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One Health in human-environment systems: Linking health and the sustainable use of natural resources

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Abstract
Social-ecological system (SES) approaches have been used for strategic analyses of sustainable use of natural resources like rangelands, fishing grounds, livestock or forests. Elinor Ostrom's concept of "governing the commons" contradicts the so called "tragedy of the commons" that assumes that common pool resources are inevitably overused and irreversibly destroyed. We expand the SES to One Health in Social-Ecological Systems (OHSES) by including humans as a resource system that contributes to the human capital of a nation's gross domestic product (GDP). Ill health leads to a reduction of health and wellbeing benefits through premature death, disability or temporary reduction of work capacity. The OHSES analysis framework uses game theory and mathematical modelling for strategy evaluation and comparison. It enables us to analyse the system's current situation and find possible Nash equilibria, Pareto-optimal solutions, and best resource management strategies while maintaining sustainable ecosystem services. A first example on the elimination of dog rabies in Africa shows that when compared to human post-exposure vaccination, coordinated mass dog vaccination is the best strategy for all countries, leading to human capital benefits of US$10 billion over a period of 30 years with the possible elimination of the disease. Inaction and all other strategies have lower welfare benefits and could not lead to the elimination of dog rabies. Further case studies relating human and animal health and sustainable natural resource use are proposed. Epistemological assumptions and ethical issues of a OHSES approach are discussed in the light of pressing needs to combine human and animal health with the sustainable use of natural resources to address the broader impact of the contemporary threats such as antimicrobial resistance, biodiversity loss and climate change.

One Health statement
This article is a theoretical and methodological contribution to One Health science. It extends the social ecological systems approach of "governing the commons" by Elinor Ostrom through the inclusion of human resources as part of resource system and resource units as One Health in Social-Ecological Systems (OHSES). The concepts of "governing the commons" and "One Health" overlap through the participatory transdisciplinary processes or interactions embedded in both approaches that lead to outcomes or added value for managing shared natural resources and promoting human and animal health. A first case study on the elimination of rabies in Africa is summarized, demonstrating the power of a game theoretical strategy analysis for addressing complex problems of both health and natural resource management. We emphasize system thinking, participatory transdisciplinarity, collective action, equity and gender and the added-value as the main principles of One Health implementation to be evaluated.

Several holistic and interdisciplinary approaches exist to safeguard health. Three of the most influential concepts are One Health, EcoHealth, and Planetary Health with actually important differences between them (Lerner and Berg, 2017; Zinsstag *et al*., 2023a). Here we add a quantifiable framework to the qualitative concept of Health in Social-Ecological Systems (HSES), coined in 2011 (Zinsstag *et al*., 2011). OHSES encompasses not only human and animal health but also biodiversity, ecology, climate change, agricultural systems, and various social sciences as an integrated systemic mixed quantitative and qualitative approach to relate environmental sustainability and the health of all species.

Keywords: One Health, social-ecological system, game theory, strategy analysis, rabies, Africa, pasture, Mongolia

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Introduction

THE TRAGEDY OF THE COMMONS

In 1968, Garrett Hardin published an article entitled "The Tragedy of the Commons", postulating that limited resources that are accessible to all, will inevitably be overexploited and destroyed (Hardin, 1968). Hardin takes as his starting point individual "rational actors" bent on maximizing utility and refers to the overuse of pastures, overfishing of the oceans, polluting the environment and, above all, human overpopulation as the driver of overuse. Hardin had an exceedingly pessimistic assessment of the human rationality of self-restraint.

More than five decades later, Hardin's pessimism about the human willingness to limit itself seems to be confirmed. We continue to live in the 21st century as if our natural resources are inexhaustible, ignoring the damage we do to the planet. Because we put the economic profit of our activities before everything else, we, the entire world population, face several increasingly visible tragedies of the commons: climate warming and its consequences on extreme weather events and human and animal health threats, the loss of biodiversity and the associated risk of collapsing ecosystems, and increased risks of emerging, possibly pandemic, diseases. We continue to consume unlimited amounts of antimicrobials, and the resulting increasingly resistant pathogens are leading to more previously preventable human and animal deaths. The oceans are overfished and there are huge mountains of waste floating in them. We find microplastics almost everywhere and do not understand how this pollution is affecting the food chains. Many people feel existentially threatened by these impending tragedies and have apocalyptic fears of doom that show themselves in movements like the Extinction Rebellion (Pelluchon, 2023).

GOVERNING THE COMMONS

In 1990, Elinor Ostrom conceptualized the governing the commons (Ostrom, 2015). She agrees in principle with Hardin's thesis of the tragedy of the commons, but criticizes his narrow view of the commons and its management (Ostrom, 2007). Hardin's egocentric actors are isolated and act without consulting other stakeholders. Ostrom shows the opposite as those involved in natural resources management usually enter into direct and coordinated dialogue, clarify their interests and agree on rules that are binding for all. She describes examples how natural resources are managed sustainably in this way by mostly smaller groups of people, sometimes for centuries. Her first example describes how the community of Törbel in the Upper Valais (Switzerland) has been managing its pasture, forest and water resources sustainably for over seven hundred years (Ostrom, 2015). Natural resources and their management form a social-ecological system (SES) or a human-environment system.

Ostrom argues: "Understanding the processes that lead to improvements or degradations in natural resource use is limited because the different scientific disciplines involved, use different concepts and terminology. An overarching framework is needed to better understand the complex processes at work and to capitalize on the accumulating knowledge." She proposes a generalizable, multi-tier Social-Ecological System (SES) (Ostrom, 2009) (Fig. 1). Resource systems (RS) such as pastures, forests, fishing grounds produce resource units (RU): livestock, timber, fish that are quantifiable and economically valued. Users (U) of those resource systems manage them according to existing management or governance systems (GS). In doing so, they interact with each other at multiple levels and types of activities (Interactions (I)), which leads to certain outcomes or results (Outcomes (O)). The SES is externally determined by the social, economic and political (S) and ecologic (E) framework conditions.

