animals through a process of science-based policy making. Reports are published by the different partners involved, and explain the annual outcomes and results, for example surveillance of antimicrobial use in animal production systems, health status of the country, reports about AMR cases, and final reports about relevant research projects initiated by government-supported research institutions. These reports are publically available and presented at public seminars, allowing change to be observed and implemented depending on the outcomes of the system, situation and public concern. The most comprehensive and consistent sources of information about AMR in humans and animals in Denmark, as well as the use of antimicrobials in animals, are the annual DANMAP reports (available at www.danmap.org, accessed on 26 July 2018).

As represented in **Figure 1**, **actors** in the system are located in the ministries of health, agriculture, environment and commerce, the health care system (including hospitals), pharmaceutical industry, food and agriculture industry, private practices for animal and human medicine, and research and education

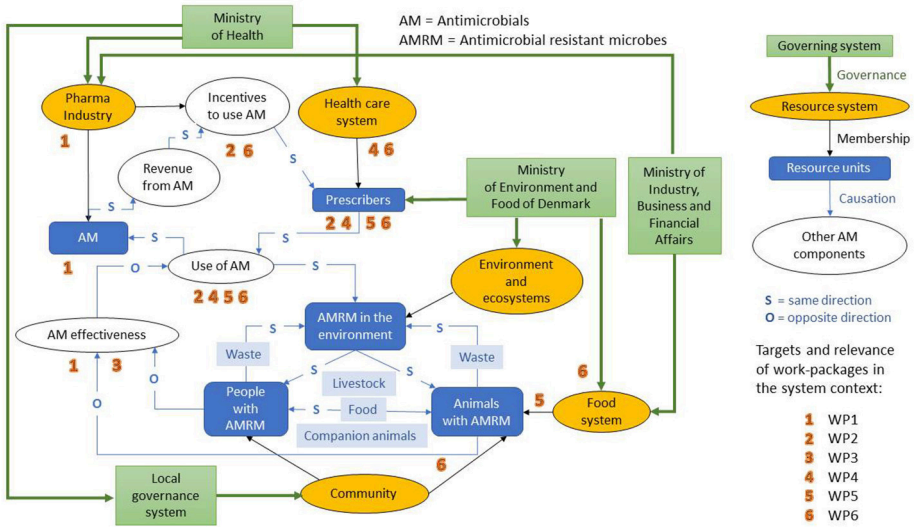

FIGURE 1 | Visual representation of the context of AMR within Denmark relative to the UC-CARE research project, and an illustration of where UC-CARE work packages belong in the system. Work packages are described in the main manuscript text [Source: Modified from Rüegg et al. (26)].

institutions. The relationships among actors are represented in **Figure 1**. Weighted links were not considered in the figure. Changing legislation and providing research grants should alter the activities of the different actors. Depending on the previous results of the system, actors should be able to react and modify their behavior and activities.

The **stakeholders** are also represented in **Figure 1**: community, patients, future actors (e.g., students). If the system produces the expected outcomes, the stakeholders should be directly affected by the improved health and reduced risk of resistant infections in both humans and animals. Changes from stakeholders can also be expected after suitable awareness campaigns, e.g., appropriate use of antimicrobial therapy from patients.

The main **dimensions of the system** include geographical, temporal, political, and legislative, as well as dimension of life, network and economy.

- **The geographical dimension:** the AMR threat is a worldwide public health issue, and any improvement would be valuable in every country. However, the system of immediate relevance to UC-CARE was the Danish AMR context and the impact on the human and animal populations of Denmark.
- **The time dimension** of the system is mainly based on years. Any changes within the system, e.g., developing and applying new legislation, application, and use of research results would require several years. Moreover, many research projects are executed on an annual or multiple-year basis. The system has no time limit, i.e., as long as the final objective has not been reached, i.e., as long as AMR continues to be a health threat, the system will remain.
- **The political dimension** is significant within the system. Several ministries are direct actors; industries are part of the decision and possible change within the system. Moreover, stakeholders such as the community are more and more concerned about AMR and the consequences for their health. The political dimension is limited by economic questions (e.g., costs of research, burden of the disease), public health issues (e.g., health threat, special care needed for infected patients) and progress of the research (e.g., discovery of new drugs).
- **The legislative dimension** is also significant in the system. The Danish legislation is of course the first step, but European and international legislation can also affect the system. Legislation provides a framework within which people and organizations can add their own decisions and standards to improve health for everyone. Results from research projects, drug discovery or the participation of researchers in evidence-based decision making could influence the legislative framework of the system.
- **The economy is also an important dimension** of the system. Costs and benefits are of concern to people and organizations at all levels, possibly limiting the progress and implementation of new discoveries.
- Also, **several** levels of the **dimension of life** are included in the system such as cell, wild and domesticated animals, individual humans, plant life, and the interaction of the human and animal populations. The network and the links between people and organizations are therefore a significant dimension of the system as they dictate the impact across the wider environment of animals and plants, as well as the human population.

The OH Initiative UC-CARE Within the System

The initiative gathered 14 departments from four different faculties of the University of Copenhagen, aimed at different aspects of the fight against AMR. Different disciplines were integrated in the initiative through veterinarians, microbiologists, economists, vaccinologists, pharmacologists, chemists, sociologists, psychologists, and physicians. Multiple

sectors were targeted through the research, which aimed to: develop new antimicrobials, improve antimicrobial effectiveness, understand the mechanism of AMR, develop alternatives to antimicrobials (including vaccines and estimating their costs) and understand the drivers for prescribing antimicrobials. Human and animal sectors are commonly targeted. UC-CARE had six different WPs acting at different levels (**Figure 1**): WP1—drug discovery and translational research, WP2—alternative control strategies with focus on vaccine development, WP3—optimization of antibiotic therapy, WP4—comparison of current practices in human and veterinary medicine aimed at improving diagnostics, WP5—cost-benefit analysis and effects of management-based control options in livestock and WP6—societal issues and governance.

The initiative aimed to have an "impact on the life of humans and animals by providing new knowledge and solutions for enhanced diagnostics and antibiotic therapy of bacterial infections, leading to a significant reduction in the use of antibiotics in human and veterinary medicine" (extract from UC-CARE research funding proposal). The OH approach was integrated into the initiative at the proposal writing phase. It became apparent from the beginning that interdisciplinarity should be considered when deciding who should be involved in the initiative. Disciplines, hierarchies and responsibilities were shared among WPs from the beginning of the project.

Actors were from the University of Copenhagen, and included professors, PhD students, post-docs and other scientific and technical/administrative personnel. They were all located geographically close to each other as many were based in Copenhagen.

Stakeholders other than the actors were involved from the onset of the project, which aimed to include all possible partners from human and veterinary public institutions and private organizations. They were identified through the consortium (cf. OH sharing), and some were even more integrated into the process by participating in the research, being co-supervisors of students. They were referred to as "external partners," and they could have an impact on the research and its development.

No legal **restrictions** were identified. The discovery of new drugs is not subject to regulation, only the market release, so no particular factor limited the initiative. Sociologists, psychologists, linguists, and economists included in the project aimed to identify any social restrictions among antimicrobial prescribers, patients, and animal owners in order to understand the drivers of antimicrobial use and any alternatives. In addition, the social stigmatization of people and owners of farms with AMR infections was investigated.

Some **consequences** or **impacts** of this initiative were expected at societal level, although it was hard to infer before initiation of the project which were most likely to be realized. For instance, some decisive findings could lead to other research projects and the future development of new drugs or vaccines, and the consortium could be expected to have an impact on decision making through engagement with stakeholders.

The main **dimensions relevant to the initiative** were the geographical, temporal, and legislative dimension, as well as the dimension of life, network and economy (i.e., most of the dimensions identified for the underlying system). When describing the dimensions reflected in UC-CARE outcomes, all stakeholders that responded to the online questionnaire had quite a global and holistic point of view (**Figure 2**).

Evaluation Element 2: Theory of Change of the Initiative

The TOC of the UC-CARE project is presented in **Figure 3**, and represents the different societal impacts that the initiative aimed for, together with the expected outcomes and the outputs determined by the different inputs and the linkages between these. Actions and inputs of the initiative were based on different sources and resources, such as results from previous studies, available Danish data, interviews with actors at governmental and societal level and the participation of patients, animal owners and prescribers in several studies.

Evaluation Element 3: One Health-ness Evaluation of the Initiative

Degree of One Health-ness

The NEOH tools were completed based on the responses to the online survey and face-to-face interviews, as well as the information provided in the consortium proposal and mid-term evaluation report. The most relevant outcomes of the interviews are detailed below and the completed assessment table is available in Annex 3 (**Supplementary Material**).

The UC-CARE was a 4-year project and was therefore limited in time relative to the system. Moreover, the project was focused on the Danish system: all researchers were based in Copenhagen and some WPs focused on the particularities of the Danish system (e.g., cost-benefit analysis, effects of changed legislation, treatment guidelines for antimicrobial use). Other WPs worked across borders (e.g., prescription practices and perceptions of doctors in Denmark, France and Italy) and some of the technical results (e.g., within drug development) are of international relevance. Therefore, several outputs might still have an impact at European and international levels for years after the finalization of the project.

The main tool for communication among all participants was the annual consortium meeting. The meetings were the only opportunity to gather all participants, external partners, stakeholders, and advisory board members. The only other consortium-based support for communication and exchange of progress, results and updates among the participants and WPs was the International Conference on One Health and Antimicrobial Resistance (ICOHAR), organized by several of the consortium members and held from 30 September to 2 October 2015. During these events, the consortium partners had the opportunity to discuss and gain a better understanding and a more global overview of the topic of AMR and its issues. All interviewees mentioned that they gained a more comprehensive way of thinking about the AMR challenge and an understanding that all actors were involved and responsible. The annual consortium meetings were described by some interviewees as "generally interesting," but also as "very superficial" and a "political aspect of the project." Some compared it to reading

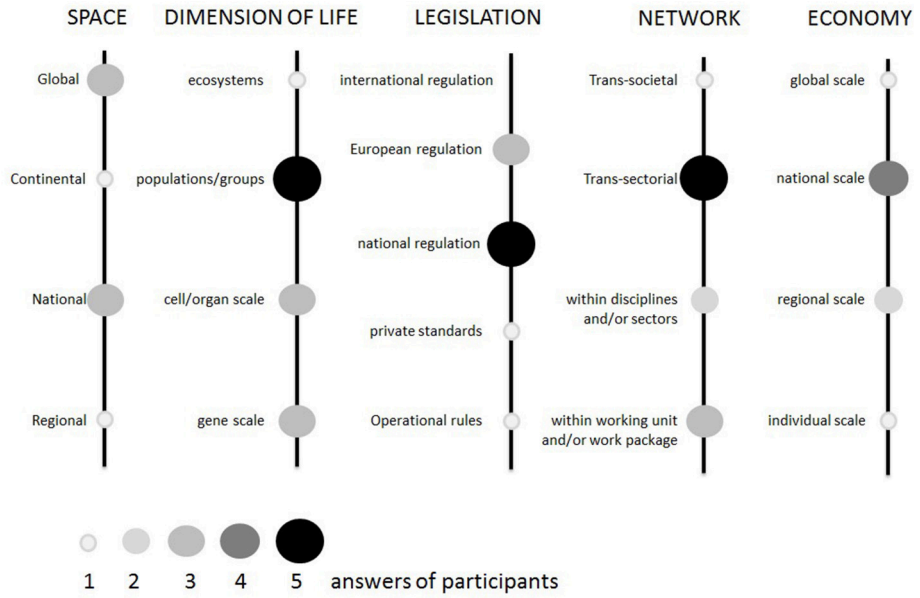

FIGURE 2 | Answers from eight stakeholders and external partners to the online question, "how are the following dimensions (or aspects) reflected in the UC-CARE project outcomes? (Or how comprehensive is the project with regard to these dimensions of One Health?)".

a newspaper: "really interesting to hear about new things, but forgot them right after the meeting." Others were less impressed and described the meetings as "horrible" and "incoherent" with no real interaction between people, and not very informative. All interviewees mentioned that the difficulties experienced with communication during the annual meetings were probably linked to the major issue of not speaking a common scientific language across disciplines, and a lack of focus on making the methods and results understandable for everyone.

WP6 on "societal issue and governance," and to some extent WP5 on "cost-benefit analysis" were mentioned by participants from other WPs as not being easily integrated into the discussions. Some interviewees had the perception that the economists and sociologists did not understand the research at a cellular level and became somehow excluded from discussions, becoming less and less involved in both the discussions and meetings. Interestingly, the sociologists and economists did not share this perception. Also worth noting is that all participants from other WPs indicated that results from WP5 and WP6 were really interesting.

Interaction with and interest from stakeholders varied a great deal among the WPs: from external and strong partners being directly involved, to limited contacts. Several interviewees mentioned that the impact of stakeholders was low, and their participation in the annual consortium meetings was described as decreasing over the duration of the project. The meeting took place once a year and included an exchange of results, but stakeholders' input was limited. Some interviewees mentioned that the project could not be completely transparent with the stakeholders, and that it was not possible to share data with them. They had limited exchanges because the project researchers had to "keep their cards close," and the ownership of data was a major issue, with intellectual rights/technology transfer departments on both sides drastically slowing possible exchanges of data. This could explain the limited interactions with companies. One WP organized an exchange with a diagnostic company for PhD training. However, one WP reported sharing of data with stakeholders without any issues. No stakeholders from the general public (e.g., consumers or animal owners) were involved in the project except as study participants or animal owners in some of the observational studies in WP4, WP5, and WP6.

Differences were highlighted among the WPs in their global organization and the application of OH. This clearly led to different experiences of the OH approach among the participants. Discussions and knowledge sharing were usually organized among the different disciplines within the WPs to discuss progress and methodology. The WP4 "mapping of current practice in human and veterinary medicine" was mentioned four times by interviewees as the "real" OH WP of the project, with an advanced joint research among different sectors and disciplines. Three interviewees mentioned that the project was mainly focused on PhD students and post-docs, and that it was difficult to maintain interdisciplinarity because PhD students and post-docs need to focus on a particular topic to reach a necessary level in their field. The perception seemed to be that completely integrated, interdisciplinary research would be more easily driven by more experienced researchers.

Collaboration was mentioned among some WPs, but mainly between researchers from closely related disciplines. Interviewees also mentioned regular collaborations with scientific partners outside the project. This could include researchers from the same university or foreign partners.

