

THE VEOLIA INSTITUTE REVIEW
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BIODIVERSITY AND HEALTH



Foundation for
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INTRODUCTION

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Nature sustains life, yet everywhere is under threat. Almost every ecosystem is eroded, contaminated, or degraded. Although biodiversity is in reality far richer than previously imagined, since we know about only a tenth of existing species, populations of many species are in freefall. It is believed that species are disappearing at least 10 to 100 times faster than during the five previous mass extinctions.¹ The sixth mass extinction event is now under way, and humans are the prime culprits. Fragmentation and destruction of natural habitats, pollution from chemicals, light and sound, overexploitation of land and sea, climate breakdown, invasive species, excessive resource extraction: these are the primary drivers behind biodiversity erosion.

Biological invasions, involved in 60% of plant and animal extinctions recorded globally, are one of the most powerful factors in biodiversity loss (see article p. 44). 7,000 to 10,000 different marine species travel the seas in ships' ballast tanks every day. And every year 200 alien species colonize new environments and begin competing with indigenous species. Asian hornets in Europe, Nile perch in Africa, Japanese knotweed in North America: invasive species – species that have managed to survive then thrive when introduced outside their natural range – are becoming more widespread, disrupting local balances.

Chemical pollution is global and permanent, just like climate change. To take one example, recent studies show that two thirds of the planet's watercourses have significant concentrations of antibiotics (see article p. 26). Certain forms of pollution are well known but most are not, notably emerging pollutants such as microplastics, pesticides, hydrocarbons or endocrine disrupters.

And when we harm biodiversity we harm our own health. Ecosystem erosion alters the prevalence and transmission of diseases to humans. Most emerging zoonotic diseases can be traced back to deforestation, changes to natural habitats, trading in wild animals and the intensification of farming practices. Invasive species can also act as vectors for transmitting pathogens to humans. Then there is the issue of ecosystem transformations that create food insecurity and increase the risk of hunger and malnutrition among vulnerable groups.

The disappearance of species deprives us of remedies that could have provided tools for combatting current or future diseases. The natural world is also a vast therapeutic reservoir that has, in a process of trial and error, solved extremely complex medical problems over millions of years. Nature is astoundingly inventive. Seven centuries ago Leonardo da Vinci was already advising us that "nature is the source of all true knowledge."

We cannot escape the fact that we are dependent on other species. Human health and the health of environments where we live are inextricably linked: there is, ultimately, only one health. It is well known that restoring and preserving biodiversity is very much in our interest, that it should attract as much attention as climate heating. Using the prism of human health is a more effective way of defending biodiversity as it impacts us directly. And defending biodiversity is all the more important because time is running out. Biodiversity decline is happening almost out of sight, apparently slowly but actually very rapidly in terms of geological cycles: a matter of falling birth rates rather than generalized calamity.

How can declining biodiversity be reversed? Although some issues have to be tackled at the global level, there are many others where people can act at the local level: fragmentation and destruction of natural environments, pollution, overexploitation of land and fishery resources, invasive species, and so on. Better and more accurate knowledge, multiple indicators for mapping and tracking regional data, and the accretion and cross-referencing of multi-disciplinary datasets are of considerable help in acting accurately and effectively for the long term. There is no question that biodiversity erosion could be slowed by implementing more ambitious regeneration strategies and, most of all, increasing conservation efforts: the fact is that one of the best ways to protect nature is leaving it in peace. But do we want to? Are we capable? Nature is wonderfully resilient; the self-cleaning capacity of wetlands is just one example. Very often, providing that the irreversibility threshold has not been reached, the natural world can return to its initial state simply by being left alone for a few decades.

Reducing environmental pressures, regulating risky interfaces between humans and the natural world to limit pathogen spillover, eco-epidemiological surveillance in sensitive regions, and controlling the trade in wild animals are all important measures. By explicitly embedding human health into biodiversity protection policies, and incorporating biodiversity protection into public health policies, governments can roll out actions that deliver a double benefit.

¹ IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany. <https://doi.org/10.5281/zenodo.3831673>.





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They also need to move beyond curative health policy approaches to ensure that prevention of zoonotic diseases is embedded as a feature of biodiversity protection policies. Sadly, the success of a prevention policy is not visible; it succeeds when nothing happens. But our health is dependent on preventive rather than curative policies.

Improved insights and understanding are vital to better protection for ecosystems and human health. Many new human diseases come from animals, wild animals in particular. Without in-depth knowledge of wildlife and, more generally, how ecosystems operate, it will be difficult to properly protect human health.

And when we harm biodiversity we harm our own health. Ecosystem erosion alters the prevalence and transmission of diseases to humans

Experience shows it is possible to preserve biodiversity and restore degraded ecosystems. Their decline is not irreversible. In France, populations of many species of hoofed wild animals, raptors, egrets, and white storks are all increasing strongly. Beavers, grey wolves and European otter populations are rising fast. In 1970 there were only three species of fish living in the Seine in Paris; today there are around 40.²

Appropriate financial support and regulatory frameworks are needed to encourage scaling up of solutions. The solutions for protecting and restoring biodiversity exist, are proven and immediately deployable. Looked at in isolation they can seem derisory, but adopted massively and persistently over time they will have a major impact. What

we lack is not so much the solutions as the political will and financial incentives for everybody to get involved, from policymakers, businesses and farmers to administrations, NGOs, and private individuals.

Biological diversity is how nature adapts to change. For people, it offers a form of health insurance. Nature and humanity share a common destiny: depleting nature depletes humanity, protecting nature protects humanity. If humanity is biodiversity's worst enemy, we can also, when we want to and when we give ourselves all the tools we need, be its best friend.

² SIAAP, Service Public de l'Assainissement Francilien [Public Service for Sewage Treatment in the Ile-de-France Region], <https://www.siaap.fr/metiers/biodiversite/>.



FOREWORD

Harvey V. Fineberg

Professor of Health Policy and Management, Emeritus, Harvard T.H. Chan School of Public Health,
Member of the Veolia Institute's Foresight Committee

Biodiversity and Human Health: A Vital Yet Underestimated Link

Six years ago, the world was shaken by the emergence of a novel disease, later identified as COVID-19 and declared a global pandemic by the World Health Organization. Although the exact origin of SARS-CoV-2 remains uncertain, many devastating human infections, such as HIV, originated as animal spillovers. Human health is tightly connected to wildlife and ecosystems.

We are linked to biodiversity both physically and mentally. It shapes our well-being in many ways, including the abundance, variety, and quality of food, the functioning of our immune system, and the medicines we use. This edition of the FACTS Reports review explores these multiple interdependencies between human wellbeing and biodiversity.

As noted, biodiversity influences health directly through the risk of zoonotic infections. Several articles examine how imbalances and shifts in species dynamics can create conditions for the emergence of human pathogens (see articles p. 44, p. 50 and p. 56).

We are linked to biodiversity both physically and mentally. It shapes our well-being in many ways, including the abundance, variety, and quality of food, the functioning of our immune system, and the medicines we use

Biodiversity is also a fundamental pillar of nutrition and food security. Pollinators, soil organisms, and plant-insect interactions sustain crop productivity and food quality, and biodiversity loss or intensive agricultural practices can compromise yields, degrade soils, and exacerbate nutritional inequalities. These and related issues are covered (see articles p.10, p.16 and p.82).

This review also explores biodiversity as an inspiration for medical innovation and treatment. Biomimicry offers novel ideas for new preventive, diagnostic and therapeutic pathways (see article p.26).

Biodiversity underpins essential ecosystem services that are fundamental to human well-being (physical and mental). Natural and restored ecosystems support clean air and water, climate regulation, and living environments that sustain quality of life. Several articles explore these links, underscoring the importance of preserving and restoring natural spaces (see articles p.16, p. 66 and to some extent articles p.92 and p.96).



Beyond these benefits, the review also highlights what happens when these regulatory functions are weakened. It shows how pollution interacts with biodiversity loss to amplify health risks, and how degraded ecosystems – down to the human microbiome – struggle to maintain their essential regulatory roles, affecting air, water and soil quality (see articles p. 20, p. 34, p. 36 and p. 40).

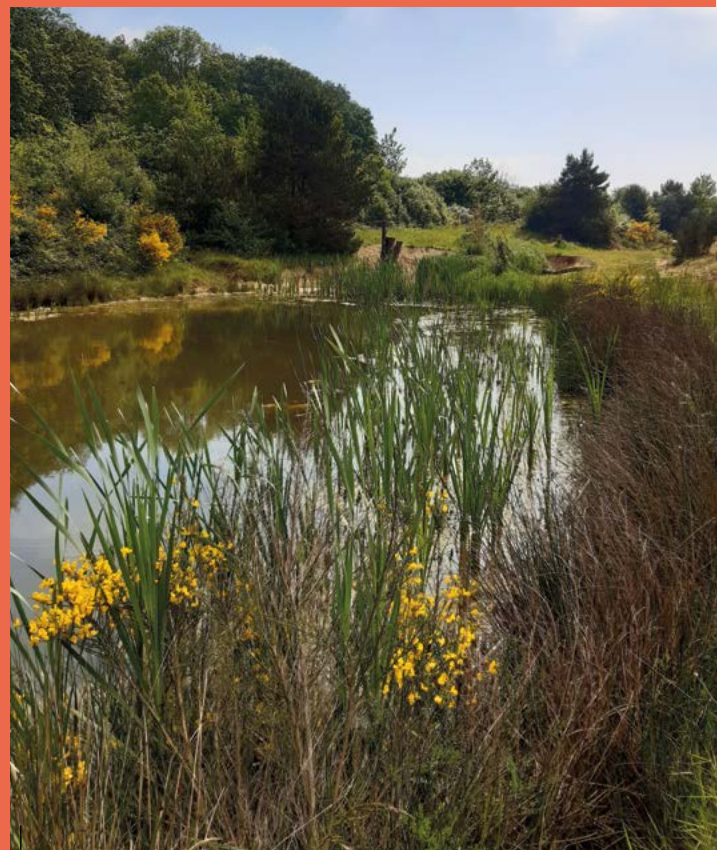
Many articles additionally underline the contribution of biodiversity to climate resilience. Diverse ecosystems help buffer extreme weather events, limit the spread of climate-sensitive disease vectors, and strengthen the adaptive capacity of communities and supply chains. Preserving biodiversity is therefore not only an ecological imperative but also a strategic priority for long-term human health and wellbeing.

Beyond the diagnosis of threat of degraded biodiversity, the key question is: what do we do? The report outlines avenues for action, especially in the final section that identifies possible solutions: which must be rooted in science mainstreaming the One Health approach, rethinking food systems for resilience and equity, safeguarding the world's remaining “global pharmacy” (for example through initiatives such as “30 x 30”)¹, and embedding biodiversity into urban and territorial planning. Sound public policy – from global frameworks to local initiatives – can accelerate progress (see article p. 72), and improved indicators and data infrastructures can better connect scientific knowledge to decision-making (see article p. 78).

Diverse ecosystems help buffer extreme weather events, limit the spread of climate-sensitive disease vectors, and strengthen the adaptive capacity of communities and supply chains

Finally, progress will not be achieved without innovative financing solutions (see article p. 96) and without citizen engagement, calling for a renewed dialogue between science and the public (see articles p. 88 and p. 92).

Ultimately, the articles assembled here converge on a core message: protecting biodiversity is inseparable from protecting health. In an age of misinformation and political controversy, this review aims to reconnect evidence, policy, and collective responsibility – offering insights, solutions, and a forward-looking vision of planetary health.



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¹ A global goal aimed at protecting and conserving at least 30% of the planet's land, freshwater, and oceans by 2030, adopted as part of the Kunming-Montreal Global Biodiversity Framework in 2022.



An Interview with Harvey V. Fineberg

Harvey V. Fineberg

Professor of Health Policy and Management, Emeritus, Harvard T.H. Chan School of Public Health,
Member of the Veolia Institute's Foresight Committee

WHAT MAJOR GLOBAL FORCES AND CHALLENGES ARE RESHAPING THE BIODIVERSITY-HEALTH NEXUS TODAY?

First, the relationship and growing interdependence between biodiversity and health – further intensified by climate change and human activities – can be understood as part of what I define as *global mega-challenges*: complex, deeply interconnected issues with far-reaching consequences that require coordinated responses at the global level. Recent international gatherings, such as the 2022 United Nations Biodiversity Conference of the Parties (COP15), which led to the adoption of the Kunming-Montreal Global Biodiversity Framework,¹ illustrate the vital importance of bringing together actors from across the world to jointly define priorities and strategic directions.

This makes the protection of planetary health not only urgent but essential for the survival of life in all its forms

A second major force is the unprecedented impact of human activity on the planet. The speed and scale of environmental change now exceed the adaptive capacity of ecosystems and species, accelerating biodiversity loss and threatening public health. For the first time in Earth's history, a single species is the primary driver of such disruption. This reality underpins the debate over the Anthropocene, a term introduced in the 1980s by Paul Crutzen and Eugene Stoermer to describe a geological age shaped by human influence. Although contested, the underlying reality is clear: human-driven change now outpaces biological adaptation and places ecosystems under extraordinary strain. A clear example lies in modern agricultural practices. Large-scale monoculture narrows genetic diversity and weakens food systems' resilience, while the expansion of livestock and the decline of wildlife – driven by habitat encroachment and practices such as poaching – further destabilize ecosystems. These pressures also significantly increase the likelihood of zoonotic spillover: as humans push deeper into wild environments, pathogens jump more easily from wildlife to humans or livestock, fueling pandemics such as HIV/AIDS and outbreaks such as Ebola.

A third key challenge is the fast-expanding human ability to alter biological evolutionary processes. Humans have evolved to the point where they not only have a profound impact on the environment, but also the technological capacity to have directed evolution, apart from natural evolution. Advances in genomic technology, especially CRISPR,² give us unprecedented power to alter genomes, raising the prospect of a form of "neo-evolution".³ While promising for treating severe diseases, such techniques pose profound ethical risks when applied to engineering human traits. These ethical and biological uncertainties reinforce the need for biodiversity conservation: genomic intervention cannot replace systems shaped over millions of years and call for humility, restraint, and renewed commitment to protecting the living world.

Finally, the rise of artificial intelligence, combined with robotic systems and miniaturization of electronic components, adds another unpredictable layer of influence over humans' experience of life and the ecosystems that sustain it. Combined with the pressures of the Anthropocene, insufficient global cooperation, and expanding genetic manipulation, these forces form a convergence reshaping humanity's relationship with biodiversity. This makes the protection of planetary health not only urgent but essential for the survival of life in all its forms.

HOW HAS BIODIVERSITY HISTORICALLY SHAPED MEDICAL INNOVATION, AND HOW DOES IT CONTINUE TO INSPIRE BIOMEDICAL RESEARCH TODAY?

Nature has long served as a foundation for medical innovation. Penicillin emerged from Fleming's observation of a fungus inhibiting bacterial growth; quinine and artemisinin, two cornerstone antimalarials, originate from traditional

¹ United Nations Environment Programme (2022) - Kunming-Montreal Global Biodiversity Framework | UNEP - UN Environment Programme.

² CRISPR is a genome editing tool that allows geneticists to cut out targeted DNA sequences. Questions and Answers about CRISPR | Broad Institute.

³ Refers to a new phase of biological evolution in which humans now have the ability and desire to shape evolution through science and technology – Ted-ed (2011) Are we ready for neo-evolution? - Harvey Fineberg | TED-Ed.



plant-based remedies; and digitalis, derived from foxglove, shaped the treatment of heart failure for decades. These examples illustrate how careful observation and extraction of natural compounds have repeatedly advanced medicine.

Given this legacy, it is no surprise that pharmaceutical companies continue to invest in exploring nature as a source of future therapeutics. Today, research programs at the National Institute of Health⁴ and within the pharmaceutical industry continue to explore plants, bacteria, fungi, marine organisms, and symbiotic systems such as the human microbiome as promising sources of new therapies, reinforcing that biodiversity – both within and around us – remains an essential reservoir of biomedical discovery.

HOW DOES BIODIVERSITY SHAPE PUBLIC HEALTH POLICIES AND RESEARCH PRIORITIES, AND WHY IS HEALTH A CRITICAL LEVER IN BIODIVERSITY STRATEGIES?

The main bond between public health policy and biodiversity lies in the One Health approach,⁵ which integrates human, animal, plant, and environmental health. This framework shows how environmental degradation and biodiversity loss heighten health risks and must therefore be embedded in policymaking. A second domain of connection concerns nutrition and sustainable agriculture: plant-based diets, resilient food systems, and biodiversity-preserving methods remain crucial to long-term population health. A third area is mental and urban health, where designing cities with green spaces, diverse plant life, and access to nature demonstrably improves well-being. Together, these pillars stress the need to systematically include biodiversity into public health agendas and show that neglecting biodiversity increases epidemiological, nutritional, and psychological vulnerabilities.