ONE HEALTH

One Health is an integrated approach that considers the health of people, animals and the environment simultaneously. An

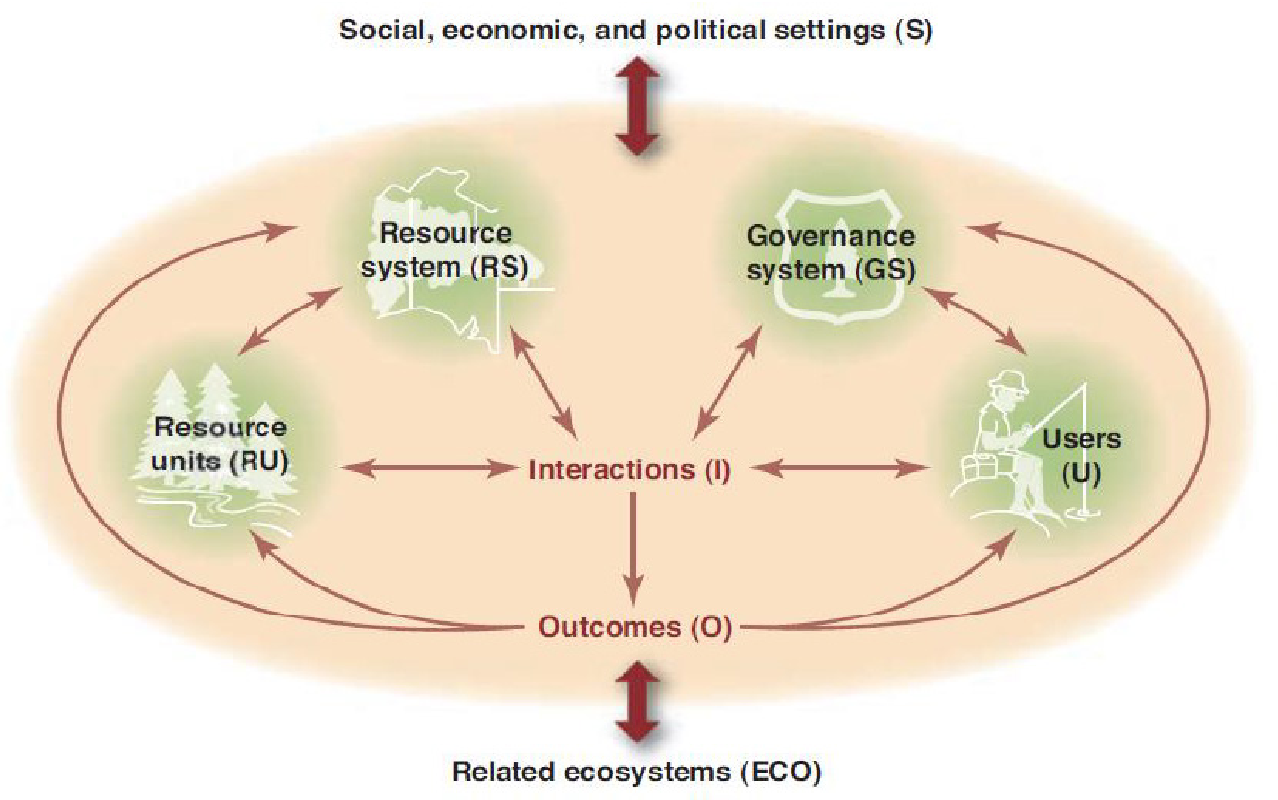

Fig. 1. The core subsystems in a framework for analysing social-ecological systems (Ostrom, 2009).

integrated view of human and environmental health is not new and has roots in India and China. In this article, we can only mention the history of integrated approaches to health and refer the reader to the more recent historical literature. (Woods *et al*., 2017). In the middle of the 20th century, the American veterinary epidemiologist Calvin Schwabe, inspired by his work with Dinka pastoralists in Sudan, coined the term "One Medicine" in which he clarified: "There are no different paradigms between human and veterinary medicine. Both sciences have a common basis in anatomy, physiology, pathology and the causes of disease in all animal species" (Schwabe, 1984). With the increasing incidence of diseases transmitted between animals and humans towards the end of the 20th century, such as Bovine Spongiform Encephalitis or Avian Influenza, integrative approaches gained increased interest from both a wildlife conservation and public health perspective. The Wildlife Conservation Society coined the term "One World One Health™" in 2004 (Karesh *et al*., 2002; Osofsky *et al*., 2005). It signifies how important the health of people and animals around national parks is in order not to jeopardize the health of wildlife. The term "One Health" first appeared in the biomedical literature in 2005 in the context of health systems strengthening (Zinsstag *et al*., 2005b; Woods *et al*., 2017).

If we want to look at the health of humans and the health of animals and plants at the same time, an added value should arise to justify the resulting collaborative effort. A One Health approach should demonstrate a measurable added value in terms of human and animal lives, knowledge, innovation and financial resources, which we cannot achieved without the collaboration of physicians, veterinarians, phytopathologists and all other involved sciences. If we cannot demonstrate such added value, cooperation between the different disciplines is waste of resources and may not be necessary (Zinsstag *et al*., 2015).

HEALTH IN SOCIAL-ECOLOGICAL SYSTEMS

In 2008, one of the authors called Elinor Ostrom and asked her if health could be considered as an outcome (O) of interactions (I) in an SES. Mrs. Ostrom replied: "I never thought about it"(Zinsstag *et al*., 2020a). Unfortunately, a collaboration on health in SES did not materialize. Thus, we postulate health and well-being of humans and animals as the outcome of systemic interactions (I) that are primarily determined by resources (RS), governance (GS) and users (U) within a social, economic and political context in a given ecosystem (Zinsstag *et al*., 2011). The term "Health in Social-Ecological Systems" (HSES) refers to the health of humans and animals as quantitative and qualitative interaction (I) and impact processes (O) of SES (Fig. 2). "Humans and animals [and plants] are inextricably linked to ecosystems, both natural and man-made, i.e. socio-ecological systems. Biomedical sciences must engage with scientific developments in social systems, sociology, economics, political science, anthropology and theology. Similarly, they must interact with ecology, geography and all environment-related sciences. All these processes take place over time and scales ranging from molecules to populations" (Zinsstag *et al*., 2011). Thus the original concept of One Health gains access to complexity and systems theory (Bertalanffy, 1951). Wilcox and colleagues propose SES theory for One Health application in the Mekong region (Wilcox *et al*., 2019). "Health in" or "health of" SES is discussed by De Garine-Wichatitsky and co-workers in the context of changes in agricultural systems. In doing so, they point to the need for a methodological extension of the SES concept to include human and animal health (De Garine-Wichatitsky *et al*., 2020).

Methods

In the book chapter on the added value of One Health (Zinsstag *et al*., 2020c) we describe the methodological development of Ostrom's SES approach as follows: "Human and animal health has many faces. It has a purely private dimension and is probably the highest private good in a person's life. But health also has an important public and social dimensions. By being infected by another person or infecting another person with a pathogen, health becomes highly public and global. We can consider the freedom from disease in its non-rivalrous non-excludable quality as a common good or public good in Ostrom's perspective" (Ostrom, 2015). By analogy, the unhindered spread of disease can be seen as a "tragedy of the commons" as described by Hardin (Hardin, 1968). For example, currently, over 70,000 people, mostly children, still die from rabies every year, even though we have known for over a hundred years how this could be prevented by rapid post-exposure prophylaxis (PEP) (Hampson *et al*., 2015). A conceptual