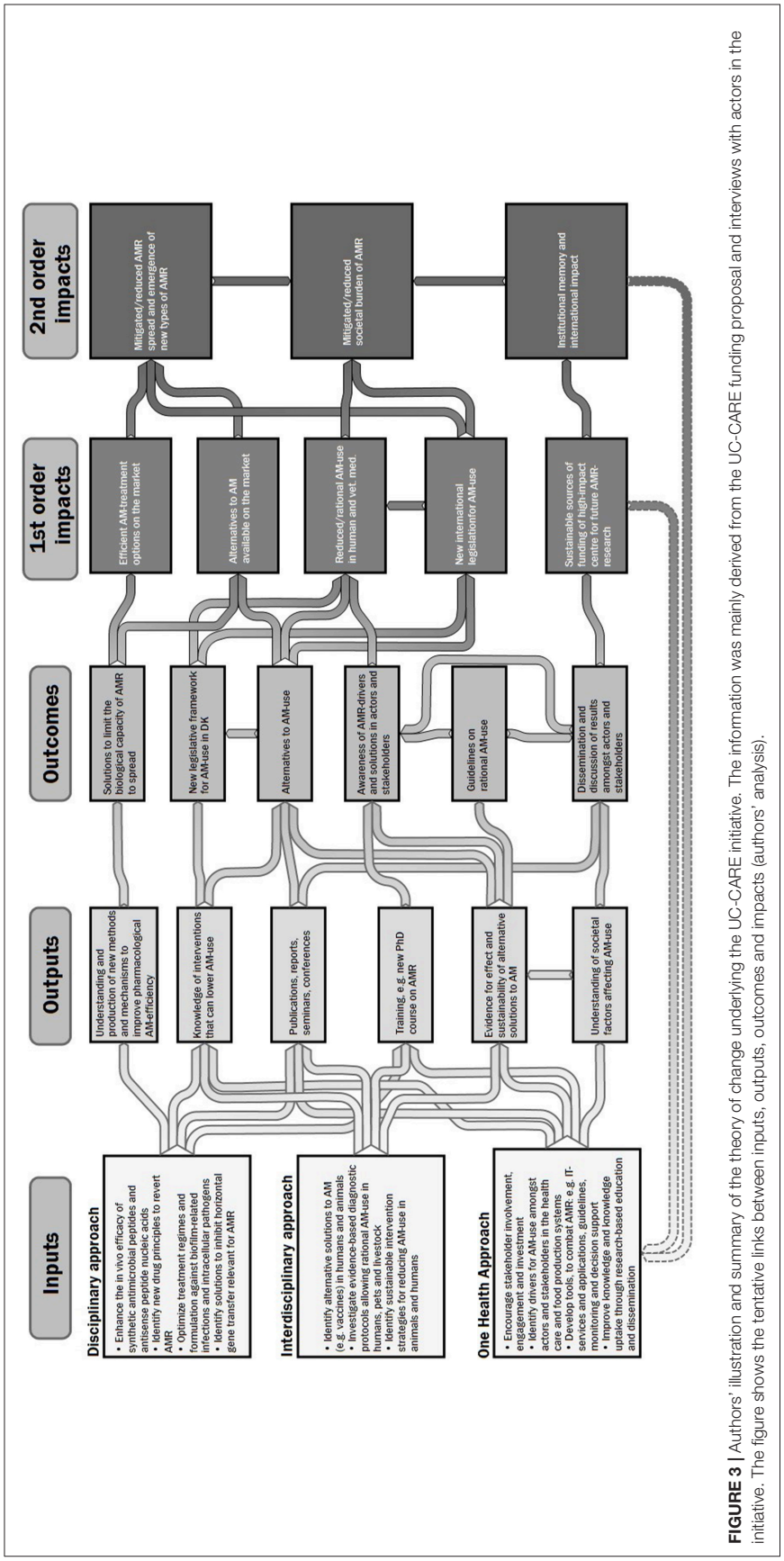

FIGURE 3 | Authors' illustration and summary of the theory of change underlying the UC-CARE initiative. The information was mainly derived from the UC-CARE funding proposal and interviews with actors in the initiative. The figure shows the tentative links between inputs, outputs, outcomes and impacts (authors' analysis).

Two interviewees mentioned that the project mainly gathered microbiologists, and that this could be related to the PI being a microbiologist. They suggested that while writing the proposal, the initial PI could have been more inclined to write it from a microbiologist point of view. Other interviewees mentioned that medical and veterinary science disciplines represented 80% of the actors, whereas e.g., chemists were less well-represented within the project. Those assumptions could not be confirmed as no all-inclusive list of UC-CARE participants was available to the evaluators.

The deficiencies identified in the working characteristics related to gender imbalance (i.e., male domination) and a disparity in the representation of different disciplines, which could be partly due to a lack of open-mindedness toward other disciplines and sectors. We also identified a lack of mid- and long-term flexibility due to fixed research objectives for PhDs and post-docs, as well as a lack of regular collaboration among the different units in the consortium. UC-CARE did not manage to allocate resources for internal communication processes and tools, nor to generate the planned IT-tools dedicated to monitoring and decision support for patients/farmers and doctors/veterinarians and for communication and mediating technologies.

In summary (**Figure 4**), the project was well-intended and thought through, as shown by the relatively high scores for planning, thinking and systemic organization. The project leaders' understanding was global and integrated all important aspects of OH. However, implementation during the project period was more difficult, particularly in terms of working and sharing, which can eventually also affect learning across such a consortium. This fact was mentioned several times by the participants and is reflected in the low overall scores on working, sharing and learning.

The OH index of UC-CARE was 0.34, which according to the NEOH framework can be interpreted as a mediocre level of implementation of an OH approach in the initiative. The OH ratio was 1.1, indicating a balance (close to 1) between the OH operations and supporting infrastructures. However, the ratio does not say whether these were then prioritized sufficiently. The formulae for calculating the index and ratio are provided in the introduction paper by Rüegg et al. (26) and in the OH Index Ratio sheet in Annex 3 (**Supplementary Material**).

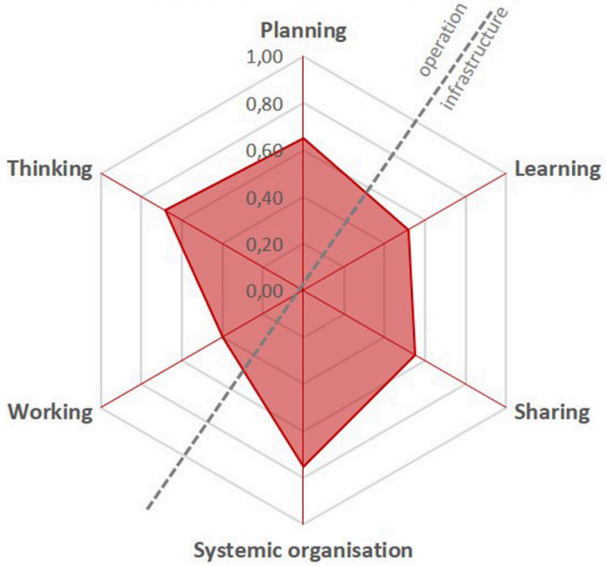

FIGURE 4 | Spider diagram representing the scores allocated to the elements Thinking, Planning, Working, Learning, Sharing and Systemic organization of the OH-ness assessment of UC-CARE on a scale from 0 to 1 for each element.

Pros and Cons of the OH Initiative Implementation

The UC-CARE participants stated that the main advantage of the consortium was its ability to broaden their interest in other disciplines and methodologies. They also mentioned that the project increased and improved their networks, which in some cases had led to new partnerships and research applications that would not have been realized or would have been constructed differently without the consortium. During group interviews with PhD students and post-docs, all interviewees mentioned they would search for OH working roles in the future, if possible. However, two interviewees clearly mentioned that it was not a main driver for their future jobs in research.

Two interviewees mentioned that interdisciplinarity in research was difficult because publishing together was a challenge. Some papers were written with authorship from different disciplines, but publishing a single discipline-targeted paper was found to be less challenging.

Critical Review of the Initiative in Relation to an OH Approach

All interviewees mentioned that this project and this new approach changed their mentality about other disciplines and even about the AMR challenge. They acknowledged that their understanding of the issue on a global scale had improved during the project. Interest in other disciplines grew among all interviewees, but for most of them it was not highly influential in their daily work. However, they all mentioned that the OH approach could have been pushed further in UC-CARE, and that it was not fully pursued due to a lack of experience with the OH approach.

Moreover, several WP leaders mentioned that the OH approach did not reach the people working in the laboratories, but was instead mostly perceived at senior/WP leader level. This was confirmed by the early-career researchers, who explained that they were not previously aware of OH. They learnt about this new approach and about working together in an interdisciplinary environment through the project. However, the interviewed early-career researchers did not have the opportunity to experience multi- or interdisciplinarity in their daily work.

Interviewees stated that they sometimes developed ideas and learnt lessons from this first OH initiative to establish better links among research WPs and disciplines. Some stated that more funding would have allowed larger teams (hence with a larger impact) with more legitimacy to spend time on

collaborations and interdisciplinary work, and with someone in charge of coordinating joint work. The PI's commitment was not considered sufficient to sustain an OH approach in this consortium; a greater investment of resources would be needed to promote more transdisciplinary tasks. In addition, the WPs could have been organized differently, with continuous and common goals identified. An interviewee mentioned that co-supervision of PhD fellows within and between WPs would support interdisciplinary research.

Stakeholders and external partners reported having a good understanding of OH and its importance (**Figure 5**), with all agreeing that an OH approach is relevant to the AMR topic. However, the application of an OH approach was more difficult because more time was required for it to be realized and because the workload did not appear to be truly balanced among disciplines. The stakeholders reported that the final results were less remarkable than they had expected. However, they also indicated that UC-CARE seemed to be a good experience that should be extended and developed.

Evaluation Element 4: Outcomes

Numerous and diverse outputs and outcomes were identified in UC-CARE and these are detailed in **Table 1**.

The UC-CARE proposal included the objective to provide "new knowledge and solutions." It was expected that OH outputs and outcomes would have an impact on human and animal populations through new knowledge and guidelines for the prudent use of antimicrobial. It was also expected that the actors would produce many types of publications and that disciplines would learn from each other and start up new projects and collaborations. Finally, new educational activities created in collaboration among multiple disciplines were planned at PhD level (**Table 1**).

The final number of publications will not be known until the final UC-CARE report becomes available during 2018, as no central collection of publications is currently available. However, according to the mid-term report that was sent in for evaluation by an external panel in April 2016, 33 international peer-reviewed journal papers had been published, 13 more submitted and 25 papers were listed as being in the pipeline. Most of these were outputs of specific disciplines, but it was noted in the report that an additional 25 publications were anticipated in the UC-CARE consortium, many of which would be authored by interdisciplinary teams. As mentioned by the interviewees, it seems that it typically takes longer to write and publish papers from interdisciplinary teams. The fact that it was difficult to extract information about the output of the consortium in terms of publications is reflected in the relatively low scores for sharing and learning in the NEOH framework. Structures to improve knowledge and information sharing across OH consortia should be considered. These could include online resources, newsletters explaining new results, transdisciplinary research activities, interdependent tasks and more joint teaching activities among the WPs.

Several points were highlighted by participants throughout the interviews. Participants clearly indicated that they achieved new knowledge and solutions in their own research field. The problem of AMR had been understood a bit more, allowing going further in terms of improving health. Some results could even have a very high impact, yet there tended to be a gap between the results and their applicability that would need several further steps. Some results, however, could already be applied at the time of the evaluation. One interviewee mentioned that results were important but, in a project such as UC-CARE, outcomes had to be explored and thought of differently and in broader terms. They explained that when looking from a different perspective the success of the project could be attenuated. Future collaborations were agreed and the money was fairly well-spent, yet they thought that disciplines could have provided more "strict" science results. Their definition of "strict" scientific results indicated a paradigm of hypothesis-led research with little understanding of how the hypotheses were originally framed and constructed, and which is largely driven by previous work and available measurement tools. They admitted that UC-CARE involved many scientific disciplines, which contributed greatly to the common goal.

TABLE 1 | List of different outputs and outcomes of the UC-CARE project for the categories: disciplinary, interdisciplinary, OH and unexpected outcomes and outputs.

Disciplinary outcomes and outputs	- A large number of scientific papers - PhD theses - Department/university recognition at international level - Development of new networks and projects - New high-profile funding for a long-term research efforts based on UC-CARE - New funding for long-term research efforts based on UC-CARE
Interdisciplinary outcomes and outputs	- Some scientific papers - Development of new networks and projects - Interest of participants in interdisciplinary work and results - Treatment guidelines for antimicrobial use for humans and animals
OH outcomes and outputs	- OH courses at DK university for PhD students and post-docs - Common course for human and veterinary medicine candidate students - Interest of participants in OH approaches - Learning/understanding of the planning of organization and resources in OH consortia
Unexpected outcomes and outputs	- New experience that it was difficult to plan, perform and report interdisciplinary research - New national Danish legislation with direct reference to UC-CARE results - Initiation of treatment guidelines for antimicrobial use at EU level - Three seats in the National Council for Antimicrobial Resistance - One seat in the Council for Improved Hygiene

DISCUSSION

Discussion of Evaluation Methodology

The evaluation process as defined by NEOH generally went well and was positively received by the participants. Those who were

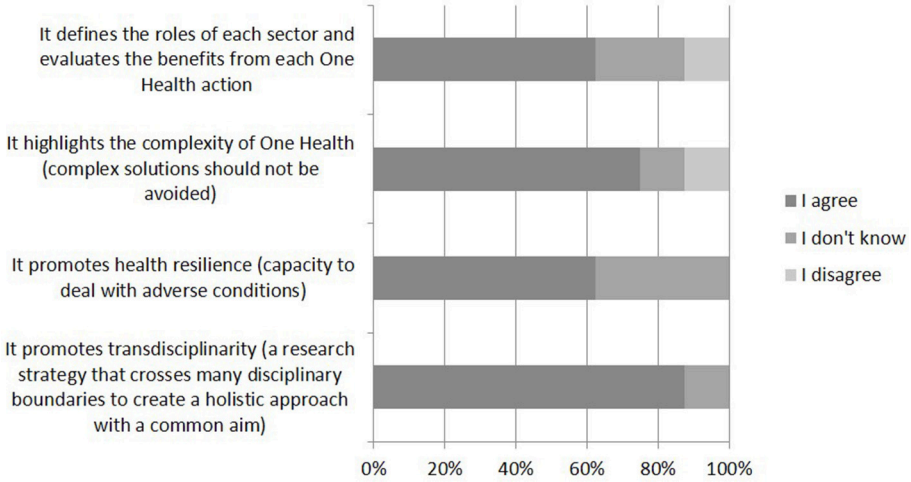

FIGURE 5 | Answers from eight stakeholders and external partners to the online question, "which of the following do you see as benefits of the One Health approach?".

contacted showed a general willingness to participate and to be interviewed. However, many early-career researchers were difficult to reach or replied that they had left the consortium after finalizing their project activities, while some never answered. The reasons for these difficulties relate to the increased workload of some individuals as their PhD projects came to an end, and some being on maternity leave and/or having already left the project. The PI and one internal partner supported formally the evaluation among the consortium (e.g., sending emails). That was beneficial and probably encouraged participation. Despite these difficulties, the study is based on a reasonable number of interviews that overall were representative of the broad range of disciplines in the UC-CARE consortium.