Biodiversity – both within and around us – remains an essential reservoir of biomedical discovery

In a broader sense, health plays three distinct but complementary roles in biodiversity protection. First, it acts as a motivator: because people consistently value and respond to health concerns, linking biodiversity to health helps mobilize public attention and support. Second, health functions as an objective, since biodiversity underpins physical, mental, and public health outcomes. Third, health serves as a foundation for policy, providing a legitimate basis for integrating biodiversity across public health, environmental, food, and urban agendas. Together, these roles – motivator, objective, and policy basis – form a coherent rationale for placing health at the core of biodiversity strategies.

IN A CONTEXT OF GROWING SKEPTICISM TOWARD SCIENCE, WHY IS THE HEALTH-ENVIRONMENT NEXUS A STRATEGIC AREA OF RESEARCH, AND HOW CAN IT CONTRIBUTE TO REBUILDING PUBLIC TRUST?

In today's context of growing public distrust in science and institutions, strengthening the interface between health, the environment, and research is more critical than ever. Scientific leadership cannot operate in isolation:

researchers working on biodiversity and environmental health must also engage with society, listen to public concerns and participate in dialogue with diverse audiences. Not all scientists need to be communication experts, but more of them must take part in public exchange, especially in an era shaped by social

media and fragmented information flows. Approaching the public first as listeners rather than instructors is essential to rebuilding trust. Mutual understanding between scientists and society is essential to inform research priorities, support effective policies, and foster collective alignment around biodiversity and health challenges.

In short, sustained progress requires scientific excellence as well as public engagement, transparency, and communication that together bridge the gap between scientific knowledge and societal expectations.

⁴ National Institute of Health (USA).

⁵ World Health Organization. *One Health*. https://www.who.int/health-topics/one-health#tab=tab_1.

About the author

Harvey V. Fineberg served as President of the Gordon and Betty Moore Foundation from 2015 to 2026 and is a member of the Veolia Institute's Foresight Committee. He previously served as President of the U.S. National Academy of Medicine (2002-2014), as Dean of the Harvard Chan School of Public Health (1984-1997), and as Provost of Harvard University (1997-2001). He has devoted most of his academic career to health policy and medical decision-making. Dr. Fineberg is the co-author and co-editor of several publications. He holds multiple honorary degrees and has received various awards, including the Henry G. Friesen International Prize in Health Research.



1

Biodiversity and Health: a Vital Alliance



Achim Steiner, former Director of the United Nations Environment Programme, describes our relationship to the living world in these terms: “Across cultures, humans inherently value nature. The magic of seeing fireflies flickering long into the night is immense. We draw energy and nutrients from nature. We find sources of food, medicine, livelihoods, and innovation in nature. Our well-being fundamentally depends on nature.” Over and above the beauty of the natural world that enchants us and the diversity of species that fascinates us, it is important that we acknowledge more explicitly our structural dependency on biodiversity: it is a necessary condition for our existence, to the extent that preserving our societies is inextricably tied to preserving the living world.

Our societies depend heavily on biodiversity in countless ways. The most well-known is without a doubt the vital role pollinators play in food production: 35% of worldwide agricultural production is dependent on pollinators, a group that includes bees, birds, and bats.² Beyond this emblematic example, biodiversity is a determining factor in human health thanks to its role supporting soil health, regulating diseases, helping our bodies function, and instigating medical innovations. In the first section of this report, we examine the multiple facets of the links between biodiversity and health, from the ecological underpinnings of food systems to the organic mechanisms inspiring new therapeutic approaches.

Firstly, we know that biodiversity is indispensable to a sustainable healthy diet. **Coline Jaworski** explains how microbial diversity in soils, pollinating insects, and bio-aggressors' natural enemies together support soil fertility, the nutritional qualities of crops, stable harvests, and a reduction in the use of chemical inputs. Given the shortcomings of intensive farming, it is clear that a shift to agroecological systems is needed to reconcile food security with adapting to climate disruption and protecting human health.

In the same vein, **Adriana Morrell** and **Dale Pulvermacher** show how fungal biodiversity forms a central pillar of soil health and the operation of land-based ecosystems. Fungi form symbiotic systems with plants that improve nutrient and water uptake, soil structure, carbon capture,

and plants' resistance to environmental stresses. Their research highlights the key role fungal interactions play in restoring grasslands and the sustainability of agroecosystems in the face of anthropic and climate pressures. Preserving this fungal diversity is vital to ensuring the soil quality needed for a resilient agricultural system.

In addition to the environments we inhabit, we must also consider the biodiversity contained within the human body. **Philippe Sansonetti** underlines the fundamental part microbial biodiversity plays in human physiology. Intestinal microbiota play a determining role in our digestion, metabolism, neurodevelopment, and maturation of the immune system. Disruptions to this symbiosis, caused mainly by modern food habits and the degradation of our environment, are associated with the emergence of chronic diseases. Recent advances in microbial medicine take an ecological approach to health that seeks to restore diversity and stability to microbiota.

Finally, the natural world is also a rich source of medical innovations. For **Peter Stenvinkel**, biodiversity offers a unique wellspring for therapeutic innovation thanks to biomimetics. Studying physiological mechanisms that certain species such as bears and mole-rats have developed paves the way for new approaches to preventing and treating human diseases exacerbated by climate breakdown. The rapid erosion of biodiversity is a direct threat to these major opportunities in the fields of science and health, meaning that an interdisciplinary transformation of medical research in the coming years is absolutely crucial.

¹ IPBES (2022) Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services, p.9.

² FAO Home | Global Action on Pollination Services for Sustainable Agriculture | Food and Agriculture Organization of the United Nations.



Biodiversity: The Springboard for a Healthy, Sustainable Diet

Coline Jaworski

Independent researcher and expert in agroecology

A healthy and diversified diet relies directly on the biodiversity that underpins agricultural systems. Microbial diversity in the soil provides fertility and soil structure, ensures water and nutrients are available, protects against pathogens, and improves the nutritional qualities of crops. Similarly, pollinizing insects ensure the production and nutritional qualities of countless crops, while the natural enemies of bio-aggressors (pathogens, herbivorous insects, weeds) limit yield losses and reduce the need for pesticides, ensuring healthier food crops. Present-day intensive farming is no longer viable as it leads to soil degradation and biodiversity decline. Agroecological transition to farming systems based on and regenerating the natural world is needed urgently in response to the challenges of climate change and to ensure food sovereignty, vital for human health. Restoring ecological functions involves reducing how much the soil is worked, diversifying crops, and maintaining semi-natural habitats. These are the mechanisms that make it possible to combine productivity with stable harvests in the face of climate uncertainty, while maintaining food quality and preserving the environment.

INTRODUCTION

A diversified diet is one of the pillars of human health, providing the fats, sugars and proteins that are the basic components of our food requirements, as well as micronutrients and vitamins. This is only possible with a diversity of crops, including cereals, pulses and fruit, mostly grown outdoors. The combined actions of a diversity of living beings is needed to ensure this variety of agricultural production, with crops drawing nutrients and water from the soil thanks to the action of macrofauna and microorganisms in the soil. Arthropod biodiversity also provides essential services such as pollination and the regulation of crop bio-aggressors, a group comprising pests that eat plants in situ, pathogens that cause diseases, and unwanted plants and weeds that compete for water, nutrient resources, and sunlight.

FUNDAMENTAL BIODIVERSITY SERVICES SUPPORTING ABUNDANT, HEALTHY AND DIVERSIFIED AGRICULTURAL PRODUCTION

1.1. Soil as rooting substrate and source of water and minerals

Soil is home to an incredible degree of microbial diversity: one gram of soil contains up to one billion bacteria from 4,000 different species and 2,000 species of fungus whose filaments cover a distance equivalent to 200 meters.¹ This microbial biodiversity renders the soil fertile by providing the mineral nutrients (nitrogen [N], phosphorous [P], and potassium [K]) that plants need to grow. Organic matter from plant waste and dead organisms is first broken down by macroorganisms such as earthworms, then by microarthropods such as collembola, and finally digested by millions of microorganisms. A 30% loss of microbial diversity results in a 40% reduction in this mineralization process, leading to a 30% to 40% reduction in crop growth that cannot be offset by synthetic fertilizers.² Plants need carbon (C) to grow, which they accumulate via photosynthesis from atmospheric CO₂, but they also need nitrogen (N). This is extracted from atmospheric nitrogen (N₂) by soil bacteria such as *Rhizobium*, which transform

¹ Bar-On et al. (2018) The biomass distribution on Earth. *Proc Natl Acad Sci* 115:6506-6511, <https://doi.org/10.1073/pnas.1711842115>.

² Ranjard (2022), La microbiologie des sols au service de la production agricole [Soil microbiology supporting agricultural production]. INRAE webinar, <https://www.youtube.com/watch?v=XGkkSPm7nk8>.





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it into ammonia that is then transferred to plants from the Fabaceae family, commonly known as legumes. They achieve this by colonizing plant roots, forming nodules visible to the naked eye that can provide as much as 300 kilos of nitrogen per hectare per year, equivalent to 650 kilos of synthetic urea.³ Nitrogen is transferred to non-legume crops by mycorrhizal fungi.

Soil is also a physical structure enabling the root development of crops. Decompacted, aerated soil promotes root growth. Most of this work is carried out by earthworms that ingest soil to create galleries and macroaggregates. This allows air to circulate and provides N₂ as well as water that dissolves nutrients and makes them accessible to plants. In the absence of earthworms, macroaggregate formation is reduced by 36% and water storage capacity by 10%, with water circulation falling by 30% to 50%.⁴ Microbial biodiversity plays an essential role in macroaggregate stability: a 30% biodiversity loss leads to the disappearance of 50% of macroaggregates; soil becomes compacted and is eroded more rapidly by rainfall.²

35% of worldwide farm production and 75% of crop diversity depends directly on pollination by animals

In addition, microbial biodiversity in soil provides a buffer against disturbance (climate, pollution, pathogens). It acts as a barrier to the installation of crop pathogens: a 30% loss of soil microbial biodiversity results in a fivefold increase in the length of time pathogens live in the soil.² Furthermore, the mycorrhizosphere provides resistance against drought and attacks from bio-aggressors by activating plants' natural defenses, from root to leaf (priming) and between plants (allelopathy).⁵

Lastly, soil microbial biodiversity promotes the nutritional quality of agricultural production. It increases concentrations of micronutrients available in the soil and therefore their assimilation by crops and presence in harvests (seeds, fruits). This means that products grown in soils with higher levels of microbial biodiversity are 10% to 30% richer in vitamins C, K and B, antioxidants, iron and magnesium than products produced by conventional agriculture, which works the soil intensively and uses considerable quantities of fertilizers and herbicides.⁵ These soils also show higher levels of carcinogenic heavy metals such as cadmium, found in synthetic fertilizers.⁵

³ Zahran (1999) *Rhizobium*-legume symbiosis and nitrogen fixation under severe conditions and in an arid climate. *Microbiol Mol Biol Rev* 63:968-89, <https://doi.org/10.1128/MMBR.63.4.968-989.1999>.

⁴ Hallam & Hodson (2020) Impact of different earthworm ecotypes on water stable aggregates and soil water holding capacity. *Biol. Fertil. Soils* 56:607-617. <https://doi.org/10.1007/s00374-020-01432-5>.

⁵ Montgomery & Bklé (2021) Soil health and nutrient density: beyond organic vs. conventional farming. *Front. Sustain. Food Syst.* 5, 699147. <https://doi.org/10.3389/fsufs.2021.699147>.





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1.2. Pollinators: safeguarding our nutritional balance

35% of worldwide farm production and 75% of crop diversity depend directly on pollination by animals, a service estimated to be worth between 235 and 577 billion dollars annually around the world.⁶ A large majority of fruits and vegetables, with the exception of citrus fruits, as well as certain major crops such as pulses (peas, beans) and colza (to a degree) require pollination to enable fertilization. The transfer of pollen between flowers to enable fertilization is provided almost entirely by wild insects (flies, syrphids, bees, and butterflies) and only marginally by domesticated bees (14%). Bees are Europe's primary pollinators.⁶ As well as cultivated plants, pollinators also ensure the pollination, and thus the reproduction, of 90% of flowering plants in all land-based ecosystems.⁷ This means that pollinators are indirectly responsible for the production of massive volumes of plant biomass, which indirectly provides services to agriculture such as soil improvement (section 1.1) and resources for the arthropod biodiversity that regulates bio-aggressors (section 1.3).

In addition, pollinators have beneficial effects on the nutritional qualities of crops. For example, pollination of flowers by insects increases the nutrient content of fruit. In strawberries, the acid content (an essential element in

the composition of many vitamins in particular) increases by 12% on average relative to the sugar content in fruit pollinated by bees rather than the wind.⁸

A diversity of pollinators is needed for a diversity of crops. It is thought that the fall in the population of pollinators, largely due to intensive agriculture with the use of pesticides that are toxic to pollinators and the loss of habitat and resources, results in crop yield losses of around 30% worldwide.⁶ This underscores the importance of preserving functional biodiversity among pollinators, meaning pollinators whose characteristics, in terms of their size and hairs, allow them to pollinize as wide a range of crops as possible.⁹

Functional biodiversity is also very important for maintaining stable food production in the face of climate disruption. For example, bumblebees can be active from 10°C, whereas certain species of bees are inactive until temperatures reach 18°C. This complementarity of thermal preferences enables pollination services to continue even under adverse meteorological conditions,¹⁰ which is crucial given the extremely short flowering period of certain crops (apple and peach) and increasing climate variations driven by climate change.

6 IPBES (2016) Summary for policymakers of the assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) on pollinators, pollination and food production.

7 Ollerton *et al.* (2011) How many flowering plants are pollinated by animals? *Oikos* 120, 321-326. <https://doi.org/10.1111/j.1600-0706.2010.18644.x>.

8 Klatt *et al.* (2014) Bee pollination improves crop quality, shelf life and commercial value. *Proc Biol Sci* 281:20132440. <https://doi.org/10.1098/rspb.2013.2440>.

9 Woodcock *et al.* (2019) Meta-analysis reveals that pollinator functional diversity and abundance enhance crop pollination and yield. *Nature Commun* 10, 1481. <https://doi.org/10.1038/s41467-019-09393-6>.

10 Kühnel & Blüthgen (2015) High diversity stabilizes the thermal resilience of pollinator communities in intensively managed grasslands. *Nature Commun.* 6, 7989. <https://doi.org/10.1038/ncomms8989>.



1.3. Biological regulation of crop bio-aggressors

Globally, 20% to 40% of farm production is lost to crop bio-aggressors (pests, diseases, weeds) every year.¹¹ Biological control of crop bio-aggressors, also known as biocontrol or natural regulation, involves using their natural enemies to regulate bio-aggressor populations. For arthropod crop pests such as aphids and lepidopterans, their main natural enemies are other insects, whether predatory (ladybirds, bugs, chrysops, etc.) or parasitic minute wasps that lay eggs in the bodies of pest insects. These insect enemies can make it possible to avoid 1/3 of crop losses from pests, a service worth an estimated 4.5 billion dollars in the USA.¹² The natural enemies of unwanted plants and weeds are mostly seed-eating insects (ground beetles and ants), birds, and small rodents. Encouraging these forms of natural regulation reduces the use of pesticides and, as a consequence, the presence in crops and foods of toxins harmful to human health.

Similar to pollinators, every cultivated plant attracts a very specific set of bio-aggressors, each itself regulated by a specific set of natural enemies. In terms of pest-to-parasite relationships, for example, the degree of specificity is such that there is often one parasite species for each pest species. This highly specific character also makes for more efficient regulation.¹³ Furthermore, complementarity between species of natural enemies improves bio-aggressor regulation services.¹⁴ This demonstrates the importance of maintaining a broad range of biodiversity among natural enemies in agricultural systems to ensure crop diversity is protected.

Globally, 20% to 40% of farm production is lost to crop bio-aggressors (pests, diseases, weeds) every year

Maintaining biodiversity is equally important in the face of biological invasions. Invasions by new crop bio-aggressors are becoming increasingly frequent owing to the standardization of crops planted around the world and the intensification of trading relationships, with over 60% of yield losses caused by invasive bio-aggressor species.¹⁵ These invasive bio-aggressors have not co-evolved alongside specialist natural

enemies in the invaded location. A diversified set of natural enemies can mitigate the damage they cause to crops by helping regulate together populations of invasive species.