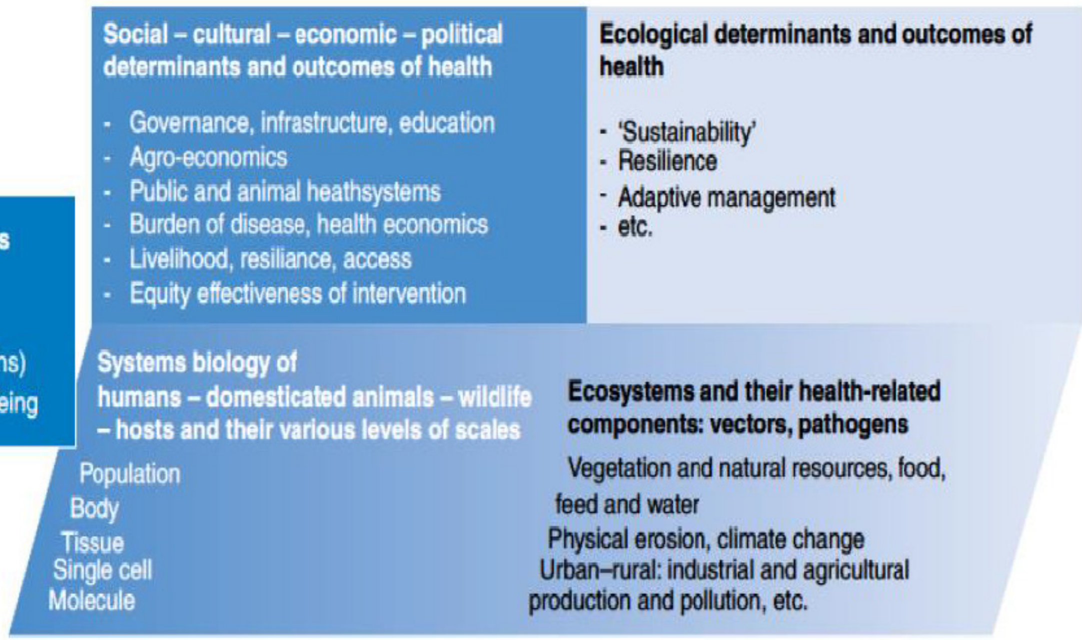

Fig. 2. Health in Social-Ecological Systems (HSES) (Zinsstag *et al*., 2011, 2020b).

framework of public health management as a common public good has already been proposed by Binot and colleagues with reference to Ostrom (Binot *et al*., 2015). However, it is not clear whether the authors consider public health as a "commons" with high competition in the consumption of resources or as a "public good" with low competition. Human health was postulated as a commons by Bodini and colleagues but without reference to Ostrom's SES concept (Bodini *et al*., 2020).

The concepts of "governing the commons" and "One Health" overlap through the collaborative governance, participatory transdisciplinary processes or interactions embedded in both approaches that lead to outcomes for managing shared natural resources and promoting human and animal health. How can we link animal and human health with natural resource management? McGinnis and Ostrom, starting from the approach proposed by Ostrom (Ostrom, 2009), present an extended SES concept with multiple resource systems at the highest level in Fig. 3 (McGinnis and Ostrom, 2014). The four-layered structure of RS, RU, GS and U (now Actors A) is retained, but becomes multi-layered in each category. This allows realistic, multi-layered, simultaneous focal points for action to be included and optimized (focal action situations).

Social, economic and political conditions (S) influence SES from the outside. These include forms of government and administration and their stability, population and economic development. In the health sector, they also include available hospitals, health centres, technologies, laboratories and drugs or vaccines for humans and animals. Ecosystems (ECO) include various patterns, processes and flows that can influence OHSES. Examples are transboundary diseases and their ecological conditions such as temperature, humidity, vegetation which in turn influence vector-borne diseases.

We extend the multi-layered SES resource systems to include human (human resources) and animal resources (wild, domestic and companion animals) and plants (wild and crops) as One Health in SES (OHSES) (Fig. 4). We also extend the list of first and second tier variables to include health-related information (Supplementary Materials: Table 1). For the second-tier properties of governance systems (GS), we used the alternative list as presented by McGinnis and Ostrom (McGinnis and Ostrom, 2014). Resource units (RU) are thus saved life years of humans and animals, which in turn contribute to the human capital of the SES. Both Hardin and Ostrom use grazing systems and their use by animals as examples for their argument. Animals can contribute both to the overuse of pasture and to the restriction of use caused by disease or death.

Thus, we can directly link animal health to the use of natural resources (pasture). Similarly, we can consider the human population as a resource (RS) that contributes to national income as a health-augmented human capital production function (Bloom *et al*., 2018). Sick people can work less and deaths lead to a loss of contribution to national income over the remaining working life (RU). People use natural resources which leads to interactions with other resource systems (RS). Actors (A) are individual stakeholders as well as the different levels of social organization (household, community, province, nation). Governance (GS) also reflects the different levels of the social organization, coordination of health care. The actors of the different layers of the social organization determine the health policy, its measures through their interactions. The resulting effects determine the degree of resilience of a society, analogous to Brigit Obrist's approach of multi-layered social resilience (Obrist *et al*., 2010).

With the extension of SES to include the human resource system as OHSES, we can analyse dilemmas between divergent interests and different strategies with their corresponding or consequent interventions/interactions (I) and outcomes (O) (Fig. 4 and Supplementary Materials: Table 1). For example, the economic maximization of land use through the cultivation of crops such as cereals or fruits by pesticides is opposed to their health impacts for humans and animals. Indirectly, the loss of biodiversity associated with pesticide use leads to the risk of emerging diseases. The