As expected, data collection was the most critical and time-consuming part of the evaluation. The NEOH tools require a large amount of data and information, and as with any thorough evaluation process, this can raise difficulties. Data were not always available from written internal documents and had to be supplemented with interviews, providing potentially subjective information. As the data needed were unusual and differed from other types of research evaluations, the questions sometimes puzzled the interviewees, yet they all made the effort to answer the questions and rethink their project activities. The semi-open interview format allowed information that was not predetermined to be gathered. The online questionnaire for the external partners and stakeholders was less successful (only eight answers out of 27 people contacted), which could be due to: (i) the length of the questionnaire, (ii) some stakeholders no longer being involved in the project (e.g., change of employment), and/or (iii) some stakeholders having little involvement in the project from the beginning, thus feeling that they did not have much to contribute.

The first steps of the evaluation (i.e., context description and TOC) were descriptive and required a global and detailed understanding of the context, the initiative and a deep reading of all internal documents such as the project proposal and mid-term evaluation report. Ideally, this exercise should have been conducted by the project initiators during the proposal writing phase. The presentation of the results at the annual meeting helped gather comments and remarks about the description and understanding for the TOC elaboration. The completeness of the TOC reflects the ideas of the UC-CARE participants and could overlook important elements such as unwanted side effects of outcomes (e.g., a discovery of new drugs could lead to new types of or more AMR) or other unexpected outcomes (e.g., durable impact of knowledge gained through courses among PhD students and the scientific community) (29). Durable feedback loops in the TOC were not identified or anticipated in the proposal. The project would probably have benefited from more consideration about the logics in the TOC in advance. Participants and partners would have been able to better understand the expected changes in the context and to identify the OH outcomes. To assist evaluators of OH initiatives, the authors recommended that NEOH elaborated on proper TOC descriptions and ways to link these with the OH-ness evaluation and the expected and unexpected outcomes in the overall evaluation in their handbook of OH evaluation.

The evaluation was mainly conducted by two assessors, but this was counterbalanced by the global review of the evaluation by two other authors and a discussion of the results with the UC-CARE consortium members. Two of the authors were internal actors and two were external to UC-CARE. The knowledge that the internal actors had about UC-CARE was very valuable to understanding the global functioning and processes of the research project, but external and internal evaluators will typically have a complementary overview of the context and initiative (30). Integrating internal partners can be a challenge as they can have a biased understanding of the initiative. However, total objectivity can never be reached (31). By integrating internal and external evaluators, we hoped for a balanced and neutral

approach in the evaluation. Moreover, due to the complexity of OH challenges, the evaluation of OH initiatives and their outcomes cannot be expected to be an intuitive and easy task (15, 32), and combining the strengths of several evaluators should be an advantage.

Discussion of Results

As described above, the mid-term evaluation of UC-CARE deemed the project successful, based mainly on traditional research evaluation criteria focusing on the number and impact of publications and disciplinary research outputs, successful pursuit of PhD and post-doc tasks and dissemination and uptake of research results in the pharmaceutical industry (24). The present study provided different and complementary insights into the underlying operations and supporting infrastructures of the UC-CARE consortium and research project, and allowed us to capture its complexity and OH approach in more detail. The OH evaluation should be valuable for the consortium as it is based on a broader range of parameters relevant to the societal impact of the initiative, and highlights other strengths, weaknesses and lessons learnt by the use of an OH approach for AMR-related challenges than traditional research evaluation methods. In the authors' view, the results of the evaluation could also be useful for future proposals by research consortia keen to build their projects on an OH approach.

Interestingly, the shortcomings identified in UC-CARE were to some extent similar to those found in an evaluation of an OH surveillance system for West Nile Fever bringing together public health, veterinary public health and entomology experts (11). Indeed, working and learning characteristics were also scored lowest in the West Nile Fever-initiative albeit higher than for UC-CARE. We also identified a lack of mid- and long-term flexibility, planning processes, and resources dedicated to sharing. This is unfortunate as it has previously been shown that societal learning is important for control strategies to have an effect (33). In other words, although the idea behind UC-CARE reflected in the TOC was highly relevant, reasonably well-planned before the initiative and seemed highly integrated with many disciplines and with relevant stakeholders involved from the beginning, it proved difficult to carry out the OH approach in practice, and many of the actors went back to uni-sectorial and disciplinary work in their daily tasks. This was to the benefit of the disciplinary outputs, but potentially reduced the societal impact of the initiative.

Also, participants mentioned several times that it was difficult to publish interdisciplinary papers. Researchers and research projects are usually evaluated by the disciplinary quality and impact of their publications, whereas the OH approach has not been perceived and promoted as a quality characteristic in journal papers to date. Early-career researchers were particularly concerned about this, and the issue is underpinned by journals targeting OH issues being ranked low on impact, see e.g., One Health: https://www.journals.elsevier.com/one-health (accessed on 26 July 2018).

The low scores obtained for working, learning and sharing can be explained by several factors. The project was a first attempt at a large OH project in this organization, so there was little experience to build on. Due to the funding framework, the project promoted young researchers, who must focus on particular disciplines in order to become specialized. This refers the issue back to funding bodies, who must appreciate that the impact of research is influenced by additional means other than publication metrics, while scientists tend to base their activities on criteria and indicators that are applied in evaluations (34).

Changes in the mentality of the scientific community would promote OH by, for example, defining interdisciplinarity as a specialization. However, thinking, planning, and systemic organization received high scores, and the project was prepared and built in a clear and conscientiously way by the first researchers involved in the proposal, who all seemed to have a good understanding of OH approaches. Interviewees mentioned several ideas to improve the quality of the OH approach, e.g., allocating resources differently and defining a specific budget for OH (including collaboration, engagement of the public stakeholders, coordination promoting new collaborations across sectors) that could be used throughout the project. In addition, the WPs could be organized differently, to encourage more interaction among the different disciplines. The supervision of PhD students could be shared among different disciplines and could involve more senior researchers who could dedicate part of their time to interdisciplinary activities and allocate a larger budget so that more laboratory personnel could be involved. The project could also benefit from having a budget for a specific OH coordinator in the project, whose role might include promoting the exchange of information and results among center members, organizing workshops and learning activities, and developing the relationship with stakeholders. Importantly, limitations in the project did not reduce the motivation of partners in pursuing OH projects in the future.

It should be noted that the OH index and ratio are single numbers that cannot reflect the variation among actors in terms of their personal experience. Indeed, each UC-CARE member experienced the initiative differently according to their experience, the WPs and their personal interest. The index and ratio might eventually be compared across OH initiatives to assess whether it is important to score certain characteristics higher than others to promote health-improving societal changes, e.g., sharing and learning, as suggested above.

Differences were identified among the WPs in UC-CARE. For example, WP4 was already organized to provide an interdisciplinary environment to compare human and veterinary medicine practices. All interviewees of WP4 were enthusiastic about their experience and acknowledged that working in this interdisciplinary environment improved the quality of their work and outputs. Differences in experiencing OH were also seen at an individual level. Some interviewees were more reluctant and disparaging of their experience than others. Conducting several interviews for each target group allowed us to gain a better understanding of the real situation, and highlighted the potential differences between WPs and individuals.

UC-CARE involved the different stakeholders in the process from an early point. This is not unusual for such projects, but it indicates the interest of UC-CARE in providing useful

results. Some partners worked closely with PhD students, allowing the exchange of data and discussions concerning the progress of research. This aspect is expected to be important and valuable for the project (35). The process of stakeholder selection was not systematic, but no major gaps were identified. This may be attributed to experienced researchers bringing their trusted networks into the consortium; an important quality to acknowledge.

Finally, noteworthy positive mental and structural changes and improvements were consistently identified across interviews. For example, all actors mentioned a new interest in the disciplines and work of others, and in future joint proposals, as well as expanded networks. They all acknowledged the necessity for and benefit of working with other disciplines, and from this point of view, the initiative was a success. In addition, the outcomes identified during the evaluation (**Table 1**) can be expected to have an impact on AMR development, and unexpected outcomes were identified, which led to changes in legislation and strengthened representation in advisory forums, which may in turn lead to more evidence-based policy development. The latter is indicative of the lasting impact of the initiative on AMR policy, which can be considered the ultimate goal of research conducted with public funding.

AUTHOR CONTRIBUTIONS

AL and LN were substantially involved in all steps of the study from the conception to the design of the work. They also primarily drafted the paper and implemented several substantial contributions from other co-authors. KS and JR were also involved to some extent in these steps. Their contribution was valuable and essential to the final version of the paper. AL, NL, KS, and JR approved the final version of the paper, submitted to Frontiers. They also agreed to be accountable for all aspects of the work, in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2018.00194/full#supplementary-material

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Application of the NEOH Framework for Self-Evaluation of One Health Elements of a Case-Study on Obesity in European Dogs and Dog-Owners

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Obesity is a malnutrition disorder of global concern with increasing prevalence driven by underlying societal, economic and environmental mechanisms leading to changed physical activity patterns, eating behaviors and diet compositions in both humans and in their pet-dogs. A questionnaire-based study was carried out as a joint effort across 11 European countries. It was considered a One Health (OH) initiative between scientists from human and animal health sectors aiming to identify factors associated with obesity in dog owners and their dogs. Expected outcomes of this approach included new insights unachievable by single-sector research initiatives, and hence potentially leading to new cross-sectorial solutions. We performed an internal evaluation among the actors of the obesity initiative using the framework for evaluation developed by the "Network for Evaluation of One Health" (NEOH). It served as a case-study for the NEOH consortium to illustrate the application and provide feedback on the utility of the framework. The evaluation was performed by a subgroup of scientists also involved in the obesity study group, and it consisted of: (1) the definition of the initiative and its context, (2) the description of the theory of change, and (3) the qualitative and quantitative process evaluation of operations and supporting infrastructures scored on a scale from 0 to 1. In the One Health operations, the obesity study initiative scored medium high on OH-thinking (0.5) and OH-planning (0.45), and relatively high on OH-working (0.7). The supporting infrastructure score was high for systemic organization (0.8), but low for sharing (0.45) and learning (0.28). The calculated OH-index was 0.29 (on scale 0 to 1) indicating that the full potential of health integration and collaboration was not exploited in the initiative, and the main issue identified was a lack of stakeholder engagement. The OH-ratio of 1.1 indicated equal focus on operations and supporting infrastructures. Hence, the evaluation identified potentially counterproductive as well as

beneficial characteristics, which are further discussed in this paper in relation to the expected outcomes. The NEOH framework for evaluation requires that the evaluators have a good understanding of systems thinking and the mechanisms of the health issue targeted by the initiative.

Keywords: obesity, one health, evaluation, canine, dog, human

INTRODUCTION

Today, obesity is considered the most frequent malnutrition disorders in many parts of the world. It is increasingly recognized as a "wicked problem," because it is highly complex and resistant to resolution with no clear stopping points. Furthermore, attempts to solve it might reveal or create new problems, because it is a symptom of other underlying problems with systemicsocietal, environmental and economic drivers (1). Obesity is associated with different pathologies including orthopedic and respiratory diseases, endocrinologic and oncologic disorders, compromised well-being, and decreased life-span (2, 3). In addition to the increasing societal burden of obesity related to the increasing health expenses, disabilities, reduced life-expectancy and productivity losses, there appears to be detrimental environmental impacts such as increasing emissions of greenhouse gases associated with increasing population rates of obesity (4). All of this is a growing concern, since the prevalence of obesity is continuously increasing in both dogs and humans (5, 6). Hence, all potential obesity mitigation opportunities should be explored, including links between and factors explaining the links between obesity in dog-owners and their pet-dogs. Studies have shown that such links are relevant with common underlying environmental factors including physical activity patterns, eating behavior and diet compositions likely to be driving the development in both species (7, 8). Even though initiatives have been carried out and are on-going to mitigate the obesity development in humans, and in pets, respectively, transdisciplinary approaches bridging different disciplines and health sectors, e.g., human and veterinary medicine, sociology and psychology and targeting both species simultaneously through joint interventions are likely to be more effective or at least to contribute to improved mitigation of the obesity trends (9). Such transdisciplinary efforts including focus on human behavioral changes benefitting animals as well as the environment are often referred to as One Health (OH) initiatives, when they are aiming to achieve improved human and animal health and welfare simultaneously. Kushner et al. (9) demonstrated the benefits of a combined people and pet weight loss program. However, dog-ownership has hitherto mainly been investigated as a tool for human health status improvement. An example of this is the study by Wohlfarth et al. (10) that illustrated significantly higher level of some types of physical activity in obese children between 8 and 12 years old, who were enrolled in a comparative intervention trial with dogs vs. human co-performers of movement tasks.

Aiming to identify social, environmental and economic drivers of obesity in dog-owners and their dogs, a questionnaire-based study was performed to collect and analyze information on self-reported body mass parameters, physical activity, eating patterns, diets and diseases in both humans and dogs, as well as perceptions of the dog owners by scientists related to both human and pet health sectors in 11 European countries. Potential cross-sectorial solutions with added value toward obesity mitigation were the main targets of that study, which will be referred to in this paper as "DODOS" (i.e., *D*og *O*wner And *D*og *O*besity *S*tudy). Because of the joint research team being multidisciplinary (**Table 1**) and because the target was the detection of social and environmental drivers of obesity in two populations, dogs and their owners, this research initiative could be considered an example of a OH approach to a health challenge that not only occurs in at least two species, but also seem to be linked by common factors related to the two species. We therefore used DODOS as a case study of an OH initiative about a non-communicable disease for illustration and evaluation of a new framework and tools developed to facilitate evaluation of OH initiatives. Over the last decade, there has been growing interest for the OH approach implementation in the health research, systems and services, since mutual benefits are expected in comparison to single-sector approaches—also referred to as "silo-approaches" to health issues (11). The benefits include improvement in animal-, human-, and eco-health and well-being, higher quality or larger quantity of relevant information and economic efficiency (11). However, no validated science-based evaluation protocols for quantitative measurement and evaluation of OH activities have previously been available. In order to fill this gap, a "European Union Action on Coorporation in Science & Technology" (EUCOST Action, TD1404) "Network for Evaluation of One Health" (NEOH) designed science-based guidelines for qualitative and quantitative evaluation of OH-initiatives. The NEOH framework (12) is recommended for external evaluation of OH-initiatives. However, it might also provide useful information and feedback, if used for self-evaluation within an initiative.