Unlike synthetic pesticides, biological control strategies are not designed to eradicate bio-aggressors but to rebalance communities, maintaining populations below the threshold that causes harm to crops. This means that the cultivated plant is in contact with very low densities of bio-aggressors, a level of exposure that can activate the plant's natural defenses and help it build up natural defense compounds, particularly antioxidants, that are beneficial to human health.⁵

CULTIVATING THE NATURAL WORLD FOR BETTER, HEALTHIER CROPS

Today's dominant agricultural systems are founded on mechanization and the use of crop varieties that produce very good yields, providing they receive massive inputs of fertilizer and pesticides. These intensive models are unsustainable in the face of planetary boundaries because they degrade soil, provoke biodiversity decline, and lack resilience to unplanned climate events. There is an urgent need to transition to greener agricultural systems founded on using and regenerating ecosystem services. This transition may initially result in lower yields, but they will be offset by greater long-term stability of production in an era of climate change.

2.1. Regenerative agriculture: cultivating and regenerating soil biodiversity

Regenerative agriculture involves reimagining agricultural systems to focus on restoring soil functions while maintaining agricultural productivity, marking a clean break from today's dominant intensive systems. Regenerative agriculture aims to produce a living soil that is rich in nutrients with a structure that allows water and air to circulate freely and roots to grow at depth by following five combined principles: (i) work the soil as little as possible; (ii) do not leave bare soil; (iii) preserve living roots all year round; (iv) increase diversity of crops; (v) incorporate livestock into crop rotation plans.¹⁶

¹¹ Savary et al. (2019) The global burden of pathogens and pests on major food crops. *Nature Ecol Evol* 3, 430–439. <https://doi.org/10.1038/s41559-018-0793-y>.

¹² Losey & Vaughan (2006) The economic value of ecological services provided by Insects. *BioScience* 56, 311–323. [https://doi.org/10.1641/0006-3568\(2006\)56\[311:TEVOES\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2006)56[311:TEVOES]2.0.CO;2).

¹³ Monticelli et al. (2021). Chapter Six—Multiple global change impacts on parasitism and biocontrol services in future agricultural landscapes. In Bohan, Dumbrell & Vanbergen (Eds.), *The Future of Agricultural Landscapes, Part III* (Vol. 65, p. 245–304). Academic Press. <https://doi.org/10.1016/bs.aecr.2021.10.002>.

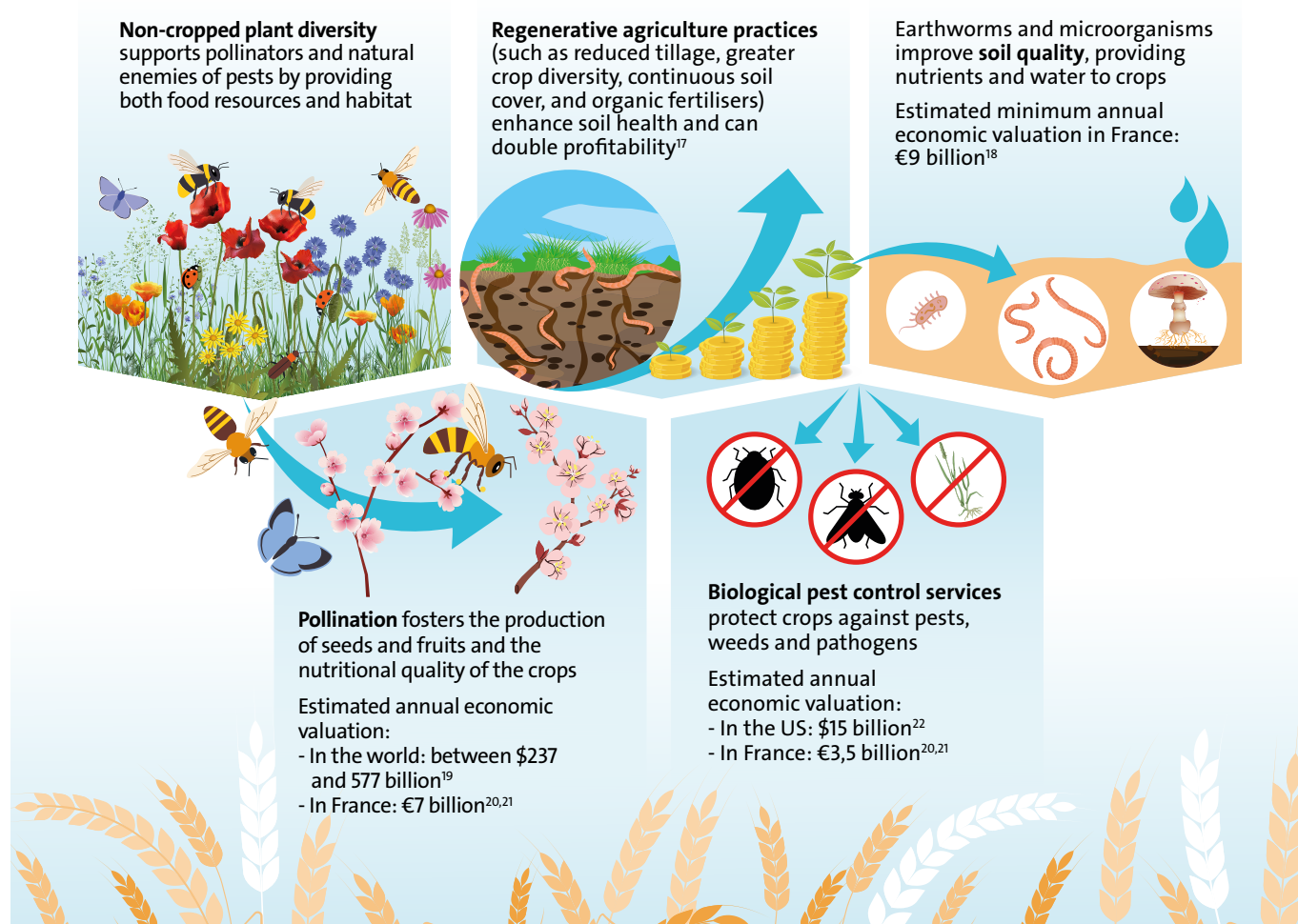
¹⁴ Jonsson et al. (2017). Relationships between natural enemy diversity and biological control. *Curr. Opin. Insect Sci.* 20, 1–6. <https://doi.org/10.1016/j.cois.2017.01.001>.

¹⁵ Pimentel et al. (2005). Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecol. Econ.* 52, 273–288. <https://doi.org/10.1016/j.ecolecon.2004.10.002>.

¹⁶ Berthon, Jaworski et al. (2024) Measuring the transition to regenerative agriculture in the UK with a co-designed experiment: design, methods and expected outcomes. *Environ. Res. Food. Syst.* 1, 025007. <https://doi.org/10.1088/2976-601X/ad7bbe>.



How biodiversity keeps healthy and sustainable food on our plates



These combined principles make it possible to keep the soil uncompacted and aerated thanks to the action of roots and earthworms, which are twice as abundant,²³ as well as to permanent green cover that reduces soil compaction caused by rainfall. There is a twofold increase in organic matter, thanks to the addition of manure from livestock

and the incorporation of crop and cover crop residues,¹⁷ which promotes soil biodiversity and reduces the need for synthetic fertilizer. This advantage, combined with reduced use of high added-value products and pesticides, can deliver a twofold increase in profitability.¹⁷

2.2. Promoting arthropod biodiversity thanks to the diversity of cultivated and uncultivated plants

Intensive farming systems rely on fields that are several dozen hectares in size and sown with one crop or a few different crops as far as the eye can see, interspersed with uncultivated areas (field edges, woods, and hedgerows) that are either nonexistent or very limited. The three-yearly rotation system predominates for arable crops, with two seasons of cereal crops followed by a break year, usually with colza, which provides a fall in the pathogen load and decreases competition from unwanted plants and weeds. There are three main mechanisms for increasing the diversity of cultivated crops: (i) increase rotation length by introducing new crops; (ii) cover crops (mixtures of species

¹⁷ Fenster *et al.* (2021). Defining and validating regenerative farm systems using a composite of ranked agricultural practices. F1000Research10, 115. <https://doi.org/10.12688/f1000research.28450.1>.

¹⁸ Based on an estimated price of fertilizer of €507/ha, for France's 17,6 millions ha of crops. This is a low estimate, considering that microorganisms increase the availability of other inputs, including phosphate and water, and that with the current geopolitical situation, the prices of synthetic fertilizers are increasing.

¹⁹ IPBES (2016) Summary for policymakers of the assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) on pollinators, pollination and food production.

²⁰ Share of the United States in the global agriculture market : approx. \$410 billion (FAO, Agriculture production Statistics).

²¹ Share of France in the global agriculture market : approx. \$110 billion (INSEE, Production et valeur ajoutée de l'agriculture 2025). [Agricultural production and added value 2025].

²² Losey & Vaughan (2006) The economic value of ecological services provided by insects. BioScience 56, 311–323. [https://doi.org/10.1641/0006-3568\(2006\)56\[311:TEVOES\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2006)56[311:TEVOES]2.0.CO;2).

²³ Berthon *et al.* (2025). Measuring the socio-economic and environmental outcomes of regenerative agriculture across spatio-temporal scales. Phil. Trans. Roy. Soc. B. 380, 202040157. <https://doi.org/10.1098/rstb.2024.0157>.



with agroecological value alone, that are not harvested); and (iii) intercropping, growing several species or varieties simultaneously in the same space. The primary agronomic aim is to feed the soil, particularly by introducing pulses to fix nitrogen in the soil (see section 1.1), as well as to reduce the presence of pathogens and unwanted plants and weeds. Cover crops are particularly worthwhile for combating unwanted plants and weeds, suppressing 40% to 95% of weeds.²⁴

Aside from soil health, crop diversity promotes arthropod biodiversity by creating habitats (microclimates, refuges, egg-laying sites) and food resources (flowers, a variety of prey for crop pest enemies). It can boost the diversity of natural enemies and pollinators by a factor of 1.5 to 2.²⁵ In economic terms, a diversified agricultural system combining crops with different degrees of sensitivity will be more resilient to extreme climate events as it offers diversified sources of revenue.

Similar to crop diversity, a diversity of non-cultivated plants in and around cultivated fields supplies food and habitat for arthropod biodiversity.²⁵ Strips of grass and/or flowers between crop rows, hedges and trees all regulate the local climate: they reduce exposure to heat, wind and cold as well as maintaining the humidity that it is so important for arthropods and crops alike. They protect the soil and its microbial biodiversity and regulate water by encouraging infiltration and reducing erosion. Spatiotemporal continuity in terms of the availability of these resources is essential to properly functioning ecosystem services. To achieve this, it is necessary to plant hedgerows with a large variety of plant species that flower at different periods, and to create corridors (such as hedges and the grassy strips often seen between rows in vineyards) that promote arthropod mobility and their recolonization of plots of farmland after disruptive events (climate, soil work, herbicide treatment).

CONCLUSION

The intensification of farming has resulted in the massive simplification of agroecosystems, a decline in biodiversity, and the impoverishment of farmland. Consequently, this model of agriculture is heavily dependent on inputs of fertilizers and pesticides and is unsustainable in the face of climate events and biological invasions, with global farm output becoming increasingly unstable. This creates tensions surrounding food sovereignty, and the financial cost of inaction is considerably greater than the cost of implementing agroecological transition.²⁶ Reimagining agricultural systems that regenerate the services provided by biodiversity is key to the long-term future of agricultural production, and by extension to a healthy and diversified food supply. Microbial biodiversity ensures that soil functions as it should, providing harvests that are stable, healthy and nutritious. Arthropod biodiversity protects crops from bio-aggressors and ensures fructification thanks to pollination. A few simple actions are all it takes to encourage biodiversity services: reduce disruptions (inputs, soil work), increase cultivated diversity (notably with pulses enriching the soil), return unharvested organic matter to the soil, and promote plant diversity in uncultivated spaces. Investing in biodiversity is about building food security based on self-sustaining natural processes that cost nothing and are resilient to climate disruption, rather than being dependent on external inputs. This paradigm shift demands a new approach to agricultural policies to focus on quality and diversity of production, plant-based in particular, and taking care of the environment at the local and regional level rather than an organization centered on intensive farming methods serving meat-intensive dietary practices.

²⁴ Osipitan et al. (2019), Impact of cover crop management on level of weed suppression: a meta-analysis. *Crop Sci.* 59, 833-842. <https://doi.org/10.2135/cropsci2018.09.0589>.

²⁵ Jaworski et al. (2023) Crop diversification to promote arthropod pest management: a review. *Agric Comm* 1, 100004. <https://doi.org/10.1016/j.agrcom.2023.100004>.

²⁶ Which technologies for low-carbon, resilient and prosperous agriculture? The Shift Project, November 2024, Final Report.

About the author

Coline Jaworski is an independent researcher and expert in agroecology who specializes in the interactions between plants and insects and their functions in natural and agricultural ecosystems. Her research was supported by an AXA postdoctoral Fellowship. Her work looks at pollination, regulation of crop bio-aggressors, and relationships between soil health and arthropod biodiversity. She focuses on analyzing the impacts of climate change on how ecosystems operate, seeking to identify levers for restoring ecological functions. Her recent work examines mechanisms for transitioning agricultural systems toward agroecology by working with farmers to build knowledge together.



Fungal Diversity Bridging Soil, Climate, and People

Adriana Morrell: Scientific Lead, Mycology Research Laboratory, Centre for Business, Arts and Sciences, Lethbridge Polytechnic, Alberta, Canada.

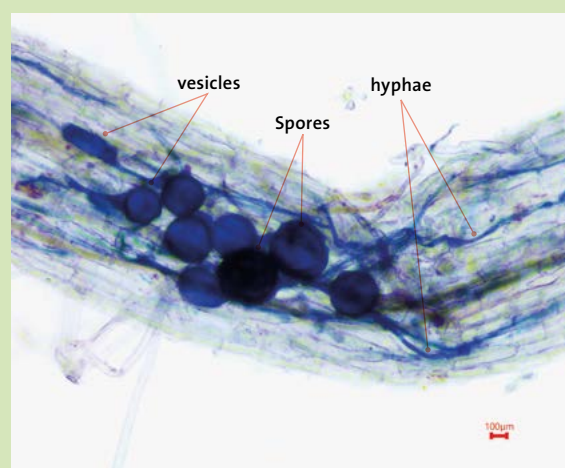
Dale Pulvermacher: Research Assistant / Student Technician, Mycology Research Laboratory, Centre for Business, Arts and Sciences, Lethbridge Polytechnic, Alberta, Canada.

Fungi are more than just a tasty addition to any meal; they are an integral part of the biosphere. Neither plant nor animal, evidence suggests fungi evolved long before either, some 950 million years ago.¹ In partnership with algae, fungi were early ecosystem engineers, recycling nutrients, cycling carbon, and breaking down rock to form the first soils, laying the foundation for plants and animals to colonize what had once been barren land.² They continue to play this role today, while also providing services central to modern society and human well-being.

This contribution becomes especially evident in how we produce food. In a world of more than 8.3 billion people, food production occupies a substantial proportion of Earth's terrestrial surface, placing growing demands on agricultural systems. Modern cropping systems must therefore be both highly productive and environmentally sustainable to support global food security.³ Soil fungi play a central role in agroecosystem functioning, influencing nutrient cycling, plant health, and soil structure. As a result, managing soil fungal diversity is increasingly recognized as a key strategy for sustaining crop yields under changing environmental conditions.

Arbuscular mycorrhizal fungi (AMF) are ubiquitous in terrestrial ecosystems and form symbiotic associations with the roots of more than 80% of plant species worldwide (**Figure 1**).⁴ As host-dependent organisms, they rely on living plants for carbon and cannot complete their life cycle without a host.⁴ In return, AMF enhance plant access to soil nutrients and water, improve tolerance to environmental and biological stressors, contribute to carbon sequestration, and help to bind soil together while reducing erosion.

Figure 1. Arbuscular mycorrhizal fungal (AMF) structures (hyphae, vesicles, and spores) observed in the roots of Bluebunch Wheatgrass (*Pseudoroegneria spicata*) at 400× magnification



Micrograph credits: Dale Pulvermacher, Mycology Research Laboratory, Lethbridge Polytechnic

1 Loron, C. C., François, C., Rainbird, R. H., Turner, E. C., Borensztajn, S., & Javaux, E. J. (2019). Early fungi from the Proterozoic era in Arctic Canada. *Nature*, 570(7760), 232-2,235A-235D. <https://doi.org/10.1038/s41586-019-1217-0>.

2 Szánthó, L.L., Merényi, Z., Donoghue, P. et al. A timetree of Fungi dated with fossils and horizontal gene transfers. *Nat Ecol Evol* 9, 1989–2001 (2025). <https://doi.org/10.1038/s41559-025-02851-z>.

3 Ellouze, W., Taheri, A. E., Bainard, L. D., Yang, C. et al. (2014). Soil fungal resources in annual cropping systems and their potential for management. *BioMed Research International*, 2014, Article 531824. <https://doi.org/10.1155/2014/531824>.