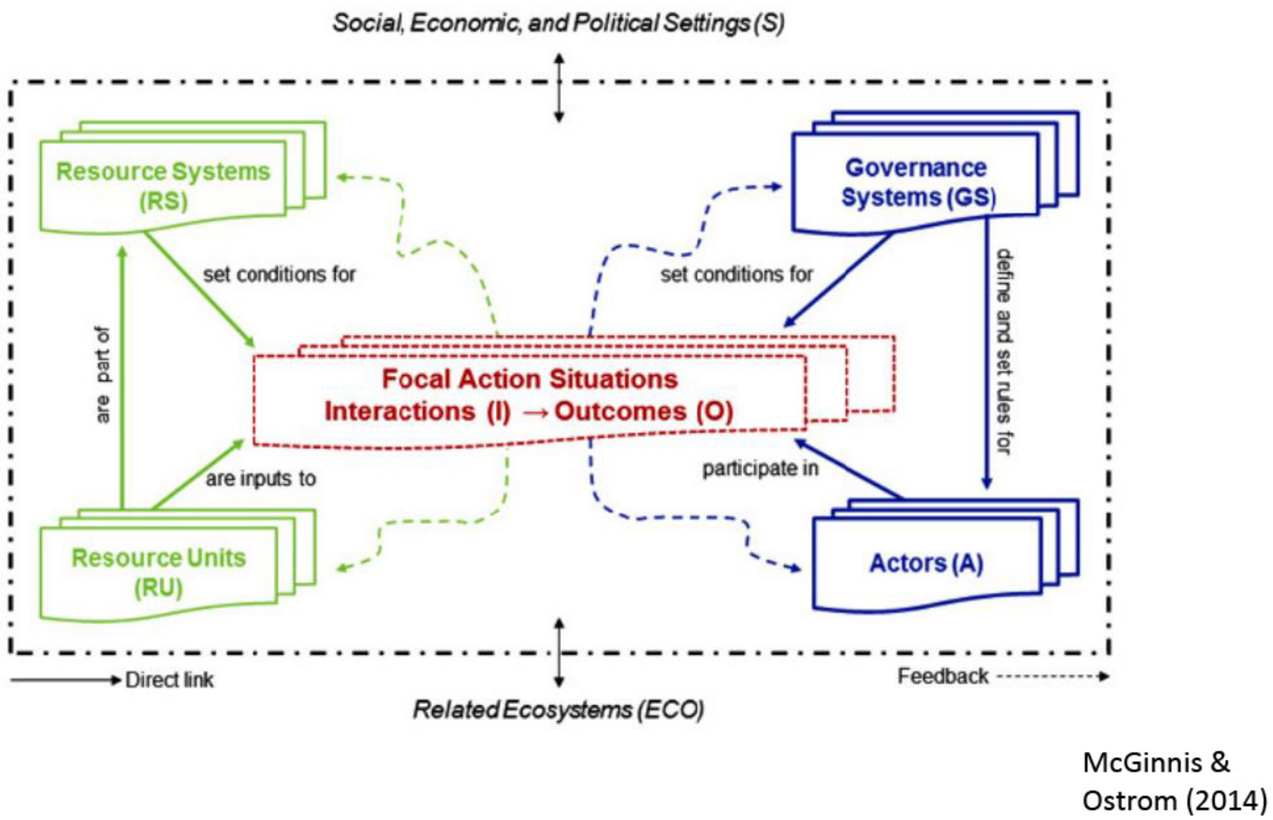

Fig. 3. Extended SES concept with multiple resource systems, resource units, governance systems and actor groups (McGinnis and Ostrom, 2014).

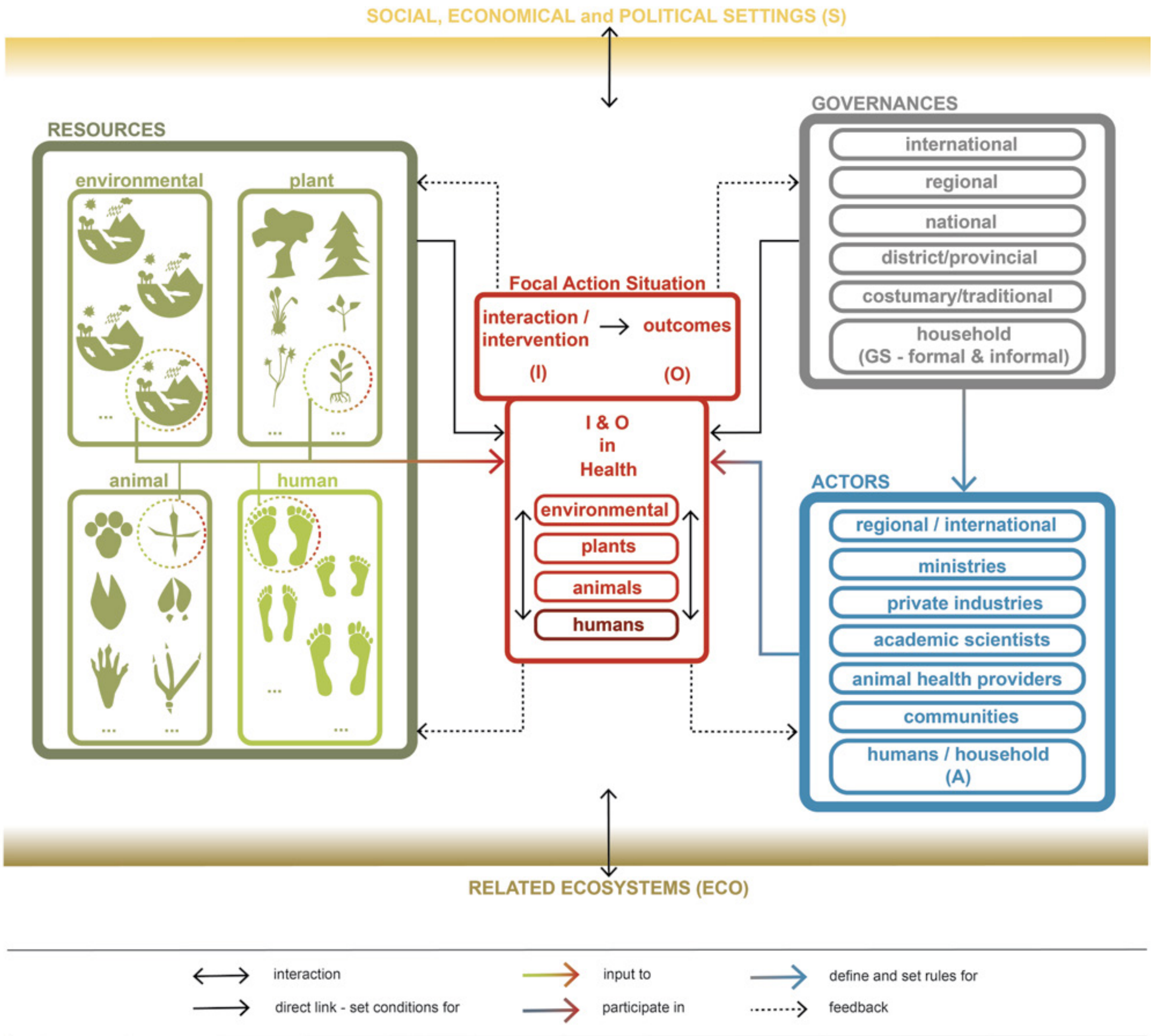

Fig. 4. Extension of SES to include human and animal resources and resource units as HSES (Figure by Aline Veillat).

unhindered spread of diseases between animals and humans leads to human capital losses, which must be weighed against the costs of intervention in the animal reservoir (Table 1).

For the conceptualization, we want to define a mathematical framework as generally as possible and include all the elements mentioned above in a dynamic way. We can add the temporal dimension to the system through discretization in time, i.e., we consider the states of our OHSES (One Health Social-Ecological System) at each timestep. At each timestamp T, we have the actors A_T, the quantities R_T of all considered resources in the system. The resource system may include limitations on the availability of resources, such as the carrying capacity of pastures. Such limitations can be expressed as constraints C. Limitations of resources can also be available technologies or the predictability of the system. All this can be translated as constraints on the resources' quantities or the set of actors' strategies. In the same way, the governance systems will constrain the actors' decision making processes, the strategic space and resources. We name all these constraints as C_T.