The aim of the present work was to perform an internal evaluation (i.e., a self-evaluation) of the DODOS initiative using the NEOH evaluation framework and tools to improve the learning about essential operations and infrastructures of OH-initiatives within the DODOS consortium. It also served as a case-study for the NEOH consortium to illustrate the application of the framework to a non-communicable disease, and to gain feedback on the utility of the framework and tools for further improvements.

TABLE 1 | Participating countries and involved specialists in the DODOS study evaluated in this manuscript with indication of the represented disciplines and sectors.

Nr.	Country	Involved Specialists
1	Croatia	Clinical pathology specialists (VM)
2	Denmark	Epidemiologist (VM) Endocrinologist (VM)
3	Italy	Clinical pathology specialists (VM) Internal medicine specialist (VM)
4	Lithuania	Anatomy specialist (VM) Physiology specialist (VM) Pulmonologist–pediatrician (HM)
5	Poland	Reproduction specialist (VM)
6	Portugal	Anaesthesiologist (VM) Biologist PhD student (VM)
7	Rumania	Reproduction specialist (VM)
8	Serbia	Immunology specialist (VM)
9	Spain	Clinical pathology specialists (VM) PhD student (VM) Odontologist (HM)
10	Sweden	PhD students (VM)
11	Turkey	Cardiologists (VM)

VM, veterinary medicine; HM, human medicine.

MATERIAL AND METHODS

In the DODOS, a questionnaire about the perceptions of dog-owners about human and dog obesity, factors associated with and potential drivers of obesity was designed and distributed to dog-owners in 11 European countries by means of personal contacts, veterinary clinics and social media during the period December 2016 to March 2017. The questionnaire contained 74 questions, and apart from demographic questions and questions about health status in the dogs and their owners, many questions were on a Likert scale to assess perceptions of different statements about eating behavior, diets, physical activity and perceptions about the dogs and the dog-human relationship that could be related to obesity development. In total, 3185 questionnaire responses from 10 of the 11 study countries with a sufficiently high number of valid responses were included in multivariable statistical analyses. Relevant perceptions, physical, socioeconomic and environmental factors associated with obesity in dog-owners and their pet-dogs were identified. The OH evaluation of DODOS was initiated a few months after the initiation of the DODOS. However, at the time of the performance of the last part of the evaluation, the data collection and statistical analyses were finalized, and the DODOS was reported in a manuscript submitted for peer-review in an international scientific journal. However, the results of the DODOS will not be covered in this manuscript except where directly relevant for the evaluation, as they are not the main focus of the OH evaluation.

The NEOH framework includes four overarching elements (12). However, only elements one to three were carried out for DODOS, i.e., (1) the definition of the OH initiative and its context (i.e., the system, its boundaries, and the OH initiative as a subsystem); (2) the assessment of expected outcomes based on the theory of change (TOC) behind the initiative and (if possible) unexpected outcomes emerging in the context of the initiative; and (3) the process assessment of the operations and supporting infrastructures, also known as the "OH-ness" of the initiative. Element (4), assessment of the association between the degree of "OH-ness" and the outcomes produced, could not be performed because it makes most sense to evaluate element (4) by comparing across several case studies, a task that the NEOH consortium will work on after the framework has been used for many case studies.

The background theory and each element of the NEOH framework are described in detail by Rüegg et al. (12) and a supplementary Microsoft Excel file is provided online and can be used as a template for the evaluator(s) to fill in when going through the process evaluation in element three. The system leading to human and pet-dog obesity was described by the first and last authors of this manuscript by building partly on their experience with pet-dog obesity from veterinary clinical practice and research, and partly on literature search on the system boundaries and linkages relevant for the development of obesity in humans. The TOC was deducted by logical reasoning combined with literature suggesting or illustrating the benefit of a joint effort between human and pet-dog scientists in the obesity context.

Element three was an internal evaluation mainly performed by the first two and the last authors of this manuscript, even though the interpretation of the points to be evaluated in the tool was discussed with the other authors and NEOH consortium members during the process. To be able to fill in the provided NEOH tool for the "OH-ness" evaluation and to assess the outcomes of the DODOS, the core scientific members, i.e., the 24 authors of the manuscript reporting on the DODOS, were in late May-early June 2018 asked to respond to an anonymous online questionnaire containing 20 questions about thinking, planning, working, sharing, learning and systemic organization as well as expected and unexpected outcomes. The questionnaire with introduction text, questions and frequency distributions of answers as well as written answers to open ended questions are available in Supplementary materials 1. The means of communication were otherwise mainly through email and on-line meetings with individual scientists from the different participating countries during the case study period.

RESULTS

This section provides an overview of what was found and deducted about the three first elements in the NEOH framework, in other words what the evaluators found relevant and true for the obesity case study based on the input provided by DAODOS actors and the experiences gained during the obesity case study period. It does not contain results from the obesity study itself, except where it is considered relevant to understand how the results were obtained or deducted in the evaluation.

System Definition and the Initiative Within the Defined Context

Obesity is a global epidemic health problem, for which all the dimensions of the system are highly interconnected. The following dimensions were considered in the context: *Geographical space* a highly important dimension since obesity drivers are present worldwide even though they can vary between countries. The dimension of life is an important dimension with obesity drivers acting at all scales (i.e., at cell, organ, individual, population, regional, national society, international level). *Network/organization* is a highly relevant dimension as obesity drivers and potential solutions exist at the individual, institutional, national and international levels. *Economic* drivers are important for the development of obesity. In particular socioeconomic status is important to consider, but other economic drivers of obesity can also be identified including economic incentives for companies producing obesinogenic products, transportation means etc. *Time* is an important element of obesity development both for the individual (e.g., child obesity vs. developing obesity over time due to too prolonged high caloric intake and lack of physical activity) and at societal level. The changes in drivers over time are also important to consider. *Governance* is relevant as it can provide means to prevent obesity development, e.g., by dictating development toward less obesinogenic environments in society and by allocation of funds to prevent obesity and reduce consequences of obesity through research, innovation and intervention. It might also be used to impact the economic driver through e.g., sugar or fat taxes. However, governance of health issues and potential solutions related to the global obesity epidemic are currently highly segregated into separate sectors rather than cross-sectorial and today very little obesity prevention and mitigation is based on transdisciplinary research and development (13).

A conceptual illustration of how the obesity development in dogs and dog-owners can be perceived as interlinked is provided in **Figure 1**. The context description was inspired by, but does not cover the full complexity of obesity described in, the UK Forsight Governmental project systems maps of obesity published online in 2007: https://www.gov.uk/government/publications/reducing-obesity-obesity-system-map, accessed 12 June 2018). The UK Forsight systems map illustrates individual, socioeconomic and environmental drivers, elements and feedback loops affecting obesity in humans. However, for the DODOS the animal component and animal-human bond was important and not considered in the UK Forsight systems map. The food and animal feed industry as well as food and feed consumption patterns have strong potentials to negatively affect the health of both humans and pets, even though they are usually governed (if governed at all) through different ministries in traditional sectorial governance structures. Likewise, psychological factors and obesogenic environments that affect physical activity and eating behaviors in both humans and their pets are generally only considered in the human health care system, even though there might be a potential for

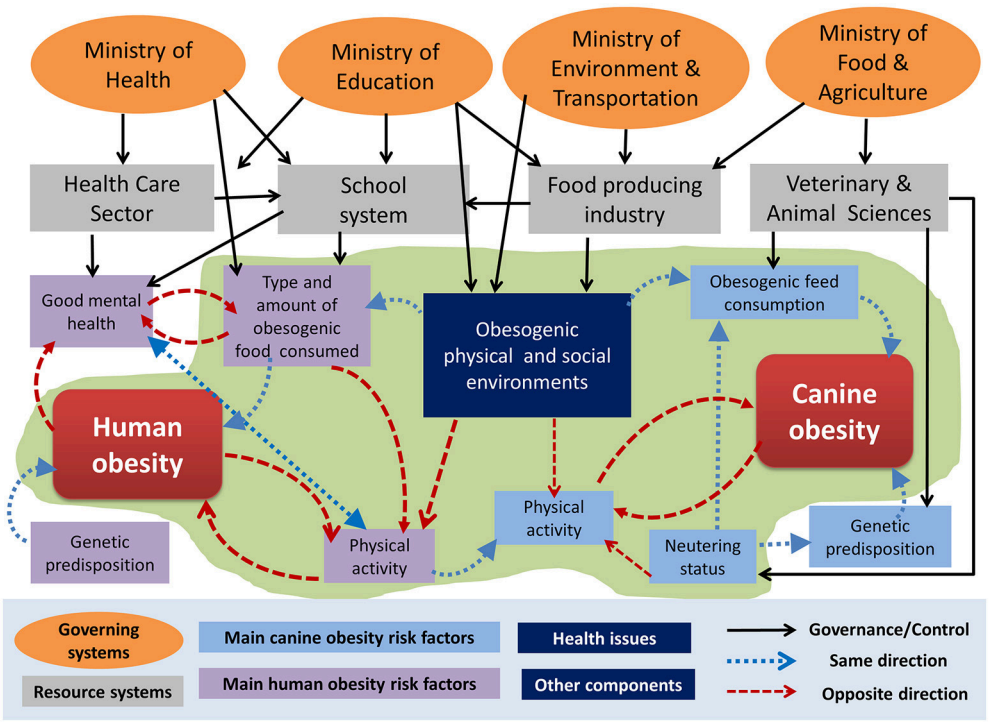

FIGURE 1 | Visual representation of the context of human and pet-dog obesity including linkages and feedback loops in the system. The list of ministries and resource units is not exhaustive and the names are examples as these vary between countries as well as over time within countries. A green shaded area covers the elements considered in the initiative under evaluation.

prevention of obesity development by utilizing the interlinked driving factor between the sectors. Two obesity drivers, social and economic, are frequently described in literature. For instance, the obesity is related with the sedentary way of living and ingestion of hypercaloric food, among others (14). Also, low incomes have been associated with malnutrition resulting in obesity; and the obesity and obesity-related diseases result in increased expenses (15).

The initiative is, however, mainly targeted at social drivers, i.e., perceptions and behaviors that can affect the social aspects of obesity, since the main stakeholders involved in the study were dog-owners, researchers, health professionals and clinicians. The following actors and stakeholders within the system illustrated in **Figure 1** were included in the obesity case study: investigators (human and veterinary medicine, health science researchers); clinicians (human and veterinary health specialists) and a biologist as well as dog-owners.

Theory of Change (Toc) and Expected and Unexpected Outcomes/Impacts

The primary long-term goal of the DODOS initiative was to contribute to decreasing obesity occurrence among dog-owners and their pet-dogs. This would lead to a second order long-term impact of improved health and well-being and reduced morbidity associated with the obesity in both species, finally resulting in decreased societal burdens and expenses. In order to reach these impacts, required inputs such as prior knowledge, human resources for research, research methods and materials, actors and stakeholders from multiple disciplines and sectors (**Table 1**), outputs such as questionnaire and analysis results, and outcomes such as improved knowledge, new collaborative networks and new solutions being created based on these (**Figure 2**).

The output will mainly be the communication of the results in publications and presentations at conferences to the scientific community, and to the public through layman communications, which would then lead to the expected outcomes (increased knowledge in the relevant populations). Some outcomes were anticipated directly as a result of DODOS, but also unexpected outcomes were mentioned by the actors in the evaluation questionnaire (**Table 2**). The first and second order impacts will depend on the uptake of the outcomes including changed governance procedures, changed behaviors in dog-owners which may affect their dogs and other humans as well, with consequential health improvements and long-term effects thereof. The fact that many households have pet-dogs provides a strong basis for creating change, if the new knowledge from the DODOS and other studies to follow is utilized.

Assessment of OH-NESS of the Initiative

The results of the qualitative as well as quantitative assessments for each point in the NEOH evaluation framework and tool can be seen in the supplementary Excel-file for the obesity case study. The evaluation points are fixed by the framework, but we

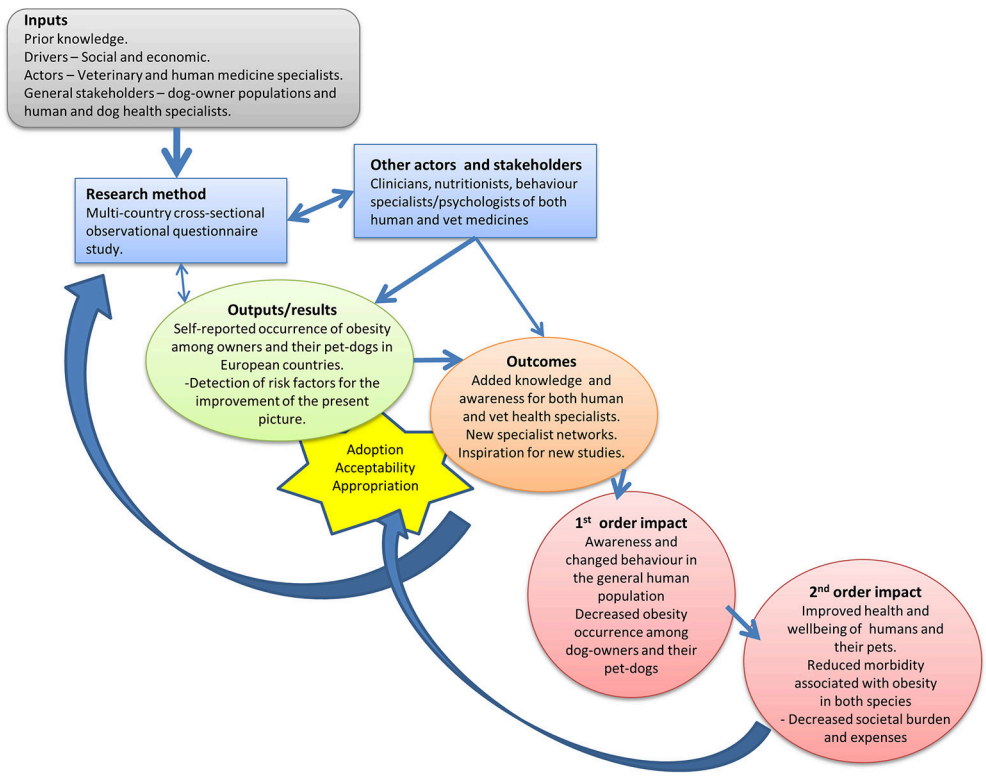

FIGURE 2 | The schematic presentation of the theory of change of the dog-owner and dog obesity study (DODOS).