4 Smith, S. E., & Read, D. J. (2008). *Mycorrhizal symbiosis* (3rd ed.). Academic Press.



Despite their importance, soil fungal communities are increasingly affected by anthropogenic pressures. Intensive agricultural practices – including tillage, monocropping, and heavy fertilizer and pesticide use – simplify plant communities and disrupt fungal networks, reducing diversity and functional complexity relative to perennial ecosystems.⁵

In contrast, soils healthy in AMF can reduce the need for synthetic fertilizers by 10-30%, lowering production costs and nutrient runoff into water systems.⁵ Reduced nutrient pollution is also linked to lower risks of harmful algal blooms, which impose billions of dollars annually in economic losses related to drinking water treatment, fisheries, and recreation. Comparative studies further show that soil fungal richness and diversity are much lower in cultivated soils than in uncultivated or natural systems,⁶ highlighting the sensitivity of AMF to land-use change.

When forests are cleared or land is converted for farming and development, the hidden world of soil microbes changes.⁵ Beneficial fungi that form partnerships with plant roots often decline, while fast-growing, opportunistic species such as the pathogenic *Fusarium graminearum*,⁶ become more common. Urbanization further fragments

natural habitats, reducing the important roles these fungi play in nutrient cycling and water filtration. Mining and other industrial activities add heavy metals and pollutants that disrupt root-fungi relationships.⁵ On top of this, climate change, through warming, drought, and shifting rainfall, adds even more stress. Together, these

pressures reshape soil microbial communities, affecting the vital interactions between plants and soil life.

The loss of fungal biodiversity has cascading effects that extend beyond soil health and crop productivity. Their decline reduces

soil resilience, increases reliance on external inputs, and heightens ecosystem vulnerability to pests and disease.⁵ From a human health perspective, degraded soils can lower the nutritional quality of our food, increase environmental pollution through nutrient runoff, and reduce the land's ability to store carbon and regulate climate, ultimately affecting the air we breathe, the water we drink, and the food we rely on. Fungi are central to mitigating these risks: mycorrhizal fungi can enhance plant nutrient uptake, directly improving the nutritional value of crops.⁷ Fungi also directly underpin human health through medicine and environmental detoxification. Fungi have yielded life-saving drugs such as antibiotics (e.g., penicillin), immunosuppressants (e.g., cyclosporine), and cholesterol-lowering compounds (e.g., statins).⁸

Managing soil fungal diversity is increasingly recognized as a key strategy for sustaining crop yields under changing environmental conditions

5 Bach, E. M., Ramirez, K. S., Fraser, T. D., & Wall, D. H. (2020). Soil biodiversity integrates solutions for a sustainable future. *Sustainability*, 12(7), Article 2662. <https://doi.org/10.3390/su12072662>.

6 Umer, M., Anwar, N., Mubeen, M., Li, Y., Ali, A., Alshaharni, M. O., & Liu, P. (2025). Roles of arbuscular mycorrhizal fungi in plant growth and disease management for sustainable agriculture. *Frontiers in Microbiology*, 16, Article 1616273. <https://doi.org/10.3389/fmicb.2025.1616273>.

7 Wu, Y., Chen, C., & Wang, G. (2024). Inoculation with arbuscular mycorrhizal fungi improves plant biomass and nitrogen and phosphorus nutrients: A meta-analysis. *BMC Plant Biology*, 24, Article 960. <https://doi.org/10.1186/s12870-024-05638-9>.

8 Wadhwa, K., Kapoor, N., Kaur, H., Abu-Seer, E. A. et al. (2024). A comprehensive review of the diversity of fungal secondary metabolites and their emerging applications in healthcare and environment. *Mycobiology*, 52(6), 335–387. <https://doi.org/10.1080/12298093.2024.2416736>.



Many species can degrade persistent pollutants, including pesticides, petroleum hydrocarbons, and industrial chemicals,⁹ reducing their accumulation in soils, water systems, and the human food chain.

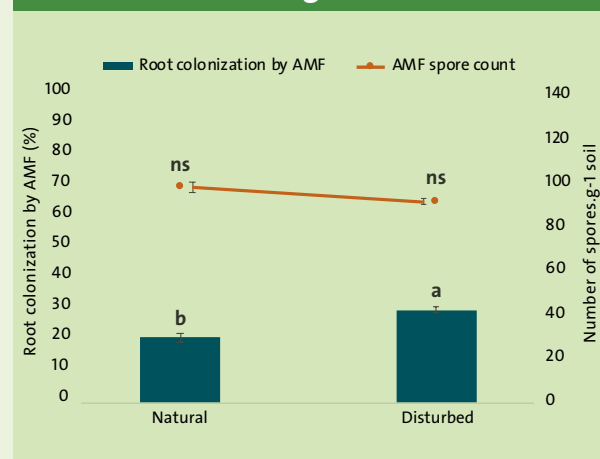
Restoration efforts that re-establish native plant communities and support beneficial fungi can rapidly increase the abundance and richness of AMF strengthening ecosystem services such as nutrient availability, forage production, and long-term carbon storage. These gains translate into societal benefits. For example, in the North American Great Plains, avoiding conversion of just 10% of remaining native grasslands to cropland could prevent carbon dioxide emissions valued at approximately \$430 million in societal costs over 20 years,⁵ demonstrating how targeted conservation can simultaneously support biodiversity, climate mitigation, and economic sustainability.

Our research in grassland restoration focuses on managing beneficial soil fungi as keystone components of ecosystem recovery. In partnership with the Nature Conservancy of Canada, and using field surveys and experimental approaches, we have examined how AMF contributes to plant establishment following coal-mining disturbance. As shown in **Figure 2**, native grasses in disturbed sites exhibit significantly higher AMF root colonization than those in adjacent undisturbed grasslands, despite similar AMF spore densities across sites.

Soil fungal richness and diversity are much lower in cultivated soils than in uncultivated or natural systems, highlighting the sensitivity of AMF to land-use change

This pattern suggests that following disturbance, native grasses rely more strongly on AMF symbioses to support nutrient acquisition and recovery, emphasizing the functional importance of fungal-plant partnerships for successful restoration. By mapping fungal diversity and integrating microbial inoculation with native plant assemblages, our work aims to restore soil function and resilience in degraded landscapes, with co-benefits for agricultural sustainability, biodiversity conservation, and human health in a changing world.

Figure 2. Percentage of root colonization by AMF and fungal spore counts in rhizosphere of native grasses from undisturbed (natural) and disturbed grasslands (coal mining 1907-1919) in Cervo 2 (Nature Conservancy of Canada property), Crowsnest Pass, Alberta, Canada. Different letters represent significant differences according to Student's t test ($\alpha = 0.05$). "ns" stands for no significant differences



⁹ Liu, X. (2025). Fungi used with mycoremediation as a sustainable solution for environmental pollution. *Microbial Bioactives*, 8(1), 1–11. <https://doi.org/10.25163/microbbioacts.8110463>.



Sector	Common Challenges	Contributions of Fungal Biodiversity
 Human Health	Human wellbeing	 Provide nutrient-rich foods and medicines (e.g., antibiotics and immune-support compounds). By building healthy soils and resilient ecosystems, fungi support physical and mental health.
	Food quality	 Improve nutrient availability and uptake through fungi-plant partnerships (e.g., mycorrhizae), enhancing the nutritional value and overall quality of food.
	Food supply	 Increase crop productivity and resilience through symbiosis (e.g., mycorrhizae) and provide nutritious edible mushrooms and other fungal foods.
	Pollution control	 Filter, break down and detoxify pollutants, improving soil, water, and air quality and helping to protect human health and mitigate climate change.
 Agricultural	Nutrient loss & pollution (leaching, runoff, algal blooms)	 Fungi-plant partnerships enhance nutrient capture and retention, reducing fertilizer loss, runoff, and the need for synthetic inputs.
	Poor nutrient cycling & soil structure	 Accelerate decomposition and nutrient cycling while improving soil structure and water-holding capacity.
	Climate stress (drought, nutrient depletion)	 Increase crop resilience to climate stressors such as drought, extreme temperatures, and nutrient depletion.
 Environmental	Climate change (carbon balance)	 Enhance carbon sequestration by increasing plant growth and carbon storage in soils, both above and below ground.
	Polluted or degraded ecosystems	 Break down contaminants (e.g., hydrocarbons, heavy metals) and support ecosystem recovery and resistance to disturbance.
	Soil degradation (erosion, low fertility, bare ground)	 Build healthy soils by enhancing structure, nutrient cycling, and microbial diversity. Fungi-plant partnerships increase vegetation cover, reducing erosion, heat build-up, and land degradation.

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Alterations to Human Intestinal Microbiota Caused by Modern Lifestyles:

Health Threats and the Emergence of Microbial Medicine

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Building on Van Leeuwenhoek's discovery of "animalcules", microbiology shines a light on the fundamental role that microorganisms play in human health. Intestinal microbiota are the fruit of coevolution and play a key role in digestion, metabolism, immune function, and neural development. Axenic animals¹ and gnotobiotic models² have confirmed this mutual symbiosis and the necessity for stable microbial diversity. Modern disruptors, such as antibiotics, caesarean section births, or ultra-processed foods, trigger dysbiosis and chronic illness. Research has identified what is sometimes termed the second human genome, analyzing the resilience and robustness of microbiota. Microbial medicine now seeks to restore this symbiosis, incorporating changes in diet, probiotics, prebiotics, and fecal treatments in a systemic and ecological approach to health.

INTRODUCTION

We have known for over three hundred years that the human body contains microorganisms. In 1683 in Delft, Antonie van Leeuwenhoek used a draper's microscope to become the first to observe the microscopic beings present in human saliva and dental plaque, which he named animalcules. This discovery revealed the existence of an invisible world.

The causal role of certain microbes in infectious diseases was established at the end of the 19th century. Most of the pathogens responsible for major epidemic outbreaks were identified between 1870 and 1910, and Robert Koch formalized the microbial causality criteria known as Koch's postulates. In an age dominated by the burden that infectious diseases place on society, a further question emerged: what is the function of the numerous non-pathogenic microorganisms found in healthy humans?

HUMAN INTESTINAL MICROBIOTA: HISTORY AND DEMONSTRATION OF A SYMBIOSIS

In 1885, Theodor Escherich marveled at the constant presence of bacteria in the gut of infants and healthy adults, and speculated that studying them would improve understanding of digestive physiology and certain intestinal pathologies. Ilya Mechnikov's theory of internal decay attributed a role in the aging process to the accumulation of toxin-producing intestinal bacteria. Noting the exceptional longevity of people who drank fermented dairy products, he introduced the concept of probiotics.

At the same time, Arthur Kendall established a relationship between diet, intestinal bacteria and metabolites detected in urine, positing as early as 1909 the role of gut flora in the host's nutritional balance and metabolism. This new thinking laid the groundwork for a functional vision of gut flora, not yet known as microbiota, a term introduced in the 1950s by Theodor Rosebury.

The next major conceptual turning point came with the ability to keep alive animals entirely free of microbes. As early as 1885, Louis Pasteur was wondering about animal viability in the absence of germs, suggesting that the microscopic world was in fact indispensable to the macroscopic world. In 1897 in Germany, however, Nuttall and Thierfelder demonstrated that axenic cultures, free of all microbes, were possible, opening the door to gnotobiology.

¹ Fully microbe-free.

² Gnotobiology involves the study of animal or plant life in a controlled microbial environment.



Subsequent studies went on to reveal the limits of this life without microbes. Axenic animals present major nutritional deficits, hypotrophy, vitamin deficiencies (A, B12, K) and immature immune systems.³ They are unable to break down and ferment the complex plant sugars that we call fibers. Fermentation produces fatty acids that have high nutritional value as well as being indispensable to gene expression, key to animal development and metabolism. Microbiota therefore play a crucial role in energy metabolism and animal nutrition. These bases provided the springboard for the concept of mutualistic symbiosis between humans and their microbiota, intestinal in particular. The two partners have sealed a contract of mutual benefit over a long period of co-evolution, known as a holobiont.⁴ The diversity of microbial species within this holobiont is indispensable to human health.

In the 2000s, meta taxonomic 16S approaches followed by ultrafast metagenomics led to an exhaustive characterization of human intestinal microbiota, revealing great interindividual variability of microbial composition but relative stability in terms of essential metabolic functions.

THE ESSENTIAL FUNCTIONS OF INTESTINAL MICROBIOTA

Gnotobiology makes it possible to analyze the progressive construction of microbiota and the ecological successions that lead to a mature ecosystem. Microbiota form a complex heterogeneous assemblage of microbial species established, to their mutual benefit, within a stable ecological niche. This robust organization ensures the health of the niche and protects it, for instance, from intrusion by possibly harmful external microorganisms. This is the barrier effect offered by microbiota.

In the 1990s, Jeff Gordon's work at Washington University in the USA demonstrated that early microbial colonization has lasting positive impacts on metabolic and immunity health, and intestinal⁵ angiogenesis.⁶ Microbiota also plays

a proven role in maturation of the mucosal and systemic immunity system⁷ and post-natal development of the central nervous system, leading to the concept of the link between gut and brain.⁸

These functional bases led to a distinction between microbiota, a taxonomic entity referring to the complete set of microbial species comprising an ecosystem, and microbiome, a functional entity covering all metabolic activities produced by these microorganisms in their symbiotic relationship with the host.

A comparison between axenic and conventional (with microbiota) animals highlights the major symbiotic functions of intestinal microbiota:

- digestion of fibers in the gastrointestinal tract since the human body does not have the necessary enzymes;
- support for the development of physiological systems needed for digesting food and absorbing nutrients;
- barrier effect against pathogens, maturation of the immune system, neurodevelopment, and close metabolic interactions with the host.

The role of microbiota thus extends well beyond supporting the host's metabolic and nutritional health alone: support for other functions such as neurodevelopment also involves a nutritional mechanism at the cellular level, particularly stem cells.⁹

Microbiota are intrinsically resistant and resilient, but the multiplication and prolongation of stresses imposed on their niche become, in time, factors for the establishment of dysbioses

Two major international programs, MetaHit¹⁰ and the Human Microbiome Project,¹¹ have established vast catalogues of microbial genes, identifying ecological organizations such as enterotypes and highlighting the importance of the genetic richness of microbiota.¹² These advances have paved the way for the

emergence of microbial medicine, combining diagnosis with prevention and restoration of the symbiosis between host and microbiota.

3 Reyniers, J.A., P.C. Trexler, et al., A complete life-cycle in the germ-free bantam chicken. *Nature*, 1948. 162(4132): p. 67. <https://doi.org/10.1038/163067a0>.

4 A holobiont is a natural living assemblage comprising a larger organism called the host (human, animal, plant) and its microbiota, i.e. the cohort of microorganisms closely associated with it.

5 Stappenbeck, T.S., L.V. Hooper, and J.I. Gordon, Developmental regulation of intestinal angiogenesis by indigenous microbes via Paneth cells. *PNAS*, 2002. 99(24): p. 15451-5. <https://doi.org/10.1073/pnas.202604299>.

6 Angiogenesis refers to the formation of new blood vessels from existing vessels.

7 Chung H, Pamp SJ, Hill JA, et al. Gut immune maturation depends on colonization with a host-specific microbiota. *Cell*, 2012; 149: 1578–93. <https://doi.org/10.1016/j.cell.2012.04.037>.

8 Diaz Heijtz R, Wang S, Anuar F, et al. Normal gut microbiota modulates brain development and behavior. *PNAS*, 2011; 108: 3047–52. <https://doi.org/10.1073/pnas.1010529108>.

9 Dang, H., et al., Maternal gut microbiota influence stem cell function in offspring. *Cell Stem Cell*, 2025. 32(2): p. 246-262 e8. <https://doi.org/10.1016/j.stem.2024.10.003>.

10 Qin, J., et al., A human gut microbial gene catalogue established by metagenomic sequencing. *Nature*, 2010. 464(7285): p. 59-65. <https://doi.org/10.1038/nature08821>.

11 Grice, E.A. and J.A. Segre, The human microbiome: our second genome. *Annu Rev Genomics Hum Genet*, 2012. 13: p. 151-70. <https://doi.org/10.1146/annurev-genom-090711-163814>.

12 Cotillard A, Kennedy SP, Kong LC, et al. Dietary intervention impact on gut microbial gene richness. *Nature* 2013; 500: 585–8. <https://doi.org/10.1038/nature12480>.





Around 160 bacterial species are present in healthy adults, but only around 20 of them form a functional core common to all individuals, essential to maintaining the major physiological functions.¹³ Among the human population, intestinal pan-microbiota comprises several thousand species, reflecting a high degree of interindividual heterogeneity resulting mainly from diet, environment, and evolutionary histories. But over and above this taxonomic vision, it is the symbiotic function that dominates, shaped by natural selection. We see that various microbial species can offer similar metabolic resources.