In order to make the model as general as possible, we assume that at each time step, the actors interact to make choices about their strategies, affecting the interactions and the focal action situations process. Let's call it the decision making process $P_{DM,T}$ and the resulting strategy profile S_T. It can be precisely defined by the governance system or be a result from the considered games, sometimes negotiation processes as a particular type of game. The Focal Action Situations are key moments of passage from the interactions, interventions and input resources to the outcomes. The outcomes can be considered as a vector of indicators; they can be used to calculate a payoff and compared to the expectations of the actors. The performance indicators are calculated using the predicted resources at the next timestep, i.e., R_{T+1}. We call $P_{FAS,T,ST}$ the process, which models all interactions between the actors, the constraints and the resources at time T given a strategy profile S_T (decisions made by actors for the interactions), giving the system's state at the time T+1.

In summary, we have two processes. (i) The decision making process, corresponding to the regular line arrows from actors (A), the governance system (GS) and the resource system (RS) to the Focal Action Situations (FAS) in Fig. 4. (ii) The focal action situations process, corresponding to the others. Concisely, we can write as the following equations:

$$\begin{cases} S_T = P_{DM,T}(A_T, C_T, R_T) \\ (A_{T+1}, C_{T+1}, R_{T+1}) = P_{FAS,T,S_T}(A_T, C_T, R_T) \end{cases} \quad (1)$$

Table 1. Interactions and outcomes of the second tier of the OHSES.

Interactions/Interventions (I) (at different levels)	Outcomes (O)
I1* – Resource use (e.g., harvesting, vaccination, etc.)	O1 – Social performance measures (e.g., efficiency, equity, accountability, Sustainability, **level of multi-layered social resilience**)
I2* – Communication and influence (e.g., Information, Education and Communication (IEC), Information sharing, Lobbying activities)	O2 – Ecological performance measures (e.g., overharvested, resilience, biodiversity, sustainability)
I3 – Deliberation and decision making processes	**O3 – Economic performance** (e.g., harvest, offtake rates of livestock, logging in forests, human capital effect (HCE))
I4* – Interplays/Interactions between actors (e.g., collaboration, coordination, cooperation, competitions, conflicts, etc.)	**O4 – Health performance** (e.g., YLL/DALYs, number of humans or animals saved)
I5 – Investment and financing activities	**O5 – Externalities to other (OH)SESs**
I6 – Organizational planning (health, environmental and agricultural policies)	
I7 – Self-organizing activities	
I8 – Networking activities	
I9* – Sectoral and intersectoral monitoring activities	
I10* – Sectoral and intersectoral evaluative activities	

*Generalization of the interaction concepts appearing in the McGinnis and Ostrom's paper (McGinnis and Ostrom, 2014).
New additions or modifications are in bold.

This approach needs detailed information about different processes and actors' structures if we want to explicitly include the multi-tier structure and their decision making. Even though such a procedure can be costly in data gathering, modelling and computation, it enables the study of system dynamics in different ways, comparing different strategies and conducting feasibility assessments.

Sustainable management of natural and human resources is only possible if actors cooperate with each other and adhere to commonly accepted norms and rules known as governance system. This is an explicit theoretical pillar of a One Health approach as a transdisciplinary participatory process, seeking consensus on societal problem solving (Zinsstag *et al*., 2023b). According to Ostrom, eight rules apply to the management of the commons (Box 1).

The transdisciplinary approach in One Health (Zinsstag *et al*., 2023b) largely adopts these rules. Rule 1: Human and animal health care always takes place within certain geographical and social boundaries. For example, mixed vaccination services for mobile pastoralists in Chad are targeted for this population group in the lakeshore area of Lake Chad (Schelling *et al*., 2007). Rules 2 and 3: One Health interventions are negotiated with local populations and authorities and adapted to local social and cultural conditions (Münch, 2012). Rules 4–6: Also in health interventions stakeholder competition, conflicts of interests and power imbalances play a role. Clearly, tracking the success and effectiveness of the interventions is also of great importance. Rule 7: Decentralized management of health planning and delivery improves its effectiveness for public health has been recognized for some time and is also pursued in the One Health approach (de Savigny *et al*., 2004; Semali *et al*., 2005). Rule 8: Decentralized health care at community level is embedded in different levels up to the level of the Ministry of Health. Non-governmental informal traditional systems exist in parallel. In our experience, patients mostly use the formal state and informal systems. In Guatemala, for example, state health care and traditional Mayan healers are consulted. We speak of a multi-epistemic knowledge of health (Zinsstag *et al*., 2022).

Box 1. Eight rules for the management of the commons (Revised): https://earthbound.report/2018/01/15/elinor-ostroms-8-rules-for-managing-the-commons.

1. Boundaries: Clear and locally accepted boundaries exist between legitimate users and non-users (clearly defined property rights).
2. Congruence: The rules for appropriation and reproduction of a resource correspond to local and cultural conditions.
3. Communal decisions: Most people affected by a resource system can participate in decisions to determine and change the rules of use.
4. Monitoring of users and the resource: There must be sufficient control over resources to prevent violations of the rules.
5. Graduated sanctions: Sanctions imposed should be in reasonable proportion to the problem caused.
6. Conflict resolution mechanisms: Conflict resolution mechanisms must be quick, cheap and direct.
7. Recognition: A minimum level of state recognition of the right of users to determine their own rules is required.
8. Embedded institutions (for large resource systems): When a common resource is closely linked to a large resource system, governance structures are "nested" at multiple levels (polycentric governance).

We hold that the "One Health" approach can be merged with the "governance of the commons" as OHSES. Why is this significant? How can we apply the OHSES concept in science? OHSES matches in principle the Doughnut economy approach but is more explicit on including human and animal health methodologically (Raworth, 2017). Here, we present the first game-theoretically mathematically and economically analysed example of an OHSES approach to rabies elimination in Africa and map it within McGinnis and Ostrom's extended SES approach (McGinnis and Ostrom, 2014). We outline an analogous example of sustainable and disease-free animal husbandry in Mongolia and reflect on the epistemological and ethical consequences of the OHSES approach.

CASE OF ELIMINATION OF DOG RABIES IN AFRICA

The following section is adapted from (Bucher *et al*., 2023): "Rabies remains a neglected disease and a persistent human and animal health problem in developing countries. Rabies is a fatal neurological disease transmitted primarily by dogs, causing an estimated 59 000 human deaths, 3.7 million disability-adjusted life years lost and US$ 8.6 billion in economic losses each year, and at least 250 000 to 500 000 deaths in dogs. The World Health Organisation (WHO) has set a target to reduce the number of deaths from dog-borne rabies to zero by 2030. Human deaths from rabies can be prevented by the timely administration of post-exposure prophylaxis (PEP) to people who have been bitten. However, PEP remains poorly available in most local health systems, and adherence to PEP is poor and vaccination of dogs is limited." Dog-mediated rabies can be controlled and eliminated through mass vaccination of dogs if sufficiently high (70%) vaccination coverage can be achieved. The main challenges in canine rabies vaccination campaigns are access to vaccines and the mobility of dogs, mostly through human-mediated dog transport, leading to almost certain reintroduction of rabies pathogens at local and national levels. Active protection of national borders could prevent reintroduction from outside, but is probably not feasible across countries.