TABLE 2 | Dog-owner dog obesity case study (DODOS) outputs, expected and unexpected outcomes and impacts according to direct communication and responses to an online questionnaire for actors in the DODOS consortium.

Disciplinary outcomes and outputs	- New collaboration partners - Knowledge about risk factors for obesity in humans and dogs, respectively - Inclusion of the study results in a PhD thesis
Inter-disciplinary outcomes and outputs	- A scientific paper or report being published - New collaboration partners across disciplines - Identification of risk factors for obesity that bridge two species - Knowledge about perceptions in dog-owners that may affect the development of obesity in both humans and pet-dogs
OH outcomes and outputs	- Comparison of factors affecting obesity in dog-owners and in dogs leading to a better understanding of underlying factors that might not be directly measureable - New linkages between collaboration partners across disciplines and sectors in different countries of Europe - An improved interest of participants in OH approaches - Experience with international collaboration and team-work - Learning about the planning and organization of future One Health initiatives - Experience useful to improve the study design for future obesity studies at the human-animal-environment interface - Awareness of direct and indirect obesity drivers and consequences, both among animals and owners - Ideas and plans for new projects
Un-expected outcomes and outputs	Actors highlighted unexpected outcomes for the following points: - perceptions among dog-owners, e.g. that obesity is not considered a disease by all people and that not all consider the OH approach plausible to combat obesity - Actors learning about opportunities as well as biases and other study design challenges in questionnaire studies involving social media for recruitment of respondents - Actors learning about complicated publication processes

have supplied comments relevant for each evaluation point in six spreadsheets about each of the characteristics of OH initiatives to be assessed, i.e., the main OH-*operations*: thinking, planning, working, as well as the *supporting infrastructures* (learning, sharing and system organization). In brief, the OH-thinking in the evaluated initiative was reflected by the multiple dimensions mentioned above, because it evaluated the obesity problem in both humans and dogs and in two life dimensions—individuals and populations; and two geographical dimensions—individual country and Europe. The DODOS scored 0.5 on OH-thinking. The OH-planning of this study was led by one person supported by a specialists composing core committee, who contact the rest of the responsible persons in each country. OH-planning initiative scored 0.45. OH-working, scored 0.7, was reflected by the multidisciplinary collaboration (human medicine, veterinary medicine and a biologist) and inclusion of stakeholders (owners and clinicians) to the problem evaluation and possible ways of its solving. For OH-learning the score was low at 0.28 indicating limited adaptive and generative learning within and outside the initiative, and for information and data sharing the score was 0.45. Systemic organization which is mainly indicative of team-work organization and leadership was scored high at 0.8. **Figure 2** illustrates the OH-scores and OH-index, which was 0.29 (on a scale from 0 to 1) indicating that the full health integration and collaboration potential suggested by NEOH for OH-initiatives tackling complex problems was not exploited in the DODOS study. The ratio between operations and supporting infrastructures was 1.1 indicating a balanced focus on operations and infrastructures (**Figure 3**).

DISCUSSION

To date only small-scale studies have indicated associations between obesity in dog-owners and obesity in their dogs and assessed potential causal factors (8–10). With this in mind, a large scale, multinational study was designed aiming to identify dog-owner perceptions, potential causal factors and behaviors of the owner relative to his/her pet that might lead to or increase the risk of canine obesity as well as his/her own obesity. As highlighted above, the human-animal bonds are usually overlooked in existing obesity context description (7, 16, 17). The main aim of OH-strategies is to improve health and well-being across different species and their environment (or ecosystem) through targeted collaboration between disciplines and sectors, and the involvement of essential stakeholders is important in OH-initiatives. This often includes engagement of relevant groups of citizens. Although in recent years OH-based studies have increasingly gained attention in scientific literature, no validated guidelines for quantitative measurement of OH-activities have been available previously, and prior obesity initiatives have not been evaluated with focus on OH-approaches. Hence, the NEOH evaluation framework provided an interesting opportunity to learn about shortcomings and beneficial aspects of the DODOS initiative. Both objectives of the present evaluation study were achieved, namely to evaluate the DODOS study and consortium as well as to assess the usefulness of the framework for OH-evaluation.

Psychological factors and obesogenic environments affect physical activity and eating behaviors (18), but human-animal bond related physical activities are frequently not considered in the human health care system even though there are potentially strong obesity preventing measures that would be easy to apply in other sectors, e.g., dog-play activities for children as well as dog-assisted physical activities for adults, "health schools" in which humans can learn about healthy food consumption practices through the learning about appropriate diets for healthy dog and humans. Hence, some OH-initiatives for reducing obesity in both dogs and dog-owners clearly build on learning

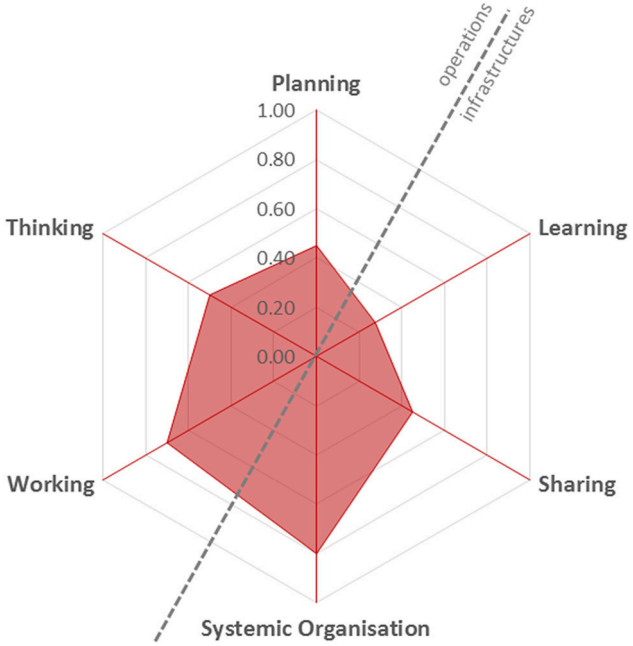

FIGURE 3 | The NEOH evaluation spider diagram indicating overall scores for six One Health characteristics of a case study on obesity among dogs and their owners in 11 European countries.

as an important element in the OH-initiative. Unfortunately, it became evident that OH-learning was the element in the DODOS study that was scored lowest mainly due to lack of learning infrastructures among stakeholders and actors which would go beyond basic learning and support adaptive learning, i.e., learning that focuses on correcting or improving existing procedures, processes, competences and technologies, as well as generative learning, i.e., learning that focuses on questioning the existing norms and that encourages to see beyond the existing situation to generate new paradigms. One way this could have been improved in DODOS would have been to engage stakeholders as well as decision makers in governing institutions early on, i.e., during the planning process as well as during the dissemination process during and after the study period.

The moderate OH-thinking score suggests that the lack of stakeholder engagement might have been grounded in a lack of general acknowledgment in the DODOS consortium that addressing more of the obesity context including feedback loops that could have been targeted in the initiative might have created other outcomes and led to a larger impact of the initiative. During the DODOS design and planning the OH-thinking was less accepted by human health specialists, and the majority of the approached specialists did not consider the obesity to be a health problem for pets and seemed to think that transdisciplinary solutions were not efficient or not possible to perform. For this reason, the majority of actors driving the DODOS were veterinary specialist with scientific and/or practical experiences. This was one of the main limitations for implementing an OH approach.

Carrying out an OH-evaluation using the NEOH framework requires a good understanding of systems thinking and OH in general. Stakeholder involvement in the evaluation is required, since a lot of information related to study objectives, planning of the work and the way of working such as data analysis, sharing of information and leadership is needed. This particular evaluation was performed by several of the DODOS actors as a self-evaluation, which might have introduced some biases. Clearly there were differences in how well the processes, outputs and outcomes of the initiative were known and understood by the 21 actors who responded to the actor questionnaire. This would probably have been less of an issue, if more/better sharing and learning infrastructures had been ensured in the initiative, but might also be related to economic and human resources and leadership choices made during the study design, performance and finalization.

The application of the evaluation questions and tools provided by NEOH allowed identifying strengths and limitations of the case study with regards to the OH approach. These strengths and limitations might impact the ability of the study to achieve some added value compared to disciplinary projects within the topic obesity in dogs and humans. An OH-index of 0.29 out of a possible total of 1 indicates that several indicators did not achieve high scores. However, it is difficult to say whether this has an impact on the desired outcomes of the study. This remains to be investigated when the OH-index is compared across different initiatives in the future. An OH-ratio of 1.1 indicated that infrastructures underpinned the operations in the initiative even though this value also has to be seen in relation to the scores of each of the elements learning, sharing and systemic organization which were not all scored high for DODOS. Limitations were mainly noticed in the thinking, sharing and learning parts of the evaluation, and in the identified outcomes.

Information sharing is described to be one of the basic criteria for OH-studies (19). Although data sharing occurred in DODOS, it was uni-directional and the full raw data set was only available for the core committee. However, later the results summary reported by core committee would be discussed and was planned to be analyzed by all the participants in order to achieve the holistic approach of the obesity as a disease, in this way aiming to improve the sharing in DODOS. One option would be to disseminate the new knowledge and information from the study through the same channels that were used to recruit dog-owners to reply to the DODOS questionnaire.

One of the fundamentals of OH-studies is to obtain higher impact of outcomes in comparison to conventional single sector or single discipline approaches in terms of improved health and well-being, and reduced economic costs or improved cost-benefit ratios (20, 21). This could not be directly measured from this study. However, other outcomes were identified by the actors in the actor questionnaire (Supplementary materials 1, **Table 2**), mainly related to the following overall categories: scientific knowledge and understanding of factors associated with obesity in dogs and dog-owners, increased awareness of the linked obesity issue between pets and pet-owners, learning about study design and publication processes in large international consortia which is an important capacity building aspect,

improved knowledge and understanding of OH approaches and important new collaboration linkages across the consortium. However, stakeholder involvement was not deemed sufficient for the initiative to have a certain societal impact at the point of evaluation. This is an important point for the consortium members to consider, not only for the DODOS, but also in future research initiatives within the field. However, as emphasized by Bartges et al. (17) this requires "efforts and leadership of a committed group of like-minded individuals representing a range of scientific and medical disciplines. Interested parties will need the means and opportunities to communicate and to collaborate, including having the resources and funding for research." In fact, resources for engagement of actors and stakeholders were very limited in the DODOS and were mainly build on voluntary engagement.

In conclusion, the utility of the evaluation tools for the evaluation and potential improvement of OH-initiatives was illustrated. Short-comings in critical elements were identified in DODOS. It would have been useful to use the NEOH evaluation framework and the evaluation tools as a checklist during the project design and planning phase since this could help to identify the limitations of the study and consortium composition, which might be corrected before the study begins or during the study period. Moreover, using the framework facilitated targeted communication between all actors in the initiative to gain an improved common understanding of the OH-characteristics. In this particular case study, it might have improved the participation of human health professionals and researcher or stakeholders from other relevant disciplines to have more elaborated discussions about the system description and the TOC before the study was initiated.

AUTHOR CONTRIBUTIONS

AM-P and AT data compilation and tool complementation. AM-P, LN, SM-S, JM, PL-J, SS, and AT paper drafting and paper and tool revising.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2018.00163/full#supplementary-material

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Positioning Animal Welfare in the One Health Concept through Evaluation of an Animal Welfare Center in Skopje, Macedonia

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The Animal Welfare Center (AWC) in Macedonia was established in 2009. The objectives of the center are animal welfare (AW) education, research, raising public awareness of AW, and increasing cooperation between the stakeholders. One Health (OH) was not the major focus of the AWC work initially, but, rather, a focus that evolved recently. The objective of this study was to evaluate the AWC from the OH perspective as an example case for positioning the AW within the overall OH concept. Three types of evaluation were performed: (1) assessment of OH-ness, by quantitative measurement of the operational and infrastructural aspects of the AWC; (2) impact evaluation, by conducting quantitative surveys on stakeholders and students; and (3) transdisciplinary evaluation, using semi-quantitative evaluation of the links of cooperation between the AWC and the stakeholders in society by the custom designed CACA (Cooperation, Activities, Communication, and Agreement) scoring system. Results for the OH-ness of the AWC showed relatively high scores for OH thinking, planning and working and middle scores for OH learning and sharing dimensions, i.e., dominance of the operational over infrastructural aspects of the AWC. The impact evaluation of the AWC shows that familiarity with the OH concept among stakeholders was low (44% of the respondents). However, there was a commonality among stakeholder's interest about AW and OH. According to the stakeholders' and students' opinions, the influence of AW on Animal, Environmental, and Human Health is relatively high (in the upper third of the 1–10 scale). The transdisciplinary evaluation of the AWC indicated the presence of transdisciplinarity work by the AWC, with a higher focus on the Universities and Research Institutions and some governmental institutions, and less linked with the Non-Governmental Organizations and Professional Associations (Chambers), e.g., the Veterinary Chamber in Macedonia. The evaluations conducted indicated that the AWC's work is closely dedicated to improving animal, environmental, and human health and has a considerable OH role among the stakeholders in the society. This study describes the significant role and importance that AW has in OH.

Keywords: animal welfare, center, One Health, evaluation, transdisciplinarity, impact, stakeholders

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INTRODUCTION

Implementation of the existing standards, raising awareness, and developing risk assessment criteria for animal welfare (AW) is a high priority for the European Union. The research conducted among member countries of the World Organization for Animal Health (OIE) identifies education and training in AW as among the most pivotal tools for solving major welfare problems (1). This also reflects AW initiatives worldwide, at national and regional levels, such as the National reference center for AW in Italy[1] and National reference laboratories for official control of feed, food, animal health, and welfare in Ireland[2], focusing on developing guidelines and standards, prioritizing welfare specific issues, raising awareness, implementation of EU legislation, strengthening capacities, supporting and conducting AW research, providing education and training, international cooperation and consultation practices at different levels. These were the main drivers and principles for initiating the work of the Animal Welfare Center (AWC) in the Republic of Macedonia.