However, an exogenous stress impacting conditions needed to maintain the niche's stability carries the risk of destabilizing the equilibrium of the food web and altering microbiota composition, particularly the diversity of species, creating a vacuum favorable to the establishment of predatory microorganisms. In addition to the loss of diversity, it is significant due to the loss of biological functions. This is termed dysbiosis, and the resulting disruption to symbiosis can become pathogenic to varying degrees.

In the Anthropocene, microbial biodiversity, which represents the overwhelming majority of biodiversity in the planet's living world (95%), has emerged as a major issue for global health

These are universal rules that apply to human, animal, plant, soil, and ocean microbiota. All microbiota have two key characteristics: resistance¹⁴ and resilience.¹⁵ Recent work has demonstrated that the greater the maturity of intestinal microbiota, the more resistant it is to environmental stress.

Microbiota are intrinsically resistant and resilient, but the multiplication and prolongation of stresses imposed on their niche become, in time, factors for the establishment of dysbioses.

MICROBIOTA AS AN ECOSYSTEM: SYMBIOSIS, BIODIVERSITY, AND FRAGILITY IN THE ANTHROPOCENE

Currently, human microbiota/microbiome are studied from an overall ecological perspective that incorporates the One Health concepts, underlining the interdependency of the planet's microbiota, irrespective of their niches, as all are subjected to the same environmental stresses: planetary heating, extreme rainfall, and various types of pollution.

In the Anthropocene, microbial biodiversity, which represents the overwhelming majority of biodiversity in the planet's living world (95%), has emerged as a major issue for global health. The impact on health of the decline of microbial diversity, already underway, is widely overlooked in ecological messaging.

Anthropocene and the pressures of modern lifestyles: unprecedented microbial erosion

The harmful effects of human activities on plant and animal biodiversity and the climate are very widely documented. But their impact on microbial biodiversity, human microbiota in particular, has only recently been fully acknowledged. The metagenomic revolution means it is now possible to produce a very detailed description of the composition and spatio-temporal evolution of human microbiota. These approaches

have identified a marked reduction in microbial richness and diversity, particularly intestinal, most notably in industrialized regions where it can reach 50%.¹⁶ Microbial erosion is now recognized as a major public health issue.

¹³ Lloyd-Price J, Abu-Ali G, Huttenhower C. The healthy human microbiome. *Genome Med*, 2016; 8: 51. <https://doi.org/10.1186/s13073-016-0307-y>.

¹⁴ Resistance to an exogenous stress imposed on its ecological niche, i.e. the percentage of species persisting post-stress.

¹⁵ Resilience is the capacity of microbiota to return to normal after stress, expressed as the percentage returning to normal after a given period of time.

¹⁶ Sanders JG, Sprockett DD, Li Y, et al. Widespread extinctions of co-diversified primate gut bacterial symbionts from humans. *Nat Microbiol*, 2023; 8: 1039–50. <https://doi.org/10.1038/s41564-023-01388-w>.



From hygiene hypothesis to missing microbes

The link between modern lifestyles and the rising incidence of chronic non-transmissible diseases was initially interpreted in the light of the hygiene hypothesis described by Jean-François Bach.¹⁷ He suggested that a drastic reduction in exposure to infectious agents resulting from improved hygiene, vaccines, and antibiotics could disrupt maturation of the immune system. This hypothesis was extended via the concept of missing microbes, raised notably by Martin Blaser¹⁸ who stressed early-age impoverishment of the microbiome and the loss of key species that co-evolved with humans. From this perspective, the microbiome is seen to detect and integrate stresses linked to modern lifestyles and environmental exposome.

Antibiotics: human microbiota's modern-day stressors

The neonatal period is a critical window of vulnerability for the construction of intestinal microbiota. Early exposure to antibiotics is associated with increased risk of asthma, allergies, obesity, diabetes, and neurodevelopmental troubles such as attention deficit and hyperactivity.¹⁹ Alterations to microbiota occasioned by the administration of antibiotics during this crucial period lead to lasting metabolic consequences.²⁰

Similarly, in microbiological terms, caesarean section births correspond to at-birth withdrawal of maternal vaginal and intestinal bacteria – equivalent to an early-age antibiotic treatment – and are associated with greater risk of asthma.²¹ Strategies for partial microbial restoration are envisaged following a caesarean birth or antibiotic treatment that is, naturally, unavoidable if clinically required.²²

Excessive consumption of antibiotics constitutes the modern-day paradigm of anthropic microbiota stressors across the planet

More generally, excessive consumption of antibiotics constitutes the modern-day paradigm of anthropic microbiota stressors across the planet. In addition to selection of resistant bacteria, antibiotics profoundly alter the richness and diversity of microbial ecosystems. More than 300,000 metric tons of antibiotics are discharged into the environment every year, making these molecules a truly global pollutant. Recent studies indicate that 65% of the planet's watercourses show significant concentrations of antibiotics.

Ultra-processed modern foods: junk food and alterations to human microbiota

Modern diets, generally highly unbalanced, heavily processed, and characterized by the use of a large number of food additives, constitute an additional major environmental stress for human intestinal microbiota.²³ Simple sugars replacing fiber, excessive animal protein and saturated fats, nutrient and vitamin deficiencies, and the introduction of sweetener and emulsifier additives make ultra-processed modern diets a powerful factor in the reduction in diversity as well as pathogenic dysbiosis. A foundational experiment published in 2005

demonstrated that transplanting intestinal microbiota from genetically obese mice into lean mice led to weight gain in the latter group, showing the causal role of microbiota in obesity.²⁴ These alterations to microbiota can also foster low-grade chronic inflammation of numerous physiological systems, (notably cardiovascular, metabolic, immune and nervous systems). Further study is essential for corroborating these causal links.

Junk food is unequivocally in the firing line owing to the worrying increase of incidences of pathologies such as colorectal cancers in young adults, and obesity and type-2 diabetes, including among children and teenagers. This is a pressing public health issue and research into dysbiosis must play a central role in tackling it.

17 Bach, J.F., The Effect of Infections on Susceptibility to Autoimmune and Allergic Diseases. *N Engl J Med*, 2002. 347(12): p. 911-20. <https://doi.org/10.1056/nejmra020100>.

18 Blaser MJ. Missing microbes: how the overuse of antibiotics is fueling our modern plagues. New York: Henry Holt and Company, 2014: p. 273.

19 Renz, H. and C. Skevaki, Early life microbial exposures and allergy risks: opportunities for prevention. *Nat Rev Immunol*, 2021. 21(3): p. 177-191. <https://doi.org/10.1038/s41577-020-00420-y>; McDonnell, L., et al., Association between antibiotics and gut microbiome dysbiosis in children: systematic review and meta-analysis. *Gut Microbes*, 2021. 13(1): p.1-18. <https://doi.org/10.1080/19490976.2020.1870402>.

20 Cox, L.M., et al., Altering the intestinal microbiota during a critical developmental window has lasting metabolic consequences. *Cell*, 2014. 158(4): p. 705-721. <https://doi.org/10.1016/j.cell.2014.05.052>.

21 Arrieta, M.C., et al., Early infancy microbial and metabolic alterations affect risk of childhood asthma. *Sci Transl Med*, 2015. 7(307): p. 307ra152. <https://doi.org/10.1126/scitranslmed.aab2271>.

22 Dominguez-Bello, M.G., et al., Partial restoration of the microbiota of cesarean-born infants via vaginal microbial transfer. *Nat Med*, 2016. 22(3): p. 250-3. <https://doi.org/10.1038/nm.4039>.

23 Boudaud, M., et al., Intestinal microbiota biodiversity and the modern diet: consequences for human health. *Med Sci (Paris)*, 2026. 42(1): p. 65-70. <https://doi.org/10.1051/medsci/2025253>.

24 Turnbaugh, P.J., et al., An obesity-associated gut microbiome with increased capacity for energy harvest. *Nature*, 2006. 444(7122): p. 1027-31. <https://doi.org/10.1038/nature05414>.



Microbial markers of dysbiosis

Dysbiosis is generally characterized by loss of species that are key to the functional core, and by the proliferation of opportunist pathobionts. The absence of specific species is associated with chronic intestinal inflammation illnesses or a reduction in the integrity of the intestinal barrier.²⁵ Pathobionts can be epidemic, resident or ectopic, found in oral bacteria and involved in colitis and colorectal cancer.²⁶

Pioneering studies have demonstrated a reduction in microbial diversity in certain pathologies, notably Crohn's disease, characterized by the absence of certain bacteria, as well as long-term disruption caused by antibiotics.²⁷ This research suggests a close link between dysbiosis and the risk of chronic disease.

TOWARD INTEGRATIVE MICROBIAL MEDICINE: RESTORING SYMBIOSIS

These observations tend to argue for the establishment of standardized global surveillance of the evolution of human microbiota, particularly in fast-developing parts of the world. Innovative approaches such as metagenomic analysis of wastewater provide better understanding of large-scale urban microbiota and can be correlated to medication usages.²⁸

Microbial, now molecular, ecology allows direct analysis of microbial communities based on their genetic material, as well as their functional capacities thanks to culturomics. This complementarity is essential to understanding the logic behind food webs that maintain the cohesion of microbiota. These studies rely on help from artificial intelligence since they have to establish compatibility between massive and spectacularly diverse datasets harvested during research.

25 Cani, P.D., et al., Akkermansia muciniphila: paradigm for next-generation beneficial microorganisms. *Nat Rev Gastroenterol Hepatol*, 2022. 19(10): p. 625-637. <https://doi.org/10.1038/s41575-022-00631-9>.

26 Koliarakis, I., et al., Oral Bacteria and Intestinal Dysbiosis in Colorectal Cancer. *Int J Mol Sci*, 2019. 20(17). <https://doi.org/10.3390/ijms20174146>.

27 Dethlefsen, L., et al., The pervasive effects of an antibiotic on the human gut microbiota, as revealed by deep 16S rRNA sequencing. *PLoS Biol*, 2008. 6(11): p. e280. <https://doi.org/10.1371/journal.pbio.0060280>.

28 Marechal, V., et al., Wastewater-based epidemiology: Retrospective, current status, and future prospects. *Anaesth Crit Care Pain Med*, 2023. 42(5): p. 101251. <https://doi.org/10.1016/j.accpm.2023.101251>.

Microbial medicine aims to restore functional symbiosis between host and microbiome. It aims not only to correct dysbiosis but also to incorporate host parameters such as inflammation, intestinal permeability, and oxidative stress. Approaches include measured use of new-generation probiotics, prebiotics, targeted dietary interventions, and fecal microbiota transplants.

It is clear, however, that the logic underpinning current approaches remains largely empirical. This will remain the case while there is a lack of understanding of the logic behind the composition of the intestinal ecosystem, particularly knowledge of the nature of the food webs that maintain functional cohesion in relation to the niche. Finding answers to these questions is crucial to delivering the microbiomic engineering needed to ensure the resistance and resilience of a repaired ecosystem.

In addition to human microbiota, a multi-scale, multidisciplinary approach will be indispensable for tracking the evolution of microbial ecosystems, wherever they may be, under the effects of climate breakdown and the growing ecological impact of human influence on the planet, the Anthropocene.

CONCLUSION: A NEW MEDICAL FRONTIER

Loss of diversity in human microbiota during the Anthropocene is a major public health threat. The emergence of microbial medicine is part of a systemic, ecological vision of health, where humans are seen as a holobiont. Only the combination of rigorous experimental studies, controlled clinical testing, and integrated approaches, generating massive datasets that require use of artificial intelligence, will make it possible to define realistic therapeutic applications for this fast-growing discipline.

About the author

Philippe Sansonetti is professor emeritus at the Pasteur Institute and Collège de France. He has been a member of the French Academy of Science since 2001, where he heads the Human Biology and Medical Sciences unit. One of the founders of the cellular and infection microbiology field, his research revealed the invasive mechanism of *Shigella*, establishing this pathogen as a major model for host-pathogen interactions. In addition, his work has deepened understanding of innate immunity and led to the development of vaccine candidates against shigellosis. He is also interested in the pathogenic role of intestinal dysbiosis. He has authored several publications including *Le retour des épidémies [Return of Epidemics]*, *Vaccins [Vaccines]*, *Tempête parfaite [Perfect Storm]*, *Tu aimeras tes microbes comme toi-même [You'll Love Your Microbes as You Love Yourself]*, and *Microbes sans Frontières [Microbes Without Borders]*.





Nature-Inspired Healing:

The Role of Biomimicry in Modern Medicine

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Climate change is reshaping global health by intensifying heat stress, food and water insecurity, and extreme weather, leading to rising cases of cardiovascular, renal, respiratory and metabolic diseases. Kidney injuries in particular become more prevalent due to heat exposure and increased pollution. To find solutions to this deteriorating health landscape, this article highlights the need for nature-centric approaches. Biomimicry, which draws inspiration from biological systems, offers promising solutions: animals such as bears, naked mole rats or diving seals display remarkable resistance to conditions that severely affect humans, from ischemia to extreme temperatures. Studying these features could unlock new therapies for chronic and climate-exacerbated diseases. However, biomimetic medical research remains underfunded and underdeveloped, while biodiversity loss threatens this very reservoir of biological innovations. Protecting ecosystems and rethinking diets and health systems are essential to building climate-resilient health.

COULD YOU BRIEFLY EXPLAIN HOW CLIMATE CHANGE IS LINKED TO THE DEGRADATION OF HUMAN HEALTH?

Human health globally is severely disturbed by the consequences of climate change, which amplifies heat stress, food instability, water scarcity and extreme weather events. With these disturbances comes a different disease panorama: heat stress exacerbates cardiovascular, renal, respiratory and diabetes-related conditions and has led to a dramatic increase in related deaths. An estimated 175,000 deaths a year are attributable to heat in Europe alone.¹

Kidney injuries and diseases are also on the rise and about 15% of the global population has signs of kidney disease. Since kidneys act as filters for environmental pollutants, they are particularly vulnerable to polluted and hot environments. An epidemic of Mesoamerican nephropathy, which causes lethal renal failure, is currently affecting agricultural workers in Central America and many other countries, such as Sri Lanka, who work in extreme heat conditions.²

This increase in environment-related diseases is entirely attributable to the anthropogenic organization of current societies, centered around short-term benefits, intensive use of resources and linear consumption of goods, which drives climate change and catastrophic loss of biodiversity. To preserve our health, it is essential to shift towards a nature-centric, biomimetic organization, where we draw inspiration from nature in everything we do, from resource use to dietary habits and medicine. Moving toward a nature-centric organization is an opportunity to better manage the risks to our health on a planet with finite resources.

YOU MENTION DRAWING INSPIRATION FROM NATURE. CAN YOU ELABORATE ON THIS?

The concept of solving human problems by drawing inspiration from nature is known as biomimicry, a term coined by Dr. Janine Benyus, a biologist and founder of the Biomimicry Institute, whose work inspired me to take an interest in this topic.

Biomimicry is inherently interdisciplinary. Humans have observed and drawn inspiration from nature throughout history – examples include studying the flight of birds to design early flying machines. Today, with advanced technological tools, we can analyze natural systems in unprecedented detail and apply these insights in virtually any field. For instance, the ventilation system of the Eastgate building in Harare, Zimbabwe, is heavily

¹ Johnson, D. (2024, August 2). Heat claims more than 175,000 lives annually in Europe, latest data shows. UN News. <https://news.un.org/en/story/2024/08/1152766>.

² Sorensen C. and Garcia-Trabanino R. A New Era of Climate Medicine — Addressing Heat-Triggered Renal Disease. New England Journal of Medicine <https://doi.org/10.1056/nejmp1907859>.



inspired by the structure of termite mounds: the building has numerous holes and chimneys to optimize air flow and ventilation, allowing the inside of the building to be maintained at a temperature consistently lower than outside, with minimal energy consumption.