The constant threat of pathogen introduction means that the impact of policy measures taken by individual countries depends on the efforts of other countries. Such strategic policy choices can be analysed in a mathematical framework (game theory). In such a framework, we estimate the gains and costs of different policy actions for all interacting actors; in this way, we can compare them to find the most profitable self-interested or cooperative choices. We use this approach to investigate the possible benefits of achieving a socially optimal policy equilibrium through cooperation.

Lack of or incomplete post-exposure prophylaxis (PEP) in humans and non-vaccination of dogs is currently the prevailing feature in all countries in Africa. We show that coordinated mass dog vaccination between countries and PEP would lead to the elimination of canine rabies in Africa, with a total welfare gain of US$ 9.5 billion (95% CI: 8.1–11.4 billion). Uncoordinated mass vaccination of dogs between countries and incomplete PEP in humans result in lower welfare gains and do not lead to the elimination of canine rabies. Nevertheless, mass dog vaccination is the dominant strategy in a game-theoretic sense for many countries even in the face of a possible reintroduction of rabies from other countries. Coordinated rabies control among African countries can lead to more socially and environmentally equitable outcomes by reducing fatalities to near zero and potentially eliminating rabies. Intergovernmental African platforms such as the African Union Inter-African Bureau on Animal Resources (AU-IBAR) and regional platforms such as the Economic Community of West African States (ECOWAS) are best placed to achieve such coordination in their respective space (Bucher *et al*., 2023).

For rabies elimination in Africa, we fit the OHSES (Fig. 4) to the affected resources, governance and actor systems in Fig. 5. Supplementary Materials: Table 2 shows the corresponding second-stage variables. The interactions/interventions and outcomes are shown in Tables 2 and 3.

Assumptions and considerations of the application of the OHSES framework to rabies elimination in Africa are presented in Supplementary Materials 2. In summary, the described model assumes two possible strategies for each country (actor) as a result of their respective decision making processes. Then, the strategy will define how different resources evolve in time, i.e., how the disease spreads (number of rabid dogs and infected humans) and how the quantities of PEP and vaccines increase. The description of the focal action situations (FAS) corresponds to the resource use (I1*) and is modelled by the focal action situation process in the formula (1). These focal action situations are strategy-dependent and assume that all other interaction goes in the way of assuring the success of the strategy. For example, in the case of the regional vaccination campaign, we assume that the communication for the vaccination campaign (I2*) is successful and sufficient to assure the population's adherence to this campaign. That the national policies (I6) and the regional coordination (I4*) of the vaccination campaign manage to implement it everywhere and at the same time. We assume sufficient funds and vaccines (I5), supposing the vaccines can be provided through the World Organisation for Animal Health (WOAH) vaccine bank in the interest of the global goal of eliminating rabies in Africa. Other means for financing, such as financial bonds (Anyiam *et al*., 2017), can serve as start-up funding for campaigns. We can see that other parts of the interactions were not considered at the national level but can become crucial in the implementation of a One Health policy, such as sectoral and intersectoral monitoring (I9*) and evaluative (I10*) activities, self-organizing activities (I7) and networking activities (I8).

The outcomes are calculated and summarized for different strategy profiles as payoffs, then compared in the game theoretic setting. Even though the economic performance measures (O3) were the only ones used to calculate the countries' payoffs. The model can also follow the strategies' health performance measures (O4) by comparing the number of humans and dogs saved. For the ecological performance measures (O2) of a strategy, in this case, we can talk about sustainability in the sense that the strategy has a long-lasting effect without any additional intervention. In this case, only the coordinated vaccination campaign as to eliminate rabies can be considered sustainable. We did not consider social performance measures but the implementation of the intervention, as seen before, would require transdisciplinary collaboration between stakeholders of different sectors and between different countries. If successful, this can lead to better socio-political balance on different levels, as well as to better resilience in all strata of society. The analysis showed an incremental benefit of US$ 9.5 billion for the One Health approach (coordinated mass dog vaccination) compared to the baseline. The proposed OHSES framework shows the limitations of our model and different aspects that would need consideration for a successful intervention.

CASE OF SUSTAINABLE AND HEALTHY LIVESTOCK PRODUCTION IN MONGOLIA

During the socialist period, the number of livestock (cattle, sheep, goats) in Mongolia remained at a constant level of about 25 million animals. After the end of the socialist period, the number of goats and cows grew strongly and in 2022, it was reported to be over 71 million animals (Fig. 6). Is this high number sustainable for the use of Mongolian pasture? Are we heading for pasture destruction? Livestock contribute to global warming by emitting methane and carbon dioxide. At the same time, Mongolian pasture stores carbon. What is the carbon footprint of Mongolian livestock? In Mongolia, it is difficult to grow cereals and other crops. Livestock is the best land use option for climatic and environmental reasons. In Mongolia, not only contagious animal diseases such as foot-and-mouth disease but also brucellosis and echinococcosis are common. The latter two also infect humans. Mongolian livestock farming faces a dilemma between the need to limit livestock production, effective disease control and the income of livestock farmers. Several resource systems (RS) are affected by this. The pasture with its stocking density (carrying capacity). The pastoral resources can also be characterized by the level of the floristic biodiversity and their ability to store carbon. The livestock whose products contribute to income are threatened by diseases, climate change (dzud) and limited feed availability. The people whose income depends on livestock production, also get sick from the animals. Many people migrate to the capital because they cannot earn a sufficient income in the countryside.

Mongolian authorities, livestock farmers, health professionals, agronomists and other stakeholders should formulate common goals for sustainable livestock production in Mongolia. This requires a participatory transdisciplinary process. In preparation for this, a systemic analysis could be carried out using the One Health in Social-Ecological Systems method. From economic, ecological and epidemiological perspectives, the aim of this analysis would be to find the best strategy for each resource system. How many people can earn a sufficient income from livestock whose number is limited by the stocking density of the pasture? How can animal husbandry become climate neutral, i.e., the carbon dioxide and methane emissions of the Mongolian herd can be compensated by