The AWC was established in March, 2009 as part of the Faculty of Veterinary Medicine at the Ss. Cyril and Methodius University in Skopje, Macedonia (2). Besides the permanent staff, the AWC is also a merging point for experts of different fields from both within and outside the Faculty for AW-relevant issues on a national level. In April, 2010 the AWC signed a contract for cooperation with the competent authority—the State Veterinary Office. Besides formal recognition, the signed contract with the Macedonian government gave authorization and responsibility to the AWC for the provision of professional training and strengthening capacities for the veterinary authorities and conduction of vocational training and certification for different professionals where AW could be impaired. To date, the AWC has had extensive activities in relation to AW. The AWC has developed and implemented an AW course for undergraduate veterinary students. In addition, several workshops and projects have been held where the AWC was an integral part considering implementation of EU Directive 2010/63 for protection of animals used for scientific purposes and exploration of alternative techniques, the 3Rs Concept (Replacement, Reduction, and Refinement) (3). Likewise, AWC developed training courses for stakeholders in line with the EU directives (4–7). Regarding AW research, several studies were conducted which related to animal slaughtering, transport, animal behavior, etc. On a national level, the most important studies were the welfare assessment of poultry and dairy farms for the first time in Macedonia (8, 9). AW concerns about ambient conditions and air quality in the poultry and pig farms in the country were also raised. Later, this led to the assignment of the accreditation certificate for measuring air and noise emissions from housed farm animals (MKTC CEN/TS 15675:2009; MKS ISO 1996-2:2010) in the laboratory.

One Health (OH) is a term that captures integrative approaches to health and emphasizes the commonalities of human, animal, plant, and environmental health (10, 11). The strong link between AW and animal health, human health, and environment is evident (12, 13). Previous studies recognized the importance of AW to animal health, where animal health is as a crucial part of AW or even going to the extent, outlined by some authors, where animal health is the only explanation of AW (14). Taking care of AW and implementation of these standards is contributing to the reduction of the environmental impact from animal farms (12, 15), i.e., environmental health. Likewise, food safety and antimicrobial resistance are primary factors for human health that can be regulated and influenced by AW standards (13). The review by de Passillé and Rushen (12) suggests that improving AW in farms will reduce stress-induced immunosuppression, the incidence of infectious diseases on farms and the shedding of human pathogens by farm animals, antibiotic use and antibiotic resistance, and the environmental impact from the farm animals. Recently, a "One Welfare" platform for improving human and AW was presented by Pinillos et al. (16), where the interconnections between AW, human well-being, and environment are recognized. All of this implies that AW considerably impacts on OH. However, empirical and practical examples of these theoretical presumptions concerning the link between AW initiatives and OH are lacking.

Obviously, OH was not the major focus of the AWC work from the onset. However, if retrospectively analyzed, the activities of the AWC are in line with the possible links between AW and OH. Therefore, the objective of this study was to evaluate the AWC in Macedonia as AW initiative from the OH perspective, and use this case as a model for determining the links and relations of AW within the overall OH concept (human, animal, and environmental health), a model that could be possibly applied to evaluate other AWCs. The intention of this study was neither to present the AWC and its OH approach nor to describe the working areas of this single AW initiative. Ultimately, this study describes the role and importance of AW in general to OH by using the AWC as an example case.

MATERIALS AND METHODS

From the working continuum of the AWC, the evaluation in this study was limited to one extracted timeframe. The AWC work was observed and evaluated from its commencement to the end of 2016, i.e., almost 7 years. The evaluation was conducted in the last 3 months of 2016. Three types of evaluations on the AWC work from an OH perspective were performed: assessment of OH-ness, impact evaluation, and transdisciplinary evaluation. For each evaluation, different evaluation methods, approaches, and metrics were used.

AWC Assessment of OH-Ness

For the quantitative measurement of the operational and infrastructural aspects of OH-ness of the AWC, the proposed methodology by the COST Action TD1404, Network for Evaluation of One Health (NEOH)[3] for Assessment of OH-ness presented in

[1] http://www.izsler.it/izs_bs/s2magazine/index1.jsp?idPagina=408

[2] https://www.fsai.ie/enforcement_audit/monitoring/national_official_labs.html

[3] http://neoh.onehealthglobal.net/

"A Handbook for evaluation of one health," Chapter 3—A One Health Evaluation Framework, Draft version from November 2016 was used. The assessment was performed by the staff permanently involved in the AWC from the beginning, i.e., the head and deputy of the AWC, who are experts in AW and experience in AW initiatives on national and regional levels. The given scores for each question and parameters requested in the assessment tools (S1_OH-ness Scoring of the AWC in Supplementary Material) represents the evaluation of the AWC as an OH initiative, not only as an AW initiative. These scores were the consensus of the assessors reached by taking the mean score from the scores given in the separate performed assessments. The assessment was performed for the following OH dimensions: thinking, planning, working (transdisciplinarity and leadership), learning, and sharing. The holistic approach of OH-ness was defined as a combination of the previous mentioned assessments into a One Health Index (OHI). This index is visually presented as a spider diagram of pentagonal structure and calculated according to surface of the pentagon defined by the enclosed lines that are connecting the points—assessment scores for different dimensions (from 0 to 1) (10), for details see S2_One Health Index and One Health Ratio in Supplementary Material. Precisely, the following equation was used for calculating the OHI:

$$\mathrm{OHI} = \frac{\sin\frac{2\pi}{5}}{2} * \{(\mathrm{ScP} * \mathrm{ScT}) + (\mathrm{ScL} * \mathrm{ScP}) + (\mathrm{ScS} * \mathrm{ScL}) + (\mathrm{ScTD} * \mathrm{ScS}) + (\mathrm{ScT} * \mathrm{ScTD})\} \quad (1)$$

where ScP is the score obtained in OH planning, ScT is the score from OH thinking, ScL is the score obtained in learning infrastructure, ScS is the score from sharing infrastructure, and ScTD is the score from transdisciplinarity and leadership. In the described model, the range of OHI was from 0 to 2.37.

In addition, for presenting the balance between "operation" and "infrastructure" of the initiative, the One Health Ratio (OHR) was calculated. The operational aspects involved OH thinking and planning, while the infrastructure was constructed from OH learning and sharing. Transdisciplinarity and leadership were considered as evenly important for both operation and infrastructure. Therefore, this score was considered as a fixed point for the diagonal that divides the pentagon into two structures (operation and infrastructure). Thus, for calculating the OHR, the ratio between surfaces of the two defined quadrilaterals was calculated using the equation:

$$\mathrm{OHR} = \frac{\mathrm{OHI}_{\mathrm{operation}}}{\mathrm{OHI}_{\mathrm{infrastructure}}} = \frac{(\mathrm{ScT} * \mathrm{ScP}) + (\mathrm{ScTD} * \mathrm{ScT}) + \frac{\mathrm{ScP}^2}{2}}{(\mathrm{ScS} * \mathrm{ScL}) + (\mathrm{ScTD} * \mathrm{ScS}) + \frac{\mathrm{ScL}^2}{2}}. \quad (2)$$

Impact Evaluation of AWC on OH

A quantitative survey was performed for determining the impact of the AWC work on OH. The target groups for this survey were different stakeholders, grouped according to whether they did or did not have cooperation with the AWC during the time period that this evaluation was focused on. The stakeholders included in this survey were categorized in six main categories: Farmers, Food Industry; Non-Governmental Organizations (NGOs); Academia; Governmental institutions; and Veterinary chamber. In addition, the veterinary students who took and did not take the AW course during their undergraduate studies were also involved. The survey was conducted by using a custom developed questionnaire, divided into four main sections: a general section for AW and OH; a section for respondents who had cooperation with AWC; a section for respondents who did not have cooperation with AWC; and a personal data section. The 25 questions in the questionnaire were different types, i.e., rating scales (from 1—minimum to 10—maximum), multiple choice, dichotomous, and open-ended questions (see S3_Questionnaire Form in Supplementary Material). To avoid any misunderstanding in terminology, the OH concept in the questionnaire was presented by setting questions directly focused on human, animal, and environmental health. Before collecting the data, the questionnaire was validated by 10 respondents (students and teachers at the veterinary faculty) giving feedback for improvement and polishing the final version of the questionnaire. The answers collected during the validation of the questionnaire were not part of the data collection process and were used only for the improvement of the questionnaire. Following this, the questionnaire was distributed to the respondents personally or electronically, and collected after completion.

The data collected from the questionnaire were analyzed using descriptive statistics, i.e., medians, ranges and 25 and 75% quartiles (Q1 and Q3) for the rating scale questions and frequencies of categorical and dichotomous variables. The grouping variables were based on the cooperation with the AWC, stakeholders' categories, and student's participation in AW course. Cross tabulation between different variables (questions) from the questionnaire was performed for presenting the link between AWC and OH. The correlation between self-graded knowledge about AW and the opinion of the respondents on the level of influence of AW to the human, animal, and environmental health was tested by using Spearman Rank Order test. Likewise, the differences between groups considering OH were tested by Mann–Whitney test and Fisher's exact test or by Kruskal–Wallis ANOVA, setting the level of statistical significance at $P < 0.05$. The data analysis was performed by using STATISTICA 8.0 (StatSoft Inc., Tulsa, OK, USA) software.

Transdisciplinary Evaluation of AWC

The transdisciplinary work of the AWC, i.e., the work that transcended academia and involved cooperation with different stakeholders in society (17), was evaluated by using custom designed semi-quantitative evaluation. The evaluation process was conducted in three main phases: identification; data collection; scoring and modeling. In the first phase, the relevant stakeholders were identified. Emphasis was given in identifying existing stakeholders for whom OH was specifically within their interest or their work was primarily related to human, animal, and/or environmental health. The identification procedure was performed by classifying the stakeholders into six major groups: Universities and Research Organizations; Animal farms; Government; the Food industry; Chambers; and NGOs. The

organizations and institutions (actors) within each group were selected by searching the Macedonian databases of registered organizations/institutions in the Central Registry of the Republic of Macedonia; the Macedonian Government; the NGO sector database and Google search (by sectors in Macedonia). For each actor identified, the scope of work, mission, and objectives were reviewed. From the final pool of existing stakeholders, the actors who have a direct relationship to human, animal, or environmental health in Macedonian society were selected. The second phase—data collection, consisted of summarizing all realized projects, initiatives and activities by the AWC during the evaluation period using the documentation in the AWC archive. Later, this was supplemented by interviewing the AWC head and deputy regarding the AWC work and ongoing collaborations. All findings were entered into a matrix with information for each actor about the type of cooperation, the number of realized activities, the communication frequency, and the presence of formal agreement with AWC.

The last phase of this evaluation consisted of quantifying the links of cooperation between the AWC and the identified actors and stakeholders. This was carried out by developing a custom designed scoring system, abbreviated as CACA, based on four main pillars: Cooperation; Activities; Communication and Agreement. Each pillar has an equal contribution (25 points) with a final score of cooperation, giving a maximum of 100 points. Within each pillar there were different descriptors, bearing corresponding weights, depending of the level of contribution in the pillar. The level of contribution for different descriptors was developed by equalizing the different descriptors within one pillar in relation to the evaluation period of the AWC (almost 7 years). Thus, for the Cooperation pillar, seven descriptors were used, where the contribution level was determined by considering the strength of cooperation, starting with "Participation in the decision body," indicating very strong cooperation, i.e., a contribution level of 100%. More than three "Project implementations" between AWC and the Actor within the evaluation period is considered as a strong cooperation, almost as strong as "Participation in the decision body." Therefore, the contribution level of "Project Implementation" was 30%. Cooperation in "Research" is close to the "Project implementation" and was positioned in the middle between "Expertise" and "Project implementation," whereas the three "Expertise" engagements within the evaluation period were considered was having almost the same strength of cooperation as "Project implementation," i.e., the contribution level for "Research" was 20% and for "Expertise" 10%, of the overall score of this pillar. Three "Education and Trainings" within the evaluation period were considered almost equal to "Expertise" leading to the contribution level for "Education and Trainings" of 3% and so on until the contribution level for "Meeting" of 0.2%. The same approach for determining the contribution level of different descriptors was used for the descriptors for the Communication and Agreement pillars. For the "Activities" pillar, it was considered that if there were at least 10 joint activities between the AWC and the specific actor within the evaluation period, then the maximum score for this pillar should be given, i.e., each joint activity has a contribution level of 10%. Maximum score for each pillar was 25 and the weight for each descriptor was calculated from the contribution level as a percentage of this maximum score. If the score for the particular pillar is >25 then the given score for the pillar was 25. The pillars, their descriptors, and appropriate weights of the CACA scoring system are presented in detail in **Table 1**.

The calculations for quantifying the links of cooperation represented with one score for the cooperation between AWC and the analyzed actor were carried out using Eq. 3:

$$S_{CACA} = \sum_{C_d=1}^{7} C_d + A_n \times 2.50 + C_o + A_g \quad (3)$$

where the total score for cooperation between AWC and the actor (S_{CACA}) represents the sum of the sum of weights of seven descriptors from Cooperation (C_d), number of joint Activities (A_n), Communication (C_o), and Agreement (A_g). For example, if one actor has two education trainings, one workshop and one project implementation, realized three joint activities with the AWC, communicates with the AWC on a quarterly basis and the AWC has an agreement with less than 25% of the members of this actor than the overall score will be: $(2 \times 0.75 + 1 \times 0.25 + 1 \times 7.50) + 3 \times 2.50 + 12.50 + 6.25 = 35.50$. Finalized on the scores for cooperation between AWC and the existing actors, the model of transdisciplinarity of the AWC was created, presenting the strengths of cooperation and positioning the AWC within society from the OH perspective.

RESULTS

OH-Ness

The OH-ness of the AWC revealed different scores for each dimension following the questions and parameters within the dimensions. Detailed scoring results of the AWC with the complete evaluation for the five dimensions of OH-ness are presented in the S1_OH-ness Scoring of the AWC in Supplementary Material. The score for the OH Thinking dimension of the AWC was 0.79, with the highest scores of 1.00 for: the variety of the number of dimensions and scales that reflect and integrated approach to health; thinking at structural level considering the features of the system which are targeted by the AWC; and considering the capability of AWC to target different elements of the chain of events in relation to a problem. The lowest score (0.40) within this dimension was regarding the wellness of the initiative (AWC) matching the environment. The score for OH Planning of AWC was 0.75, where half of the stakeholders within the tasks returned the highest score and the other half were mid scored. The OH Working dimension (transdisciplinarity and leadership) of the AWC was scored with 0.70 points. The scores within this dimension ranged from 1.00 for the societal aspect and broadness and 0.59 for the integration of the AWC. The lowest scores of the AWC were for the OH Learning and OH Sharing dimensions of 0.47 and 0.46, respectively. In the OH Learning dimension, the highest score (0.75) was for the learning on individual and organizational levels, while the lowest score (0.13) was for the support of the general environment for adaptive and transformative learning. The highest score (1.00) in the OH Sharing dimension was about the usage of

TABLE 1 | Pillars, descriptors, and weights of the CACA scoring system for cooperation between Animal Welfare Center and the society's actors/stakeholders.