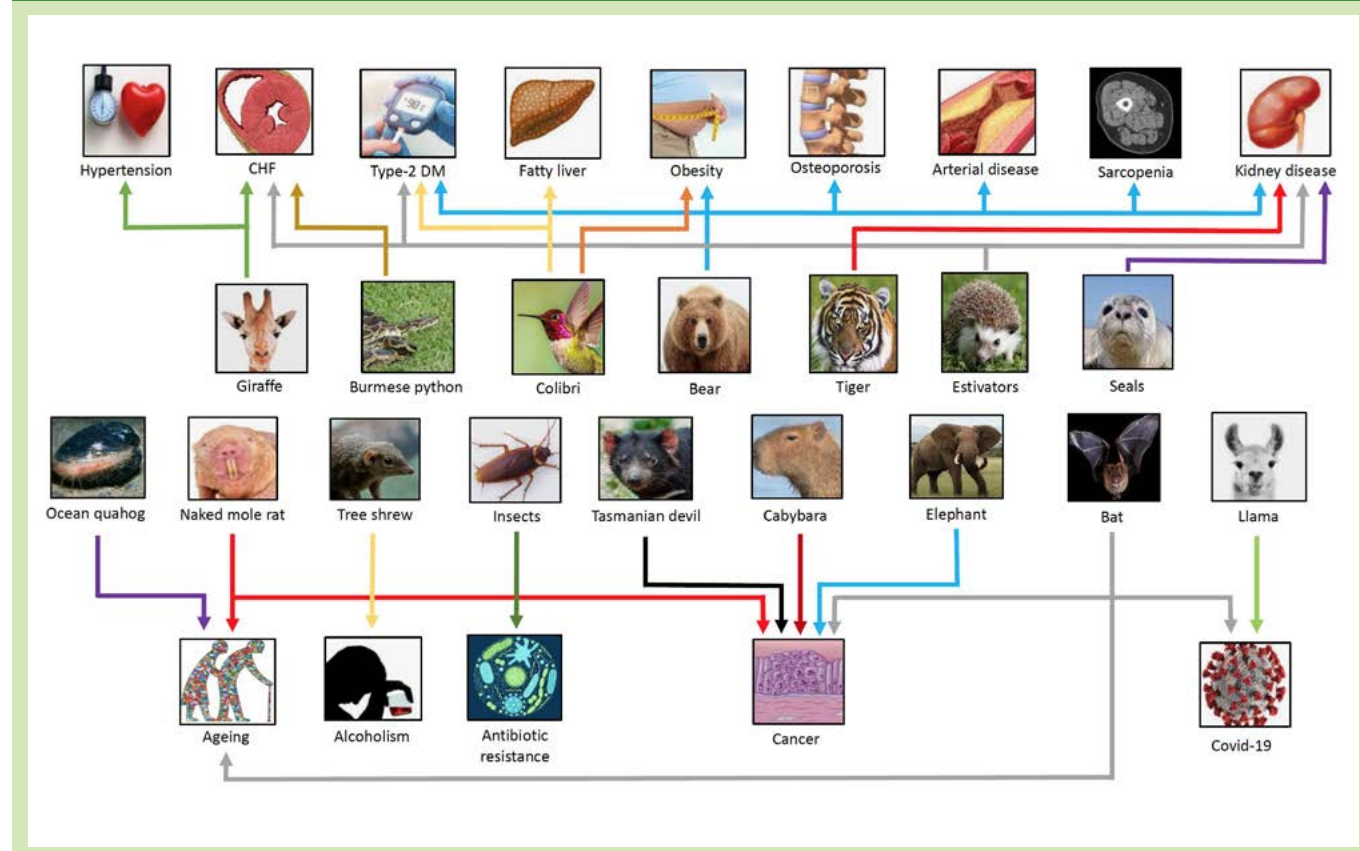
Similarly, medicine offers many applications of biomimicry, such as surfaces designed to mimic shark skin, which reduces bacterial adhesion,³ or needles inspired by the stinger of mosquitoes, bees and wasps, minimizing the puncture force required and improving maneuverability.⁴ Given the virtually infinite trove of knowledge contained within the animal kingdom, biomimicry could help us solve the health challenges exacerbated by climate change. A library of medical solutions exists in nature.

Biomimicry could help us solve the health challenges exacerbated by climate change

TO WHAT EXTENT CAN BIOMIMICRY HELP FIND ANSWERS TO HUMAN HEALTH CHALLENGES, INCLUDING THOSE EXACERBATED BY CLIMATE CHANGE?

Many species exhibit remarkable abilities and mechanisms which protect them from diseases which affect humans. For example, hibernating mammals such as bears and squirrels do not suffer from ischemia, a common condition amongst humans where blood supply is restricted in a part of the body or organ, and which can be fatal. Other examples include bats that tolerate viruses that devastate humans. Elephants seem resistant to cancer. Greenland sharks live a life in slow motion for 400 to 500 years. Giraffes function perfectly with blood pressures that would terrify any physician. A jellyfish escapes death altogether and is practically immortal.⁵

Selected examples of species that have provided clues for novel targets for “burden of life style” diseases and aging, such as alcoholism, COVID-19 and antibiotic resistance, congestive heart failure (CHF) or diabetes mellitus (DM)⁶



3 Dunder Arisoy F, Kolewe KW, Homyak B, Kurtz IS, Schiffman JD, Watkins JJ. Bioinspired Photocatalytic Shark-Skin Surfaces with Antibacterial and Antifouling Activity via Nanoimprint Lithography. ACS Appl Mater Interfaces. 2018 Jun 13;10(23):20055-20063. <https://doi.org/10.1021/acsami.8b05066>.

4 Yichi M, Xiao X, Hongliang R, Max Q-H. Meng. A review of bio-inspired needle for percutaneous interventions, Biomimetic Intelligence and Robotics, Volume 2, Issue 4, 2022, 100064, ISSN 2667-3797. <https://doi.org/10.1016/j.birob.2022.100064>.

5 Stenvinkel P, Kotanko P, Painer-Gigler J, Shiels PG, Evenepoel P, Schurgers L, Natterson-Horowitz B, Kalogeropoulou S, Schiffman J, Johnson RJ. Comparative physiology and biomimetics in metabolic and environmental health: what can we learn from extreme animal phenotypes? Diabetologia. 2026 Feb;69(2):295-307. <https://doi.org/10.1007/s00125-025-06611-3>.

6 Stenvinkel P, Avesani CM, Gordon LJ, Schalling M, and Shiels PG. Biomimetics provides lessons from nature for contemporary ways to improve human health - PMC. Journal of Clinical and Translational Science 5: e128, 1-14. <https://doi.org/10.1017/cts.2021.790>.

Several species, such as the naked mole rat, are also protected from chronic inflammation and oxidative stress, which play a part in many chronic burden of lifestyle diseases, i.e. diseases caused by lifestyle choices and worsened with age, such as type-2 diabetes, obesity, congestive heart failure or cancer,⁶ and with climate change.

Another example are camels, blue whales and wood frogs, which have learned to withstand extremely high or low temperatures and water scarcity, without suffering any physiological impairment. Studying the mechanisms which enable such extraordinary feats would prove particularly useful considering the global increase in temperatures due to climate change.

Bears exhibit a remarkable metabolic state during hibernation. This enigmatic state can serve as a model for understanding metabolic diseases, providing insights into reversible insulin resistance and energy homeostasis. They are also protected against thromboembolic complications^{7,8} (i.e. blood vessel obstruction by blood clots, generally in the lower extremities of the body), which generally afflict humans experiencing long-term immobility.

The above-mentioned naked mole rat, a rodent which can live up to five times longer than similar-sized rodents, presents the unique feature that its risk of death does not increase with age, contrary to humans, and is therefore protected against age-related diseases, such as cancer and vascular disease.⁹ Although the exact mechanisms which contribute to the naked mole rat's extraordinary resilience are unknown, it is posited that this resilience is in part attributable to the rat's ability to maintain high levels of the nuclear respiratory factor 2 (Nrf2). Put simply, Nrf2 is a protein regulating the transcription of genes which protect against oxidative stress and inflammation, which drives many diseases, as well as the aging process. Studying and understanding the role of Nrf2 in the naked mole rat's metabolism could provide breakthroughs in the fight against many diseases that accumulate with aging, and in understanding how to extend humans' health span.



The bone of a hibernating bear is examined by CT-scan.
© Peter Stenvinkel

In my own specialty, nephrology, the impressive ability of diving seals to vasoconstrict certain organs – such as their kidneys – to conserve blood and oxygen flow to their heart and brain is of particular interest.⁷ Indeed, several species of seals, such as elephant seals, can dive for up to 100 minutes per dive. During the dive, a seal's kidneys are deprived of blood and cease to function, only to resume functioning without acute kidney injury when the seal emerges. Several mechanisms may be responsible for this unusual resistance of seal kidneys to ischemic acute kidney injury, such as a better adapted anaerobic (i.e. deprived of oxygen) metabolism. Studying these mechanisms could provide invaluable insight into preventing ischemic kidney injury in human patients undergoing prolonged surgery, for instance.

7 Stenvinkel P, Johnson RJ. Kidney biomimicry--a rediscovered scientific field that could provide hope to patients with kidney disease. *Arch Med Res.* 2013 Nov;44(8):584-90. doi: 10.1016/j.arcmed.2013.10.008.

8 Stenvinkel P, Painer J, Kuro-O M, Lanaspá M, Arnold W, Ruf T, Shiels PG, Johnson RJ. Novel treatment strategies for chronic kidney disease: insights from the animal kingdom. *Nat Rev Nephrol.* 2018 Apr;14(4):265-284. <https://doi.org/10.1038/nrneph.2017.169>.

9 Stenvinkel P, Shiels P. Long-lived animals with negligible senescence: Clues for ageing research. *Biochemical Society Transactions.* 2019, 47. BST20190105. 10.1042/BST20190105. <https://doi.org/10.1042/bst20190105>.



GIVEN THESE NUMEROUS AND SIGNIFICANT OPPORTUNITIES, WHAT IS THE CURRENT STATE OF BIOMIMICRY MEDICAL RESEARCH?

Biomimicry aligns naturally with many areas in medicine such as regenerative medicine, organ preservation, immune tolerance, hypoxia resistance and fibrosis control. The barriers are less about lack of ideas and more about translation. Unfortunately, despite the trove of knowledge held by biodiversity that could better our health, many limitations hinder the advancement of biomimicry medical research. First and foremost, biomimicry research in medicine remains underdeveloped by comparison to other disciplines, such as chemistry and technology. As a cause, and a consequence, funding is not readily available nor easy to secure. In collaboration with scientists from other European universities, I have been trying to secure for the past 3 years funding from the European Union for an interdisciplinary biomimicry research project on the treatment of chronic burden of lifestyle diseases, in vain.

Biomimicry research is also inherently limited. It is an extremely complex area, requiring the combination of several already complex disciplines (such as medicine, veterinary medicine, biology) and there are many translational obstacles to copying a trait from an animal to a human. And because biomimicry requires the study of wild animals and affects the human body, it requires strong regulations and ethical supervision.

Furthermore, due to its complexity, biomimicry research is slower than purely clinical studies: the time from starting the research to treatment can span decades. This slowness, combined with the massive loss of biodiversity that our anthropogenic organization is causing, is another cause of worry for the future of biomimicry. WWF has recently reported that the average size of wildlife populations has dropped by 73% over the past 50 years,¹⁰ which, in addition to its dramatic environmental, social and economic consequences, causes the definitive loss of very valuable species and mechanisms that could provide solutions to severe human problems. Diversity is so much more than just the number of species. It is also the amount of unique evolutionary history that is lost with every animal species that disappears from our planet. Thus, biodiversity is not an environmental luxury – it is the very foundation of human health. Biodiversity supports our food systems, medicines, clean air and water, climate regulation, and psychological well-being.

For biomimicry to take its rightful place in medical research, future research must be an interdisciplinary effort, bringing together medical doctors, veterinarians, ecologists, biologists and any researchers whose expertise can bridge the gap between animal and human health

DESPITE THESE LIMITATIONS, WHAT MAIN LESSONS CAN WE DRAW TODAY FROM BIOMIMICRY REGARDING OUR HEALTH AND THE FIGHT AGAINST CLIMATE CHANGE?

The fundamental lesson taught to us by biodiversity regarding our health concerns our dietary habits. Humans are omnivores and our gastro-intestinal tract may not be designed to eat red meat daily, red meat consumption having been linked directly, both in humans and in animals, with an elevated risk of CKD.⁸ This directly mirrors what has been observed in the animal kingdom: mammals with little risks of cancer and longevity have a plant-based diet, while the consumption of mammals by carnivorous animals has been linked to a significantly higher cancer risk.¹¹

The EAT-Lancet Commission has, since its creation, strongly advocated for a shift in food systems and dietary policies towards a “planetary health diet”, based on health criteria, which is rich in plants, comprises only a moderate amount of animal products (fish, dairy and meat), and minimal consumption of sugar, salt and saturated fats.¹² The global adoption of such a diet could prevent the deaths of 7 to 10 million adults each year by reducing nutritional diseases and dietary risk diseases (e.g. type 2 diabetes, cardiovascular diseases) and presents the significant

advantages of limiting climate change and human pressure on biodiversity. Indeed, current estimates indicate that the greenhouse gas emissions associated with producing one kilogram of beef (25-30 ktCO₂eq) could be more than fifty times higher than those generated by producing one kilogram of vegetables (0.2-2.0 ktCO₂eq).¹³ If the planetary health diet were to be adopted globally, it is estimated that global dietary emissions would decrease by 17%.¹⁴ A radical transformation of the global food system is urgently

needed – and the responsibility does not lie only with governments or institutions. It lies, quite literally, on our own plates.

¹¹ Vincze O, Colchero F, Lemaître JF. et al. Cancer risk across mammals. *Nature* 601, 263–267 (2022). <https://doi.org/10.1038/s41586-021-04224-5> (Cancer risk across mammals | Nature).

¹² Rockström J, Thilsted S, Willett W et al. The EAT–Lancet Commission on healthy, sustainable, and just food systems *The Lancet*, 2025; 406, 1625–1700.

¹³ Springmann M. (2025). Many diets for many people: planetary health diets and their health and environmental impacts at global, regional, national, and demographic levels [preprint]. Zenodo. <https://doi.org/10.5281/zenodo.17079404>.

¹⁴ Li Y, He P, Shan Y. et al. Reducing climate change impacts from the global food system through diet shifts. *Nat. Clim. Chang.* 14, 943–953 (2024). <https://doi.org/10.1038/s41558-024-02084-1>.



WHAT CHANGES DO YOU RECOMMEND BE MADE IN MEDICAL RESEARCH TO BETTER INTEGRATE BIOMIMICRY?

The growing intersection of climate change, health, and inequality tells us that siloed thinking and research no longer works. For biomimicry to take its rightful place in medical research, future research must be an interdisciplinary effort, bringing together medical doctors, veterinarians, ecologists, biologists and any researchers whose expertise can bridge the gap between animal and human health. This would enable clinical studies to be co-designed by various experts: ecologists and biologists, paired with clinicians, could develop comparative physiology study protocols, whereby animal species with features or mechanisms pertinent to the research would be included in the studied population. For instance, a clinical study on bedridden or sedentary patients with a high risk of thromboembolic complications would also study hibernating bears, who are protected against such complications, and compare the differences between such models.

This change of paradigm should also be implemented in the medical curriculum, where studies of the environment and animal health are currently lacking. Dr. Barbara Natterson-Horowitz, a cardiologist at Harvard Medical School and UCLA and a strong proponent of biomimicry, has long called for the inclusion of such concepts in medical education. This could take the form of modules on animal health and environmental health perspectives, comparative presentations of diseases in different species, or shared studies with veterinarians.¹⁵ These proposed changes would allow us to properly study biodiversity and deliver the major medical breakthroughs already mentioned.

AS WE CONCLUDE THIS INTERVIEW, DO YOU HAVE ANY FINAL WORDS ON THE FUTURE OF BIOMIMICRY IN MEDICINE?

As Albert Einstein stated, “Look deep into nature, and you will understand everything better”. Health is the new face of climate change, and biodiversity is an immense reservoir of inspiration on how we should live our lives, eat, build and heal ourselves. Eating less meat and preserving biodiversity are proven to have mutually beneficial outcomes for the planet and for our health. It is therefore essential, and life-preserving, that our policies start integrating nature and its ingenious solutions. Let’s not forget that nature has been solving complex medical and environmental problems for millions of years. The question before us now is whether we are ready to implement biological intelligence in science and start to “connect the dots” before it is too late.¹⁶



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¹⁵ Rabinowitz P, Natterson-Horowitz B, Kahn L, Koc R, Pappaioanou, M. (2017). Incorporating one health into medical education. BMC Medical Education. 17. 10.1186/s12909-017-0883-6. (PDF) Incorporating one health into medical education).

¹⁶ Stenvinkel P. Learning from nature. The power of biological intelligence. Publisher: Lava 2025.

About the author

Dr. Peter Stenvinkel obtained his doctoral degree in renal medicine in 1994 at the Karolinska Institutet (Stockholm). He is a world-renowned professor of nephrology, recipient of several awards, grants and an honorary doctorship. He conducts translational research with a focus on risk factors for metabolic, cardiovascular and nutritional complications in chronic kidney disease (CKD). Dr. Stenvinkel took an interest in biomimicry more than a decade ago and has since been part of a research group of multidisciplinary experts dedicated to researching in various species the metabolic mechanisms which protect them against changes in their environment, to discover new therapies.