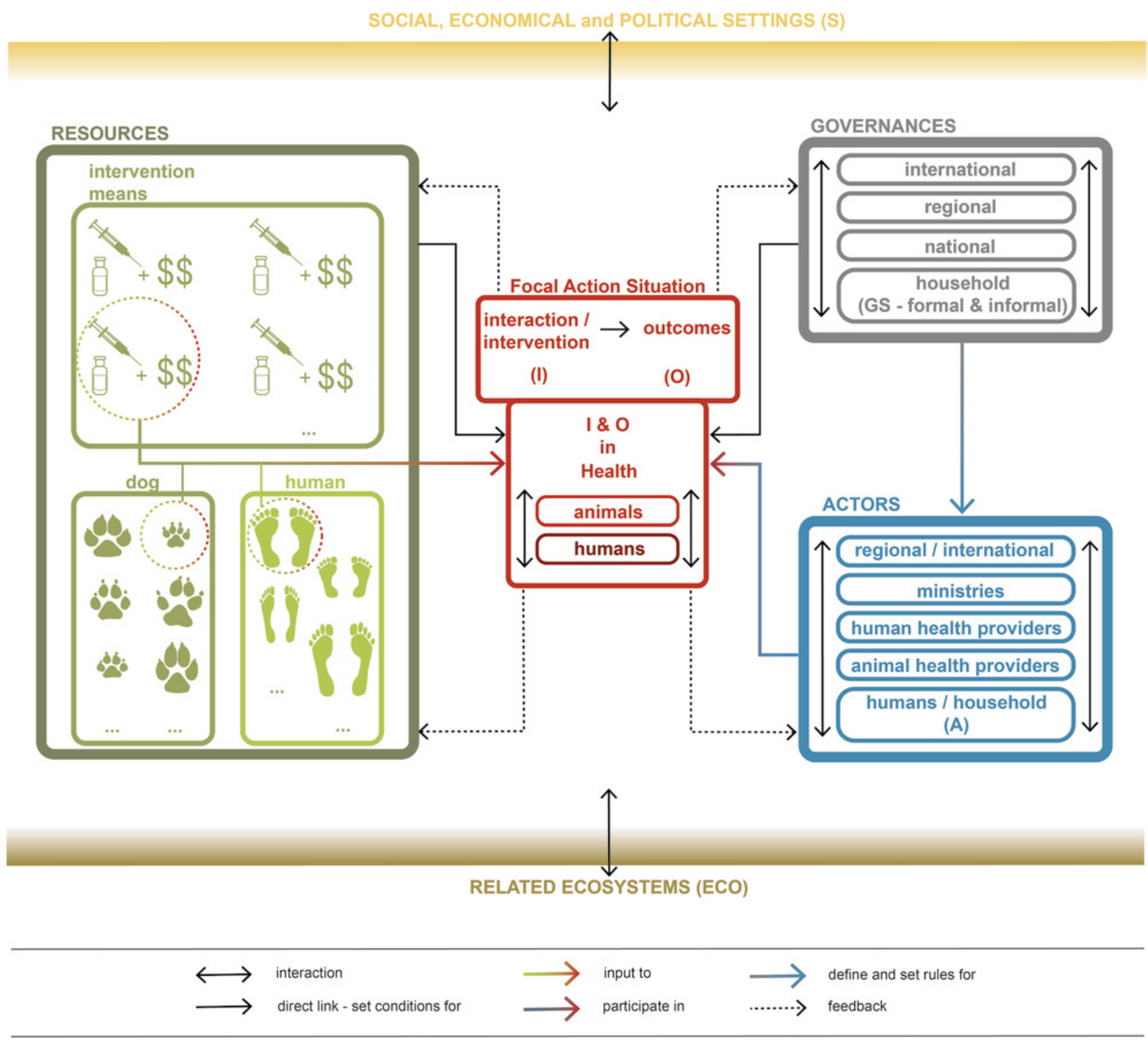

Fig. 5. OHSES for the elimination of dog rabies in Africa (Figure by Aline Veillat).

the carbon sequestration of the pasture? How can the biodiversity of the Mongolian pasture be stabilized or even increased? How can animal diseases be controlled or even eliminated and people no longer become ill from animals?

To answer these objectives, we first need a mathematical model of animal production and the associated income as a function of pasture use. This will allow us to estimate the carrying capacity (number of livestock) of the Mongolian pasture. In a further step, the carbon balance can be calculated and then the number of livestock possibly adjusted. Another sub-model should describe the relationship between pasture use and pasture biodiversity. Finally, we can add the transmission of diseases between livestock and livestock to humans. Existing models simulate the livestock population in Mongolia (Shabb *et al.*, 2013) and the transmission of brucellosis between livestock and to humans. Livestock production and health costs have also been analysed previously in Mongolia (Roth *et al.*, 2003; Zinsstag *et al.*, 2005a).

Once all these linkages between the different resource systems can be simulated, we are ready to simulate different strategies. These strategies should be negotiated between the actors. From these strategies, payoff functions can be formulated. From this, those strategies can be identified that are best for all actors (Nash equilibrium) and that bring the greatest profit for all participants (Pareto efficiency). Of course, these results must then be discussed with the actors to assess them against reality and adjust them if necessary.

This analysis could lead to policy recommendations for the government and recommendations for action for all actors. An important outcome would be that the actors maintain their cooperation for a healthy and sustainable livestock production and find a socio-culturally, locally adapted sustainable management of their natural resources.

Results

EPISTEMOLOGICAL AND ETHICAL ASPECTS OF THE HSES APPROACH

The HSES approach is based on epistemological and ethical foundations. Scientists working with governments and populations in a transdisciplinary way consider epistemological diversity. No single actor in an HSES can claim sole control over the way knowledge is created. For example, in the collaboration on

Table 2. Interventions of dog rabies elimination in Africa.

Interactions/Interventions (I) (at different levels)	Example: Rabies (Bucher *et al.*, 2023)
I1* – Resource use (e.g., harvesting, vaccination, etc.)	• Reaction to new cases using PEP • National mass dog vaccination campaign, as additional resource use if this strategy was chosen.
I2* – Communication and influence (e.g., Information, Education and Communication (IEC), Information sharing, Lobbying activities)	Assumption: The communication campaign is efficient enough to attain the needed vaccination coverage.
I3 – Deliberation and decision making processes	We simplify the decision making process only to the two final decisions.
I4* – Interplays/Interactions between actors (e.g., collaboration, coordination, cooperation, competitions, conflicts, etc.)	• Assumption: If the country is doing a mass vaccination campaign, it coordinates with other countries doing this campaign to do it simultaneously. • Assumption: No internal or external conflict such as undermine the interventions or possible coordination.
I5 – Investment and financing activities	Assumption: There is enough investing for all scenarios.
I6 – Organizational planning (health, environmental and agricultural policies)	Assumption: The country's planning is concordant with the chosen strategy.
I7 – Self-organizing activities	Not considered.
I8 – Networking activities	Not considered.
I9* – Sectoral and intersectoral monitoring activities	Not considered.
I10* – Sectoral and intersectoral evaluative activities	Not considered.

*Generalization of the interaction concepts appearing in the McGinnis and Ostrom's paper (McGinnis and Ostrom, 2014).
New additions or modifications are in bold.

Table 3. Outcomes of dog rabies elimination in Africa.