Pillar	Cooperation			Activities			Communication			Agreement		
Pillar's description	Type of realized cooperation			Number of realized activities			Frequency of communication			Formally signed agreement with the representatives within the actor		
	Descriptor	C%	W	Descriptor	C%	W	Descriptor	C%	W	Descriptor	C%	W
	Meeting	0.2	0.05	One joint activity	10.0	2.50	Once in several years	6.0	1.50	No signed agreement	0.0	0.00
	Workshop	1.0	0.25				Yearly	12.0	3.00	Agreement with ≤25% of the actors	25.0	6.25
	Education and trainings	3.0	0.75				Once in 6 months	25.0	6.25	Agreement with 26–50% of the actors	50.0	12.50
	Expertise	10.0	2.50				Quarterly	50.0	12.50	Agreement with 51–75% of the actors	75.0	18.75
	Research	20.0	5.00				Monthly	100.0	25.00	Agreement with 76–100% of the actors	100.0	25.00
	Project implementation	30.0	7.50									
	Decision body participation	100.0	25.00									

C, level of contribution of the descriptor within the pillar, in percentages; W, weight of the descriptor within the pillar.

information in learning and the lowest 0 scores were given to the sharing resources and data accessibility.

Following analysis of the scores' dimensions and using Eq. 1, the OH Index of the AWC from the OH perspective was 0.97. By using Eq. 2, the score for the Operation of the AWC was 0.68, while the score for the Infrastructure of the AWC was 0.31, leading to the OH Ratio of 2.20. The overall appearance of the OH-ness of the AWC spider diagram defined by the OH Index and Ratio is presented in **Figure 1**.

Impact Evaluation

The survey was completed by 36 representatives (85% response rate) from different stakeholders: Government Institutions, such as the Food and Veterinary Agency, Ministry of Environment and Physical Planning, Local government, and other governmental sectors; Academia, i.e., universities and research institutions; NGOs; animal farmers; food processing industry; and Veterinary Chamber (**Table 2**). Geographically, 63% of the representatives were from Skopje—the country's capital, and, regarding gender, 39% were female respondents. From the stakeholder's representatives, 53% stated that currently or in the past have established cooperation with the AWC. The student's survey included 30 veterinary undergraduate students (100% response rate), 15 of these (50%) were students who did take the AW course during their studies and rest of the respondents did not take this course. The geographical and gender structure of the students, respondents in the survey, was 73% from Skopje and 50% were females, respectively.

The overall concept of OH was familiar to 44% of stakeholder's representatives. The number of respondents who had cooperation with the AWC was significantly higher (63%) than those who did not have cooperation (24%), regarding familiarity with the OH concept. On a scale of 1–10, the level of influence of AW on human, animal, and environmental health,

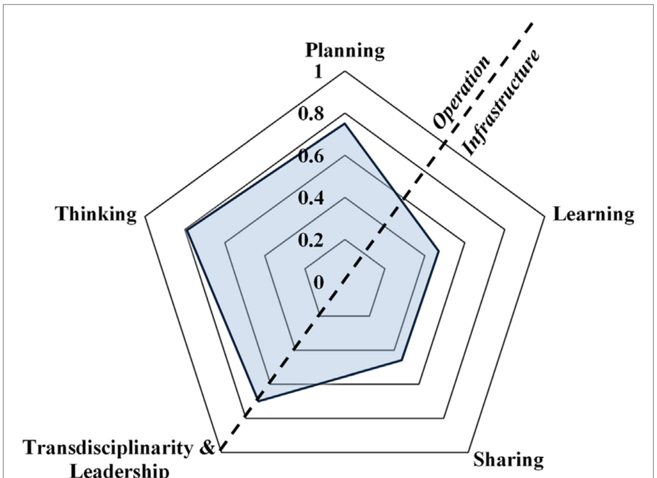

FIGURE 1 | Spider diagram based on the scores (from 0 to 1, solid lines) of the five dimensions for the One Health Index of the Animal Welfare Center (AWC) (the transparent blue structure) from the One Health perspective. The dashed line represents the division of the diagram into Operation and Infrastructure for representing the One Health Ratio of the AWC.

TABLE 2 | Scores, presented as median, range, and 25–75% quartiles (Q1–Q3), given by the stakeholders regarding the influence level of Animal Welfare on Human (HH), Animal (AH) and Environmental (EH) Health, considering their cooperation with the Animal Welfare Center (AWC).

Stakeholder (N)	Cooperation with AWC							No Cooperation with AWC						
	n	HH		AH		EH		*n*	HH		AH		EH	
		Median Score	Range (Q1–Q3)	Median score	Range (Q1–Q3)	Median score	Range (Q1–Q3)		Median score	Range (Q1–Q3)	Median score	Range (Q1–Q3)	Median score	Range (Q1–Q3)
Non-Governmental Organizations (6)	0							6	9.50	7–10 (8–10)	10	8–10 (10–10)	10	8–10 (8–10)
Farmers (5)	4	7	7–8 (7–7.5)	9.5	9–10 (9–10)	7.5	7–10 (7–9)	1	10		10		10	
Academia (8)	8	7	5–10 (5.5–8.5)	10	8–10 (9.5–10)	8	4–10 (6–10)	0						
Governmental institutions (13)	5	7	5–10 (7–9)	9*	9–10 (9–10)	9	5–10 (7–10)	8	7	5–8 (6–7)	9*	7–9 (7.5–9)	7.50	5–9 (6.5–8.5)
Chambers (2)	1	7		9		7		1	8		9		8	
Food industry (2)	1	9		9		6		1	8		8		8	

Significant difference ($P < 0.05$) between groups within the Governmental institutions considering AWC cooperation.

the stakeholders responded with the median score of 7 (range 5–10, Q1 = 7 and Q3 = 9), 9 (range 7–10, Q1 = 9 and Q3 = 10), and 8 (range 4–10, Q1 = 7 and Q3 = 10), respectively. Detailed results concerning the opinion of different stakeholders regarding the influence of AW on OH are presented in **Figure 2**. The introduction of the grouping variable for cooperation with AWC revealed no significant difference between groups when considering the influence of AW on human, animal, and environmental health. However, there were various scores among different stakeholders regarding this issue, descriptively presented in **Table 2**. Due to the small sample sizes of different stakeholder groups, the only comparison considering AWC cooperation was carried out between Governmental institutions, revealing significant differences for the opinion about the influence of AW on Animal Health (**Table 2**). The correlations between the stakeholder's self-graded knowledge of AW and human, animal, and environmental health were 0.31, 0.29, and 0.27, respectively.

The stakeholder's representatives who had cooperation with AWC graded the cooperation with average grade of 4.16 ± 0.76 (on a scale from 1 to 5). This group of respondents scored the impact of the AWC on human, animal, and environmental health, where the impact on Animal Health was significantly higher in comparison with Environmental and Human Health (**Figure 3**). Lowest and highest AWC impact median scores for different types of health considering the groups of stakeholders are presented in **Figure 3**. All respondents consider that by cooperating with the AWC they are contributing to improving human, animal, and environmental health. The respondents who have cooperated with the AWC stressed that the AWC should expand its activities almost equally in all areas in order to improve the OH (**Figure 4**). The majority of the respondents who did not have cooperation with the AWC (85% of the respondents) believe that if they cooperate with the AWC they could contribute to improving human, animal, and environmental health. Summarizing the other answers from this group of respondents and the other open-ended questions in the survey, the most frequent statement given as a major remark or as a suggestion for higher involvement was the need for better promotion of the AWC's activities.

The survey among students demonstrated that 83% were not familiar with the OH concept and that 56% of them were students who did not take the AW course. Regarding the influence score of the AW on human, animal, and environmental health, the students scored with the median score of 8 (range 1–10, Q1 = 6 and Q3 = 9), 10 (range 1–10, Q1 = 9 and Q3 = 10), and 8.5 (range 1–10, Q1 = 5 and Q3 = 10), respectively. There was no significant difference between answers of students regarding the AW influence on human, animal, and environmental health considering their participation in the AW course (**Figure 5**). The correlations between the student's knowledge of AW (based on self-grading) and how they scored the influence of AW on human, animal, and environmental health were 0.14, 0.42, and 0.57, respectively. Similar to the stakeholder's survey, over 93% of the students stated that cooperation with the AWC can contribute to an improvement in human, animal, and environmental health.

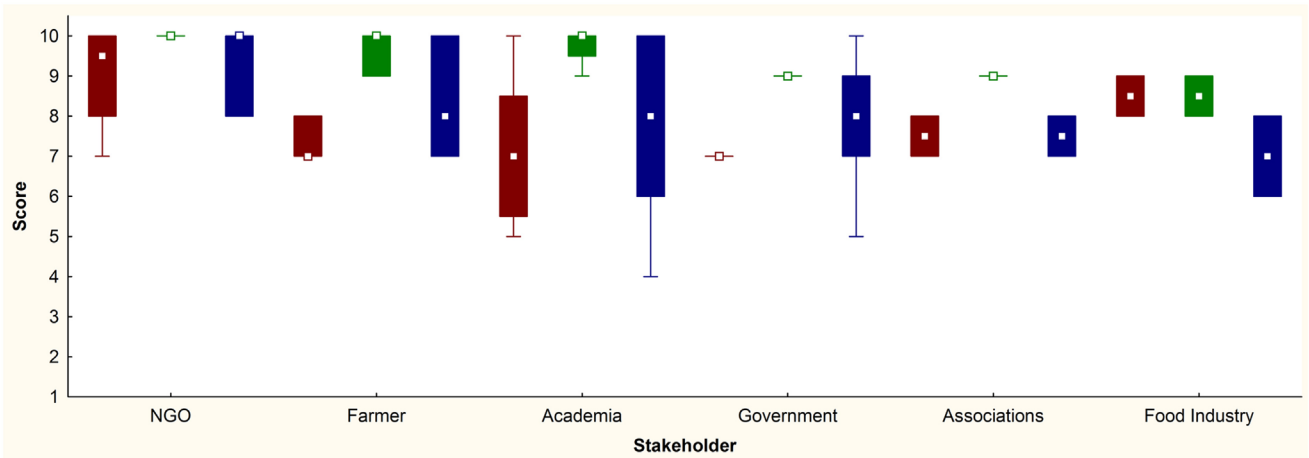

FIGURE 2 | Stakeholders' (Non-Governmental Organizations, $n = 6$; farmers, $n = 5$; academia, $n = 8$; government, $n = 13$; associations, $n = 2$; food industry, $n = 2$) opinions regarding the influence level (in scores on the *Y* axis) of Animal Welfare on Human (red), Animal (green), and Environmental (blue) Health. Median □; 25–75%, box; non-outlier range, whisker.

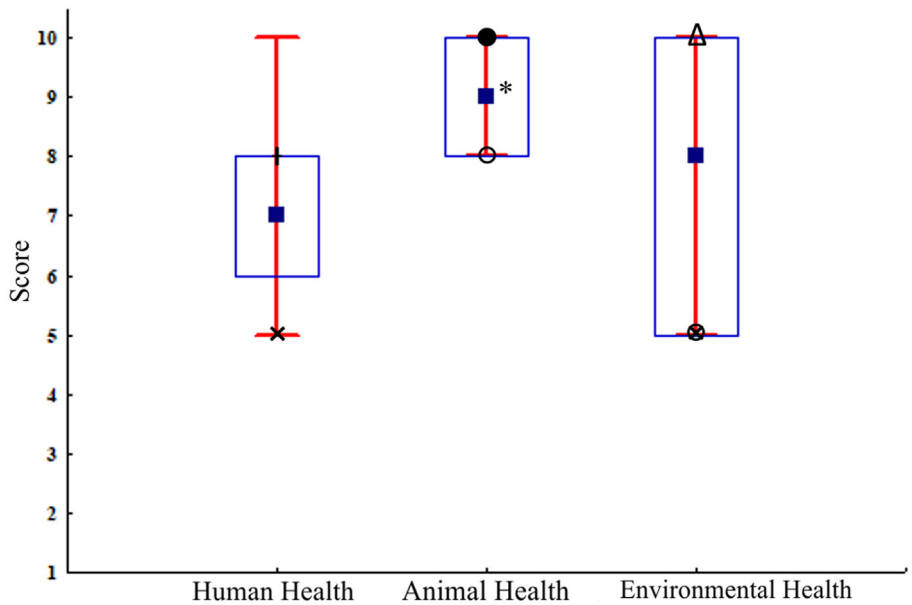

FIGURE 3 | Impact of the Animal Welfare Center (AWC) on human, animal, and environmental health on a score scale from 1 to 10 according to the respondents who had cooperation with the AWC ($n = 19$). Median □; 25–75%, box; non-outlier range, whisker. *$P < 0.05$. Lowest and highest median scores for the three types of health given by the stakeholder's groups (× Food industry, I Farmers, ○ Veterinary Chamber, ● Academia, and Δ Governmental institutions).

Transdisciplinary Evaluation

During the identification phase, 27 actors who have direct relation to human, animal, or environmental health were identified. Considering the six major stakeholders' groups, the distribution of the identified actors was: five actors in NGOs, six actors in the group Animal Farms, six actors/institutions from the Government, two in Universities and Research; six in the group called Chambers; and two actors from Food Industry. In the data collection phase, 18 different types of cooperation, with over 100 realized activities were found between the AWC and the identified actors. By using the CACA scoring system, the transdisciplinarity of the AWC from the OH perspective is presented in **Figure 6**.