The Health Costs of Biodiversity Loss



The Strategic Plan for Biological Diversity 2011-2020 and Aichi Biodiversity Targets formulated in 2010 by the Convention on Biological Diversity were intended to lay the groundwork for international action to protect ecosystems vital to human health. The failure of these targets, particularly target 14 on restoring and protecting ecosystems that contribute to health, access to water and well-being, underscores our collective inability to stem the decline of these fundamental ecological services. Continuing along the same trajectory leads to on-going reductions in the ability of ecosystems to provide these services, with disproportionate impacts on economically disadvantaged and vulnerable groups, confirming that biodiversity loss is a major structural determinant for human health, over and above the environmental issues it raises.¹

“The health of humans, animals and the environment are inextricably interwoven. We cannot protect one without protecting all three” declared WHO Director General Dr. Tedros Adhanom Ghebreyesus during a speech at the One Health Summit on April 7, 2026.² An editorial in *The Lancet*³ stresses that as well as ecosystem damage, biodiversity loss has fundamental impacts on preventive care, medical innovations, and personal well-being. The second part of this review focuses on examining these often underestimated health impacts.

It opens with three short articles highlighting three types of anthropic pollution, the harms they cause to natural environments, and the resulting increased exposure to multiple health risks for human and animal populations. **Saija Saarni** analyzes how microplastics, found in every ecosystem, disrupt living organisms and point to new toxicological concerns. **Marie-Cécile Ploy** explores the role that misuse or overuse of pharmaceutical products plays in the emergence and acceleration of a global health threat: antimicrobial resistance. And **Lars-Eric Heimbürger-Boavida** describes the history and long-term effects of mercury, a persistent contaminant, from bioaccumulation in food chains to the health consequences for the most vulnerable groups.

Next, **Franck Courchamp** and **Christophe Diagne** explain how the rise in global exchanges and species movements provides fertile conditions for biological invasions. Introduced species can permanently transform ecosystems and the health impacts they generate are frequently underestimated. As well as infectious diseases frequently associated with invasions, invasive species produce a spectrum of effects on environmental quality, local and regional resilience, and human well-being.

The identification in May 2026 of several cases of hantavirus infection on a cruise ship further underlines the risks that zoonotic diseases represent. The transformation of ecosystems by human activities modifies and accentuates dynamics behind the transmission of pathogenic agents. **Gerard Killeen** explores the risk of emergence of infectious diseases in Tanzania due to the proximity between human and animal populations, and how local communities are taking action to create effective barriers while also protecting biodiversity. Finally, **Tamara Szentivanyi** examines how habitat fragmentation and loss of biological diversity in Europe leads to an intensification of avian diseases with an increased risk of transmission to humans.

1 Secretariat of the Convention on Biological Diversity (2020) Global Biodiversity Outlook 5 – Summary for Policymakers p.12.

2 WHO Director General's closing remarks at the One Health Summit – April 7, 2026.

3 The Lancet (2024) Biodiversity loss: a health crisis.



Microplastics: From Innovation to Biodiversity Risk

Dr. Saija Saarni: Associate Professor of applied environmental geology at the University of Turku, Finland

The modern era is characterised by rapid development and a surge of new innovations, with material science and chemicals at the forefront of this advancement. The associated risks often emerge later. Since the 1970s, awareness has resulted in diverse regulatory actions, such as the banning of DDTs¹ to protect biodiversity, and of asbestos to preserve human health. Coincidentally, several observations of microplastics were reported in the seas during the 1970s.² Yet, it was only in 2004 that biologist Richard Thompson coined the term "microplastic" and described the potential risks to plankton ingesting these synthetic particles.³ Since then, our understanding of the diverse risks associated with microplastics entering natural environments has grown significantly, leading to the development of various initiatives and legislation at both national and international levels such as the EU single-use plastic ban in 2021⁴ targeting the most commonly found plastic products on European beaches (e.g., plastic cutlery, straws and plates).

The cumulative production of plastic materials has recently exceeded 10 billion tons, of which only a mere fraction is incinerated and less than 10% recycled.⁵ The rest can be found in landfill deposits or dispersed throughout natural ecosystems. Once introduced into the environment, plastic degrades, breaking down into smaller fragments due to chemical processes and physical forces such as wave action. These diminutive particles, known as microplastics, are defined by their size, measuring 5 mm or less.

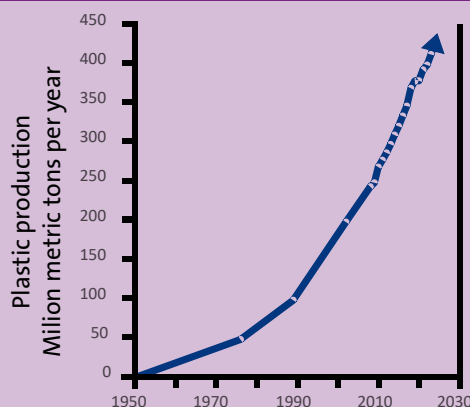
Microplastics are also intentionally manufactured, such as plastic pellets used as raw materials by the plastic industry. However, the most significant sources of microplastic pollution in the environment remain the transportation industry (paints and tyre wear), synthetic textiles, plastic packaging, agriculture and the marine industry (coatings and fishing gear).

TINY PARTICLES, BIG QUESTIONS

Microplastics particles pose a variety of threats across terrestrial and aquatic ecosystems, as they are ingested by a wide range of organisms from plankton to whales. Once consumed, plastic is not digested, and can accumulate within the digestive tracts of animals, causing blockages and inducing false satiety, which can lead to starvation. Furthermore, microplastics have been shown to induce oxidative stress and inflammation, reducing the fitness, growth, and survival of affected organisms.⁶ They can also decrease the reproductive capacity of important plankton species, thereby destabilizing the basis of entire aquatic food webs and threatening biodiversity, especially in vulnerable areas which serve as crucial spawning sites, such as coastal areas, lagoons, and estuaries.

Global plastic production is expected to nearly double by 2050, but how rapidly this will be reflected in microplastic levels in future ecosystems is unknown.

The global plastic production has rapidly increased since the beginning of the 1950's



INVISIBLE INVADERS

Microplastics can be found everywhere in our environment, and in the human body (intestines, lungs, liver, kidneys, blood, placenta and even in the brain). It is practically impossible to avoid eating microplastics, as they are present not only in seafood, but in everything

¹ DDTs refer to dichlorodiphenyltrichloroethane, a widely used insecticide.

² Carpenter, E. J. & Smith, K. L. Plastics on the Sargasso Sea Surface. *Science* 175, 1240–1241 (1972).

³ Thompson, R. C. *et al.* Lost at Sea: Where Is All the Plastic? *Science* 304, 838–838 (2004).

⁴ Directive 2019/904/EU of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment. OJ L 155, 5.6.2019, p. 1–36

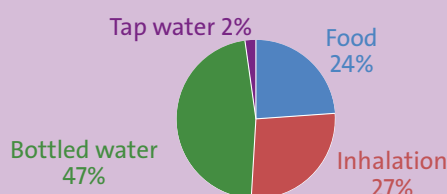
⁵ Geyer, R., Jambeck, J. R. & Law, K. L. Production, use, and fate of all plastics ever made. *Sci. Adv.* 3, e1700782 (2017).

⁶ Wang, J. *et al.* Meta-analysis of the effects of microplastic on fish: Insights into growth, survival, reproduction, oxidative stress, and gut microbiota diversity. *Water Res.* 267, 122493 (2024).



from livestock to rice, vegetables and fruits. The same is true for all drinks, yet tap water seems one of the safest options.⁷ While the debate of how much we actually do eat microplastics is on-going,⁸ it is estimated that we inhale more microplastics than we eat,⁷ and even more so in densely populated regions with low air quality.

The estimated sources of human ingested microplastics in US



Data from Cox et al., 2019.

As with many substances, the dose makes the poison. In the case of microplastics, harmful additives in the original plastic materials such as phthalates, bisphenols, fire retardants and heavy metals, enter our bodies within the plastic particles. Because we are exposed to a variety of fine particles and pollutants in our daily life, the long-term health risks of microplastics are difficult to distinguish. The potential effects include inflammation, endocrine disruption, and links to cardiovascular events, neurological diseases and cancer. However, the scientific studies and evidence linking microplastics to disease remain limited to date.⁹ We can certainly expect an increase in human exposure to microplastics

The cumulative production of plastic materials has recently exceeded 10 billion tons, of which only a mere fraction is incinerated

with the projected growing use of plastic products, but it remains uncertain when the dose becomes a significant health risk. Therefore, reducing the careless use of plastics is an important preventive step.

REDUCE, REUSE, RECYCLE – AND RETHINK

The advantages of plastic materials are numerous – lightweight, durable, versatile, and inexpensive – allowing their widespread use in virtually all fields and industries. 'Reduce, reuse, recycle' may sound familiar, but driving real change requires rethinking our behaviors and first of all reducing plastic use. Awareness is the first step already taken with first guidelines, initiatives and bans in place to reduce use and leaching of plastic into the environment. While we can expect more ecological materials thanks to innovation, modern biodegradable plastics only decompose under industrial (non-natural) conditions and therefore can not solve the problem.

Scientists have gained understanding on the global spread and local concentrations of microplastics, but still very few reconstructions exist showing how rapidly microplastic concentrations have increased in the environment since plastic materials were introduced. Some of these studies report the rapid increase of microplastics in aquatic systems around the year 2000, at a period when global plastic production nearly doubled within a decade.¹⁰

This suggests that our use of plastic is quickly reflected in environmental concentrations. But there is hope that the process could work in reverse as well: a significant reduction of plastic production and use along improved waste management will eventually lead to declining concentrations in the environment.

7 Cox, K. D. et al. Human Consumption of Microplastics. *Environ. Sci. Technol.* 53, 7068–7074 (2019).

8 Pletz, M. Ingested microplastics: Do humans eat one credit card per week? *J. Hazard. Mater. Lett.* 3, 100071 (2022).

9 Lamoree, M. H. et al. Health impacts of microplastic and nanoplastic exposure. *Nat. Med.* 31, 2873–2887 (2025).

10 Dimante-Deimantovica, I. et al. Downward migrating microplastics in lake sediments are a tricky indicator for the onset of the Anthropocene. *Sci. Adv.* <https://doi.org/10.1126/sciadv.adi8136> (2024) doi:10.1126/sciadv.adi8136.

About the author

Dr. Saija Saarni is an Associate Professor of applied environmental geology at the University of Turku, Finland. Her research supported with an AXA postdoctoral fellowship grant, examines how rapidly natural environments change in response to human activities. The rate of change is also the key to evaluate future risks related to microplastic pollution. Her work aims to measure the past and modern rates of microplastic input into environment and equally quantify how our actions to mitigate microplastic pollution are actually reflected in natural systems. In addition to her scientific work, she has written popular science books about geology.



Antimicrobial Resistance: A Global Health Challenge

Marie-Cécile Ploy: Professor of Microbiology at the University of Limoges and Head of the Bacteriology, Virology and Hygiene Department at Limoges Teaching Hospital

Antimicrobials¹ play an essential role in human and animal health by facilitating the treatment of infections and diseases. Whereas bacterial infections were the leading cause of death in 1940, they now account for just 2% of deaths in present-day France.² But the emergence of treatment-resistant pathogens risks reversing this trend. Antimicrobial resistance (AMR) has become one of the leading causes of mortality worldwide today,³ behind malaria and AIDS.⁴ Exacerbated by misuse of antimicrobials and aided by their contamination of the environment, the WHO has identified antimicrobial resistance as one of the ten biggest threats to global health.⁵

EMERGENCE AND DYNAMICS OF ANTIMICROBIAL RESISTANCE

Antimicrobial resistance refers to the capacity of organisms to resist previously effective treatments. Being part of the natural process whereby living organisms evolve, it is significantly amplified by prolonged and excessive exposure to antimicrobials favoring the emergence, selection, and spread of genetically resistant variants. The primary driver in the development of antimicrobial resistance lies in the inappropriate use of antibiotics in human medicine and agriculture. Massive recourse to antibiotics for rearing livestock and contamination of the environment via discharges from human activities therefore promote the selection of resistant bacteria. About 70% of global antibiotic use can be attributed to livestock rearing where it is used to improve productivity,⁶ albeit the use of antibiotics as growth promoters is banned in Europe.

About 70% of global antibiotic use can be attributed to livestock rearing where it is used to improve productivity

Globalization and increasingly intensive trading are additional major factors driving the spread of resistant pathogens on a planetary scale. There were an estimated 4.95 million deaths associated with bacterial antimicrobial resistance in 2019, including 1.27 million deaths directly attributable to bacterial AMR.⁷ Antimicrobial resistance also represents a substantial financial cost, estimated by the OECD to \$66 billion annually (adjusted for purchasing power parity), including \$28.6 billion borne by health systems across 34 OECD member countries.⁸

DRIVERS FOR ENVIRONMENTAL PROPAGATION

The environment plays a central role in the emergence, transmission and propagation of antimicrobial resistance, closely interlinked with the threefold crisis afflicting the planet: climate breakdown, biodiversity erosion, and pollution.⁴ Climate breakdown, rising temperatures in particular, facilitate biological mechanisms such as the exchange of resistant genes between bacteria. Certain parameters affecting water and the air, such as concentrations of oxygen and carbon dioxide, can also influence bacterial survival and proliferation.⁹ The increasing pollution of natural environments, particularly by drug residues and microplastics, creates favorable conditions for these exchanges by multiplying contacts between micro-organisms.⁹

In certain countries of the Global South, conditions can be particularly favorable to the diffusion of resistant pathogens owing to greater ecosystem vulnerability, increasing intensity of extreme weather events (floods and storms), inadequate infrastructure for access to safe water and sewage services, and insufficient controls over the use of antimicrobials.

1 All treatments to counter pathogenic agents: antibacterial, antifungal, antiviral and antiparasitic.

2 Les antibiotiques sauvent des vies - Ministère de la Santé, de la Famille, de l'Autonomie et des Personnes handicapées [Antibiotics Save Lives - Ministry for Health, Families, Autonomy and the Disabled].

3 WHO (2025) Global antibiotic resistance surveillance report 2025.

4 UNEP (2023) What is antimicrobial resistance and why is it a growing threat?

5 WHO (2023) Antimicrobial resistance.

6 Van Boeckel T. et al (2015) Global trends in antimicrobial use in food animals | PNAS in Tiseo K. et al (2020) Global Trends in Antimicrobial Use in Food Animals from 2017 to 2030.

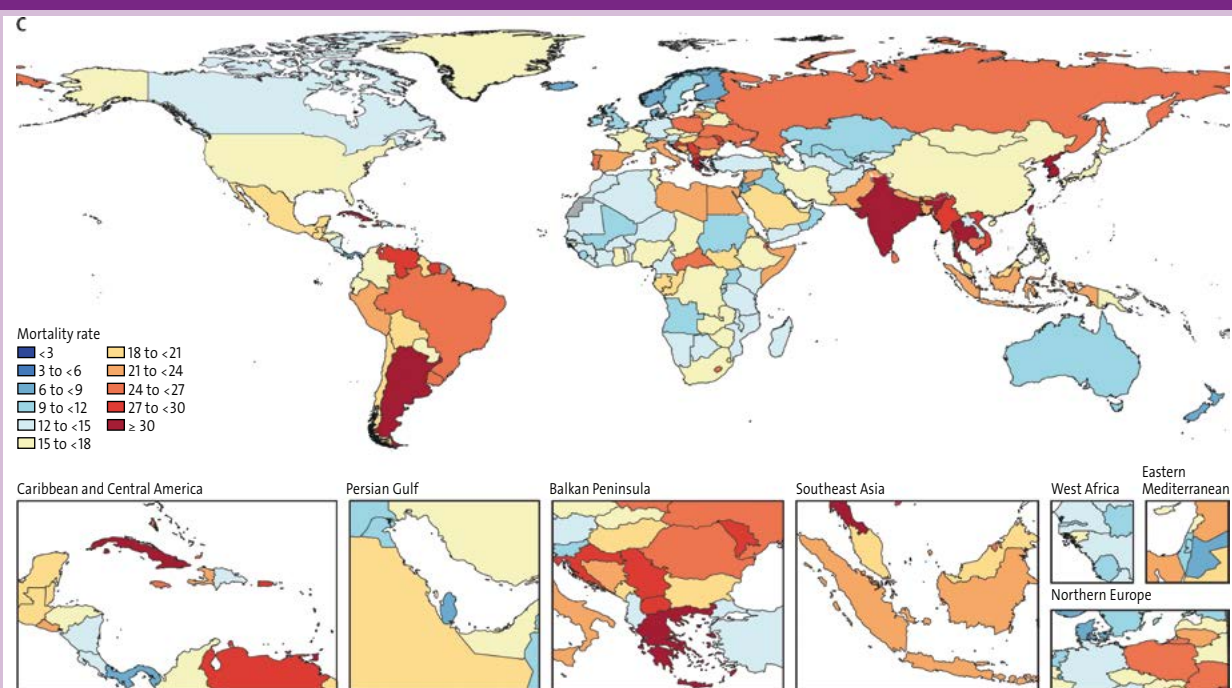
7 Murray C, Ikuta K, Sharara F et al., *The Lancet* (2022) Global burden of bacterial antimicrobial resistance in 2019: a systematic analysis - The Lancet.