Outcomes (O)	Example: Rabies (Bucher *et al.*, 2023)
O1 – Social performance measures (e.g., efficiency, equity, accountability, sustainability, **level of multi-layered social resilience**)	Not considered.
O2 – Ecological performance measures (e.g., overharvested, resilience, biodiversity, sustainability)	The strategy profile with all countries' mass dog vaccination is sustainable, as it leads to the elimination of rabies, and it would need to be reintroduced from outside the continent.
O3 – Economic performance measures (e.g., harvest, offtake rates of livestock, logging in forests, human capital effect (HCE))	Economic performance corresponds to different costs (PEP use, vaccination campaign cost and HCE). All that constitutes the payoff.
O4 – Health performance measures (e.g., YLL/DALYs, number of humans or animals saved)	In the model, several health performance indicators are calculated: • Number of human lives saved. • Number of dogs saved.
O5 – Externalities to other (OH)SESs	Not considered.

New additions or modifications are in bold.

improving health care with the Mayan population in Guatemala, both Western medical knowledge and the knowledge of Mayan healers is included (Zinsstag, 2021). The two knowledge systems are so different that they can hardly be linked, but they can coexist and are in fact used at the same time by the local population.

This also has implications for the ontology of knowledge acquisition. While the academic, biomedical actors mostly limit themselves to a purely materialistic ontology, indigenous actors contribute a mental or psychological and spiritual dimension that is an indispensable part of reality for the local population. In these interactions, a One Health approach allows for ontological openness (Zinsstag *et al.*, 2022). HSES approaches are complex, multivariate, non-linear, tiered and changeable. They abandon linear determinacies and align with complex and process-oriented approaches such as process philosophy (Barbour, 1997). The HSES approach is congruent with new philosophical currents such as Corine Pelluchon's "New Enlightenment in the Age of the Living" (Pelluchon, 2021). She is committed to overcoming the anthropocentric and dualistic ways of thinking of the Enlightenment shaped by René Descartes through a post-humanist attitude that sees humans with animals as vulnerable beings in their environment. A culture of appreciation and cooperation is to question neoliberal capitalist competition. Markus Gabriel, for his part, in "Man as Animal", with reference to Pelluchon, opposes a one-sided faith in science without rejecting its achievements. He calls for increased transdisciplinary and trans-sectoral cooperation. Humanities and social sciences should cooperate much more with natural and technical sciences and develop a new image of man together with social actors in politics, economy and civil society. Gabriel's proposal of "epistemic modesty" supports the multi-epistemic approach within the HSES approach (Gabriel, 2022). When following a HSES approach, several ethical issues arise on: 1. Human security, animal welfare and environment protection, 2. The need for cooperation, 3. Equity

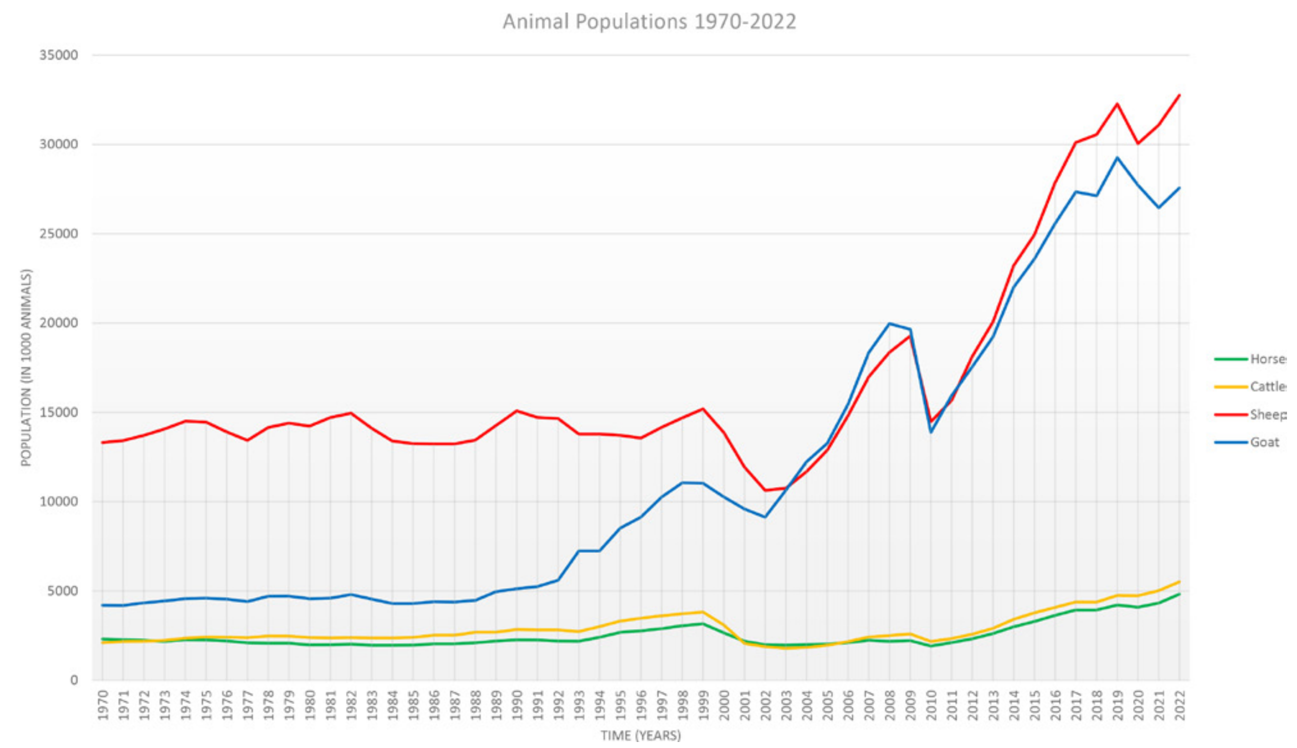

Fig. 6. Development of livestock numbers in Mongolia between 1970 and 2022.

in transdisciplinary processes and 4. Ideological, spiritual and psychological aspects (Supplementary Materials 3).

Discussion

In the face of rapidly growing and escalating issues such as pandemics, AMR, climate change (Cissé *et al*., 2022), the threat of biodiversity loss, global human migration and new geopolitical and spatio-temporal political challenges, systemic approaches such as OHSES that simultaneously integrate human and animal health together with societal frameworks and natural resources are rapidly gaining importance. OHSES approaches can help transform emerging apocalyptic fears expressed in movements such as the Extinction Rebellion into forward looking processes that emerge from a perspective of hope (Pelluchon, 2023).

CONFLICT OF INTEREST

The authors have not conflict of interest.

ETHICS STATEMENT

All ethical issues related to the preparation of this manuscript have been fulfilled. As a conceptual desk study, no ethical clearance was sought. The ethical issues of content of the paper have been addressed in Supplementary Materials 3.

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AUTHOR CONTRIBUTIONS

All authors contributed equally to the development of this article.

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