DISCUSSION

The evaluation of the AWC from the OH perspective performed in this study demonstrates that the AWC, and consequently AW in general, has had an impact and contributes to improvement and securing not only animal health but also human

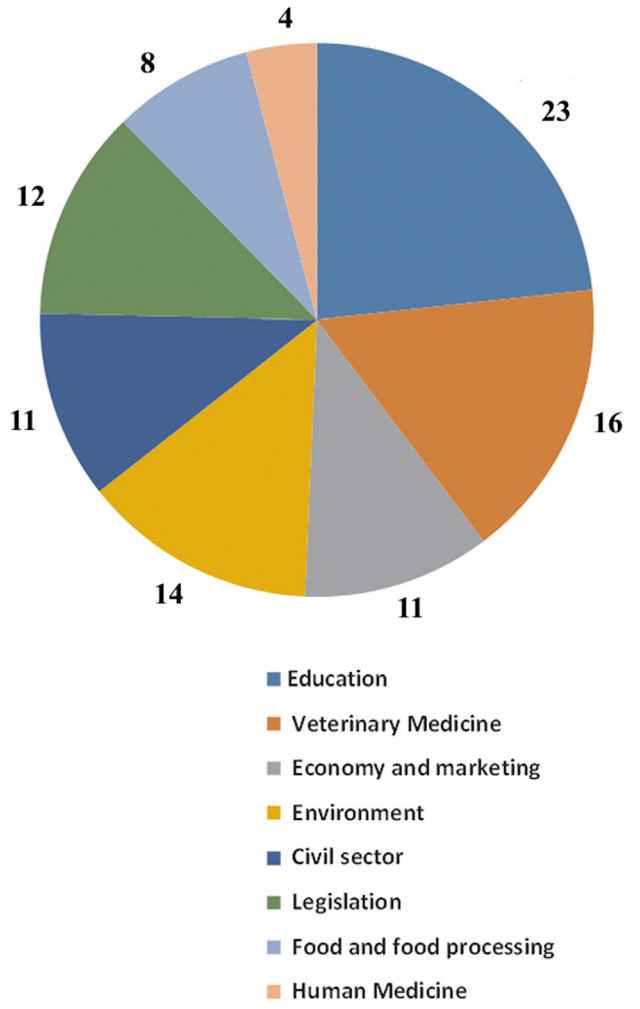

FIGURE 4 | Stakeholder's opinions, from the respondents who had cooperation with the Animal Welfare Center (AWC) (n = 19), regarding the areas where the AWC should expand its activities for improving human, animal, and environmental health (the numbers represent percentages from the responses for all areas).

and environmental health. The evaluations for OH initiatives performed in this case, mainly guided by the "A Handbook for evaluation of one health," Chapter 3—A One Health Evaluation Framework (COST Action TD1404, NEOH), presents the role of AW in the OH concept and hypothesizes that the AW initiatives can also be seen as OH initiatives.

One Health-ness as a sum of characteristics that define integrated approaches to health (17), in this case, the sum of five dimensions, was used for representing the strengths and weaknesses of the AWC from the OH perspective. The assessment of the OH-ness performed on the AWC found several remarks and challenges of the method used. These are highlighted in red in the S1_OH-ness Scoring of the AWC in Supplementary Material. However, the NEOH Handbook for evaluation of OH has been developed further than the state at which it was used in this study. In this context, the number of dimensions representing the OH-ness (**Figure 1**) requires further discussions and analyses in the forthcoming studies. Finally, more widely practical usage of the OH-ness assessment inevitably will lead to its improvement and precision. For determining the effects of the AWC on OH as a secondary (indirect) impact, the terminology established in the paper by Rüegg et al. (17), the impact evaluation of the AWC was performed. This was accomplished by summarizing the opinions of different stakeholders and students about the AWC's work and its relationship with OH (human, animal, and environmental health). However, the number of respondents participating in the impact evaluation was low for very detailed impact analysis.

The transdisciplinarity, as a vital part of the OH approach, was the core aspect for evaluation of the AWC from OH perspective. Rosenfield (18) sees transdisciplinarity as a help in health research by providing a holistic approach where the researchers will work with different stakeholders for the purpose of addressing a common problem. In addition, there was a consensus among research articles that transdisciplinarity is necessary for solving human–animal–environmental health issues (19). Summarizing the scores from the four pillars in the CACA scoring system gives an overview of the link's strength between AWC and the stakeholders in society. However, the method for identifying the stakeholders and actors in this study may introduce some bias in the final results. Nevertheless, modeling the established links in the overall network of actors and stakeholders offers an overview of the transdisciplinarity of the AWC from the OH perspective. This also raised the expectations in this study for finding the place of the AW in OH. More broadly, since the AWC is an AW initiative, this could be perceived as an opportunity to determine where the AW stands in society from the OH perspective.

Improvements in AW and raising AW standards in the system were found as a major driver of the AWC. In fact, AW in general is recognized as a "complex, multi-faceted public policy issue which includes important scientific, ethical, economic and political dimensions" (20). This inevitably leads to a higher score for OH thinking for almost all AW initiatives. The AWC was a pioneer for acceptance and understanding the AW field in society, leading to a low match of the AWC with the environment, i.e., low scores within OH thinking. The same findings were reported for the OH concept. Familiarity with the OH concept among stakeholders in society and undergraduate students emphasized the need for higher involvement of OH in the undergraduate curriculum for veterinary studies and overall promotion of the OH concept in Macedonian society. The greatest familiarity with the OH concept was among stakeholders who had cooperation with the AWC, indicating that the group that was interested in AW, also has knowledge and/or interest in OH. This additionally supports the higher score for the AWC's OH thinking.

The AWC OH planning and working were also scored highly. Higher dominant scores were the societal and broadness as one of the features of AW in general. OH working dimension includes transdisciplinarity and leadership of the AWC, also confirmed by impact and transdisciplinary evaluation within this study. The stakeholder's scoring of the AWC influence on OH was highly related with the work's perspective, knowledge, and information about the scope/work of the AWC. Thus, in the scoring for the human health, the farmers gave higher scores as the AWC was

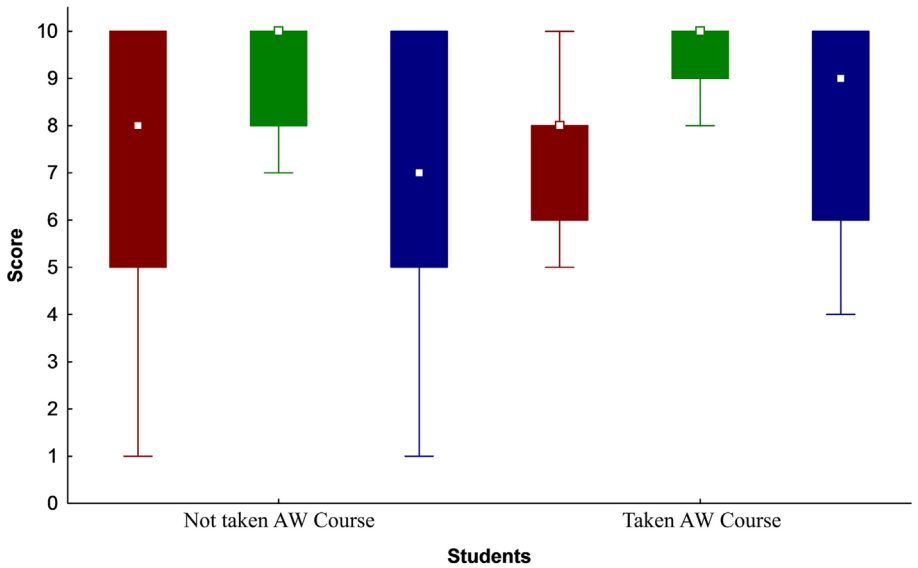

FIGURE 5 | Students' opinions regarding the influence level (in scores on the *Y* axis) of Animal Welfare (AW) on Human (red), Animal (green), and Environmental (blue) Health, groups according to whether they had taken the AW course (n = 15 for both groups) during their undergraduate studies. Median □; 25–75%, box; non-outlier range, whisker.

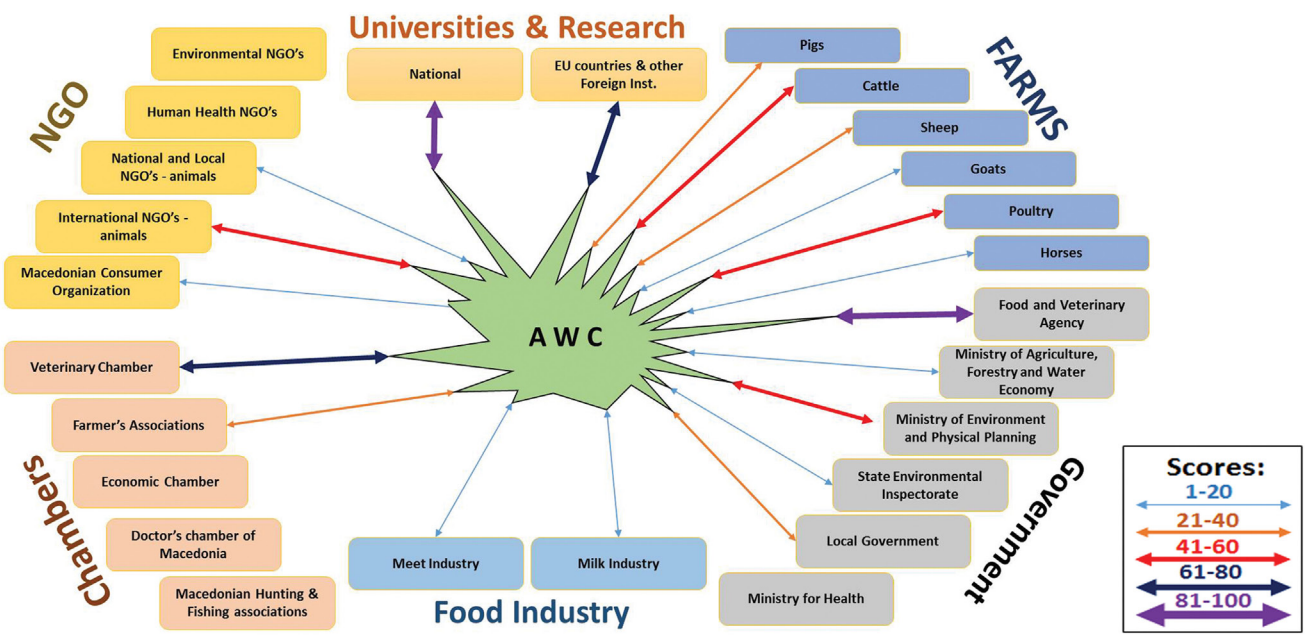

FIGURE 6 | Transdisciplinary evaluation of the Animal Welfare Center (AWC), according to the CACA scoring system. Scores for the links between AWC and the actors in the six major groups of stakeholders are represented by different colors and arrow's weights (legend on the right), while the absence of the arrows means no established cooperation. The shape of the AWC in the model corresponds to the level of cooperation of the AWC, i.e., the higher the spikes of the AWC shape, the higher level of cooperation with the actor.

promoting the links between AW and prevention of diseases (including zoonoses) and food safety. The present knowledge from Academia about AW contributes to the maximum scores from this stakeholder for the AWC influence on animal health. The higher scores for environmental health given by the government resulted from the previous collaboration with the AWC on measuring the farm's emissions to the environment. Both groups (with and without cooperation with the AWC) express their beliefs that they can contribute in improvement of human, animal, and environmental health through AWC, confirming the

impact of the AWC on the OH concept. The responder's request for improvements of the AWC from the OH perspective in all disciplines is actually supporting the transdisciplinarity approach and research in OH (21).

Transdisciplinary evaluation reveals wide spread of the AWC between different actors and stakeholders, presenting a relatively high level of overall transdisciplinarity. The shape of the AWC in **Figure 6** indicates the presence of transdisciplinary work of the AWC with higher focus on the Universities and Research Institutions and Government, and low links with the NGOs and Chambers. Considering its main objective and primary work, the strongest link inevitably were the Universities and Research institutions. Since the AWC performs welfare training, assessments, and has an advisory role for the farmers, this group was also strongly linked with the AWC, with a room for improvement. The strongest link among governmental institutions was with the Food and Veterinary Agency as the authority responsible for AW legislation implementation in the country. The next strong link in this group was found with the Ministry of Environment and Physical planning, as a result of the AWC's work on environmental measurements. There was no link between the Ministry of Health and also any other actors related to Human Health. However, human health is mainly related to the AW through the food safety and disease prevention (12, 13) which opens the doors for future close cooperation. The links with the Food Industry were present but showed a low score, due to the fact that AW training was the only activity provided. This custom designed model developed for the AWC transdisciplinarity can also be used for any other AW initiatives and would probably result in different findings of the strengths of various links. Regardless of these strengths, it is highly probable that any other AW initiative will also be widely spread in society, due to the transdisciplinary nature of the AW research and implementation.

The serious impact for a low score in OH learning was the lack of willingness of implementation of new AW standards by the society, mostly due to traditional farming practices, economic reasons, and poor awareness of these standards. This leads to very low learning focused on questioning, correcting, or improving existing practices and encouragement to see beyond the existing situation. On the other side, the impact of the AW course provided by the AWC for the students contributes to more consensual thinking about the AW influence on the three types of health. This was especially evident for animal and environmental health, where the AW knowledge had a direct effect in increasing the influence score of AW. The OH sharing score was due to the small amount of resources allocated for data sharing, the absence of procedures and mechanisms within the AWC for instant and easy information access to the stakeholders. This was also confirmed by the impact evaluation, where promotion of the AWC's activities in society was mostly suggested. The OHI and especially OHR clearly indicates domination of the AWC "Operation" versus the "Infrastructure." These results suggest that improvements and emphasis should be made in data sharing at the AWC, and further raising awareness in society for the AW standards, while the transdisciplinary evaluation gave the directions of future transdisciplinary work of the AWC.

The OH-ness of the AWC suggests that AW initiatives bear their own OH-ness, which can be scored and evaluated, like OH initiatives from all other disciplines. Stakeholders and students consider that the influence of AW on human, animal, and environmental health is relatively high (in the upper third of the scale) by setting the AW influence in the following order: 1. animal health; 2. environmental health; and 3. human health, with higher emphasis on animal health. The same was applied for the AWC influence confirming similar contribution by the AWC to OH as the AW topic itself. In addition, the AW transdisciplinarity from an OH perspective defined the AW place in the societal OH network. These results should be observed as relative findings that can vary when applying different evaluation methods or different AW initiatives. What is unquestionable is the evident impact of the AW to animal, environmental, and human health. We strongly believe that the AWC is not a unique case and that any other AW initiatives intentionally or unintentionally have an impact on OH and should be seen and evaluated as OH initiatives.

AUTHOR CONTRIBUTIONS

MR collected, analyzed the data, and drafted the manuscript. VI collected the data and revised the manuscript. MR and VI contributed to the study design and interpretation of the results. HO and DM reviewed, interpreted, and edited the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at http://www.frontiersin.org/articles/10.3389/fvets.2017.00238/full#supplementary-material.

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