8 OECD (2023) Embracing a One Health Framework to Fight Antimicrobial Resistance (EN) in OECD, Antimicrobial resistance.

9 <https://www.sciencedirect.com/science/article/pii/S258900422030208X> Rodriguez-Verdugo A. et al (2020) Compounding Effects of Climate Warming and Antibiotic Resistance - ScienceDirect.



Map of global mortality rate per 100,000 inhabitants attributable to AMR, all ages – Estimate for 2050¹¹



Saturated sewer systems and the dispersion of wastewater contaminated by antimicrobial residues, primarily from farming, hospitals and industrial activities, further contribute to the dissemination of resistant bacteria in natural environments. These dynamics underline the systemic, global character of antimicrobial resistance and the urgent need to adopt an approach based on One Health principles, recognizing the very close interdependency between human health, animal health (domesticated and wild), biodiversity preservation, and ecosystem integrity.

COORDINATED ACTIONS TO COMBAT ANTIMICROBIAL RESISTANCE

Turning the tide of antimicrobial resistance demands coordinated actions at every level, from individual behaviors to systemic frameworks. Promoting reasonable approaches to the use of antibiotics is paramount in terms of human and animal health. This relies primarily on raising awareness, such as the *Antibiotics Aren't Automatic* campaign started by the French state health insurance system in 2002 that is now an everyday phrase. Restricting non-therapeutic veterinary uses is a major lever that is insufficiently applied. Although 93% of countries have national action plans for combating antimicrobial resistance, only 11% have allocated funding and put the plans into practice.¹¹

¹⁰ Naghavi M, Vollset S, Ikuta K et al. (2024) Global burden of bacterial antimicrobial resistance 1990–2021: a systematic analysis with forecasts to 2050 - The Lancet.

¹¹ WHO (2023) Global Database for Tracking Antimicrobial Resistance (AMR) Country Self-Assessment Survey (TrACSS), in FAO (2023) TACKLING ANTIMICROBIAL RESISTANCE IN FOOD AND AGRICULTURE, p. 33.

Prevention also requires suitable and proportionate hygiene habits to reduce transmission of pathogens and avoid the emergence of co-resistances linked to the use of biocides.

One Health World – Teodor Hristov for EU-JAMRAI's Sketching Antimicrobial Resistance campaign¹²



Additionally, antimicrobial resistance requires greater efforts in terms of education and making the science accessible as well as in-depth interdisciplinary scientific collaboration. To deliver this, the PROMISE consortium¹³ has created a network of 120 partner members, experts in human medicine, veterinary medicine and environmental sciences who share their expertise through a number of working groups. The

European Union's EU-JAMRAI program also teaches the general public about antimicrobial resistance, for example, with a project called Sketching Antimicrobial Resistance featuring 30 European artists.¹² Testimonies from people who have suffered the consequences of antimicrobial resistance also help to bring these stories into our daily lives, as proposed by the charity The AMR Narrative.¹⁴

Beyond the actions of each individual, strengthening public infrastructures is also vital, particularly in terms of how wastewater and pharmaceutical waste are managed. Lastly, since antimicrobial resistance demands a global response, international and cross-disciplinary cooperation are equally essential. Harmonizing scientific indicators, sharing datasets and creating networks of actors make it possible to overcome the silos that separate human health, animal health, the environment, and policymaking. Since June 2022, the quadripartite alliance of the Food and Agriculture Organization of the United Nations (FAO), United Nations Environment Programme (UNEP), World Health Organization (WHO) and World Organisation for Animal Health (WOAH) are coordinating their approaches to offer transdisciplinary programs based on the One Health¹⁵ principle. Adopting an integrated Planetary Health¹⁶ system is clearly crucial to providing a lasting response to this systemic issue.

¹² Sketching Antimicrobial Resistance | EU-JAMRAI.

¹³ PROMISE.

¹⁴ The AMR Narrative.

¹⁵ WOA (2022) Quadripartite welcomes new political commitments in fight against antimicrobial resistance.

¹⁶ Ziveri D., Bolon I. et al. (2025) One health and planetary health in humanitarian settings.

About the author

Marie-Cécile Ploy is Professor of Microbiology at the University of Limoges and Head of the Bacteriology, Virology and Hygiene Department at Limoges Teaching Hospital. She is also Head of the Inserm RESINFIT research unit focusing on antimicrobials. Since 2024 she has been coordinator of EU-JAMRAI, the EU Joint Action on Antimicrobial Resistance (AMR) and associated infections, and PROMISE, the French interdisciplinary network for combating AMR.



AMR reaches even the wildest places – Anja Sušanj for EU-JAMRAI's Sketching Antimicrobial Resistance campaign¹²



Cold Mercury is a Hot Topic

Lars-Eric Heimbürger-Boavida: Chemical oceanographer working for the CNRS at the Mediterranean Institute of Oceanography, Aix-Marseille-University

WHY IS MERCURY A CONTAMINANT OF PARTICULAR CONCERN?

Ongoing global change includes warming climate, biodiversity loss and contaminant dispersal in the environment. Mercury exemplifies the paradox of a contaminant we have long recognized yet struggle to control. The 2018 Global Mercury Assessment, mandated by the United Nations Environment Programme, found that anthropogenic sources of mercury emit approximately 3,100 tons per year, and that all people worldwide are exposed to some amount of mercury.¹ And although we know the main anthropogenic sources of mercury (gold mining, coal combustion and cement production), the production of methylmercury – the organic and most toxic form of mercury – by the ecosystem is still a vastly mysterious phenomenon.

Among contaminants, mercury is of particular concern² due to the neurotoxicity and high biomagnification³ of methylmercury in the food web. Human societies have long understood the dangers posed by mercury. In Ancient Rome, *Damnatio ad metalla* (in English, “condemnation to the mines”) condemned slaves to lethal exposure in mercury mines. The Mad Hatter disease – as portrayed in *Alice in Wonderland* – describes the neurotoxic effects of chronic exposure to mercury vapour in millinery.

The Minamata disease, discovered in 1956, served as a trigger for the scrutinization and regulation of mercury contamination. A chemical plant near Minamata (Japan) discharged methylmercury into the bay for more than a decade, which bioaccumulated in the marine wildlife. More than 2,200 people were poisoned through their consumption of contaminated fish and suffered severe neurological symptoms, stillbirths, and congenital malformations.

The Mediterranean Sea stands out as a region of particular interest. Its enclosed geography and low productive waters favour the accumulation of mercury originating from nearby emission sources

The local population and their descendants still suffer from this disease. Methylmercury is so toxic that a few drops spilled on the glove of the American chemist Karen Wetterhahn were sufficient to poison and kill her within several months.⁴

Despite our knowledge of the effects of acute poisoning, chronic exposure to mercury remains difficult to assess. Studies have been done on cohorts of mothers and their children chronically exposed to mercury, showing that children more exposed to mercury had lower IQ tests scores.^{1,2}

HOW FAR HAS SCIENTIFIC RESEARCH GONE ON MERCURY AND ITS POLLUTION?

There are still many uncertainties surrounding the cycle of mercury. We lack clear estimates of the oceanic mercury budget, its anthropogenic share, and how climate-driven shifts, such as warming and bio-diversity loss, shape methylmercury formation and biomagnification. Current measurements of the global amount of mercury released by human activities often rely on broad estimates, and major gaps persist in understanding how it circulates between air, water, sediments, and organisms. Methylmercury is not emitted directly by human activities but is formed within ecosystems, as inorganic mercury released to air and water undergoes transformation by microbes.

In the 1970s, Swedish scientists discovered methylmercury in rotting fish and then demonstrated that it could be generated naturally in sediments.⁵ Its origin in the offshore waters of the global ocean remains elusive but is probably linked to other microbes.⁶

1 The 2018 Global Mercury Assessment <https://www.unep.org/resources/publication/global-mercury-assessment-2018>.

2 World Health Organization (2024) Mercury and Health fact sheet.

3 The process causing the concentration of a substance to increase at higher levels of the food chain.

4 Science (1997) Mercury Poisoning Kills Lab Chemist | Science | AAAS.

5 Jensen, S. & Jernelöv, A. Biological methylation of mercury in aquatic organisms. *Nature* 223, 753–754 (1969).

6 Villar, E., Cabrol, L., Heimbürger-Boavida, L. & Heimbürger-Boavida, L. E. Widespread microbial mercury methylation genes in the global ocean. *Environmental Microbiology Reports* 12, 1758–2229.12829 (2020).



Research-wise, the Mediterranean Sea stands out as a region of particular interest. Its enclosed geography and low productive waters favour the accumulation of mercury originating from nearby emission sources and microbes are more active in its warmer waters. The Arctic is also a semi-enclosed ocean basin, making it highly sensitive to external changes. Besides, this ocean contains about 2,000 tons of mercury but about 600,000 tons are lurking in permafrost, which is going to thaw faster in warming climate.⁷

ARE THERE REGIONS OR POPULATIONS PARTICULARLY EXPOSED TO MERCURY CONTAMINATION?

Ecosystem degradation accelerates the transfer of contaminants through trophic levels,⁸ increasing exposure for communities which regularly consume marine species, as marine predators concentrate the highest levels of methylmercury. Arctic communities such as the Inuit and Sámi are especially vulnerable. Historically marginalized and forcibly relocated to remote regions, these groups often rely almost exclusively on marine wildlife for food, with few alternatives available. Their exposure levels remain paradoxically high despite the Arctic not containing more mercury than other ocean basins. Coastal populations of the Mediterranean, whose diet also traditionally contains a lot of fish, also exhibit high levels of mercury contamination, despite having many food alternatives.⁹

For those reasons, my research focuses on those regions. Our measurements in the Arctic Ocean suggest that methylmercury is formed in shallow water and possibly more biomagnified in arctic



The Tara Polar Station.
© Lars-Eric Heimbürger-Boavida

animals.¹⁰ We recently discovered that our current understanding is biased, since there are seasonal changes of mercury and methylmercury in the Arctic Ocean and observations are mostly made during the summer.¹¹ We will make use of the Tara Polar Station to study mercury throughout the seasons for the next 20 years.¹²

7 Dastoor, A.; Angot, H.; Bieser, J.; Christensen, J. H.; Douglas, T. A.; Heimbürger-Boavida, L.-E.; et al. Arctic Mercury Cycling. *Nat. Rev. Earth Environ.* 2022, 3 (4), 270–286. <https://doi.org/10.1038/s43017-022-00269-w>.

8 Trophic levels refer to the different feeding levels within a food web, describing how energy and nutrients pass from small organisms (like plankton) to progressively larger predators (like fish, marine mammals, or humans).

9 Petrova, M. V.; Ourgaud, M.; Boavida, J. R. H.; Dufour, A.; et al. Human Mercury Exposure Levels and Fish Consumption at the French Riviera. *Chemosphere* 2020, 258. <https://doi.org/10.1016/j.chemosphere.2020.127232>.

10 Heimbürger, L.-E.; Sonke, J. E.; Cossa, D.; Point, D.; et al. Shallow Methylmercury Production in the Marginal Sea Ice Zone of the Central Arctic Ocean. *Sci. Rep.* 2015, 5, 10318.

11 Kohler, S. G.; Heimbürger-Boavida, L.-E.; Petrova, M. V.; Digernes, M. G.; et al. Arctic Ocean's Wintertime Mercury Concentrations Limited by Seasonal Loss on the Shelf. *Nat. Geosci.* 2022, 15 (8), 621–626. <https://doi.org/10.1038/s41561-022-00986-3>; Kohler, S. G.; Heimbürger-Boavida, L.-E.; Assmy, P.; Müller, O.; et al. Biotic Transformation of Methylmercury at the Onset of the Arctic Spring Bloom. *Prog. Oceanogr.* 2024, 103224. <https://doi.org/10.1016/j.pocean.2024.103224>.

12 JF Ghiglione, LE Heimbürger-Boavida, M Fourquez, I Hough, et al. (2026). *Tara Polaris expeditions: seasonal and long-term contaminant monitoring in the changing central Arctic*. Elementa: Science of the Anthropocene. (hal-05466231)

My group also works on hydrothermal mercury emissions, specifically in the Mediterranean Sea, because they are the only direct source of natural mercury to the ocean and because they may contribute to the higher mercury levels and human exposure witnessed around the Mediterranean.¹³

HOW CAN WE REDUCE HUMAN EXPOSURE TO MERCURY?

Since 2013, the Minamata Convention on Mercury has been the main international framework for reducing human mercury exposure. Its goals include eliminating all uses of mercury, whether intentional (such as using mercury in industrial processes or products like light switches), or unintentional (such as the release of mercury during coal combustion), banning mercury exports destined for gold mining, and implementing pollution-control technologies. Article 22 of the Convention also mandates scientific assessments to measure its effectiveness.

Coastal populations of the Mediterranean, whose diet also traditionally contains a lot of fish, also exhibit high levels of mercury contamination

Researchers found that atmospheric mercury levels have decreased in the last 20 years,¹⁴ showcasing that it is possible to reduce our environmental impact through regulation and effective action. However, progress remains fragile. The atmospheric concentration of mercury is 450% higher than the natural level because of current and historical human activities.¹⁵ The reopening of coal-powered plants risks undoing recent gains, while major scientific gaps persist.

On an individual level, we can protect ourselves from mercury exposure by changing our dietary habits. Our own mercury emissions ultimately accumulate in ecosystems and return to us through the fish we eat. In response, health agencies, such as the ANSES,¹⁶ advise limiting the consumption of high mercury species (such as tuna or swordfish) for pregnant women and young children.¹⁷ Protecting biodiversity from human emissions is therefore not just an environmental goal: it is essential for protecting human health.

¹³ Torres-Rodriguez, N.; Yuan, J.; Petersen, S.; Dufour, A.; et al. Mercury Fluxes from Hydrothermal Venting at Mid-Ocean Ridges Constrained by Measurements. *Nat. Geosci.* 2024, 1–7. <https://doi.org/10.1038/s41561-023-01341-w>.

¹⁴ American Chemical Society (2025) Mercury levels in the atmosphere have decreased throughout the 21st century.

¹⁵ Minamata convention (2026) Minamata-Convention-booklet-Oct2024-EN.pdf.

¹⁶ The French National Agency on Sanitary Security.

¹⁷ Méthylmercure : un risque pour la santé en cas de consommation importante de poissons | Anses - Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail. [Methylmercury: A Health Risk Associated with High Fish Consumption | ANSES - French Agency for Food, Environmental and Occupational Health & Safety]

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*Fish contaminated with mercury caught next to a hydrothermal vent near Milos, Greece.
© Lars-Eric Heimbürger-Boavida*

Biological Invasions:

A Growing Burden on Health and Finances

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Recognized as one of the five major drivers of biodiversity change globally by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES),¹ biological invasions are a major and increasing challenge to biodiversity in today's world. In addition to numerous ecological impacts, biological invasions also profoundly affect human, animal, and plant health. The health consequences extend well beyond infectious diseases, which are often the focus for evaluations of the impacts of these invasions. They also impact environmental quality, overall wellbeing among exposed populations, and the resilience of the ecosystems concerned.² This article provides a summary of current knowledge concerning the health implications of biological invasions, with a particular emphasis on their multidimensional nature and possible solutions for limiting them.

INTRODUCTION

The term “biological invasion” is used to describe the process involving the intentional or unintentional transport or movement of a species outside its natural range by human activities, and its introduction to new regions where it may become established and spread.³ Species introduced to new regions through human activities are termed invasive alien species. Distinct from exotic species (also known as non-native species, referring to a species introduced to a region where not naturally present), an invasive alien species is a species that establishes a lasting presence, propagates and creates negative effects on biodiversity, ecosystems, and socioecological systems (i.e., the set of systems formed by reciprocal interactions between human societies and natural ecosystems).

Biological invasion is not an ad hoc event, it is a dynamic process that requires overcoming several successive barriers: transport to a new region, survival in the new environment, reproduction, then dispersion. At each of these stages, many introduced species fail and only a tiny proportion reach the invasive stage. But even though only 1% of all introduced species become invasive, the very large number of constantly introduced species produces a great many invasions around the world.⁴

BIOLOGICAL INVASIONS: A MAJOR CHALLENGE ON THE INCREASE

While species have always moved, the pace today is unprecedented. The acceleration and globalization of human activities means the number of introductions has sky-rocketed in recent decades, with around 200 new exotic species annually.⁴ Worldwide, there are over 37,000 exotic species listed (certainly an underestimate), with around 3,500 probably invasive in at least one region of the world. These are plants, animals and micro-organisms living on land, in freshwater, or in the sea. They come from every region and no country is spared. For example, we estimate that 7,000 to 10,000 marine species travel every day in ships' ballast water, and the US customs service alone intercepts over 230 exotic pests daily.

Since these invasions occur as a result of species being transported by human activities, globalization seems to act as a catalyst via identifiable vectors such as transport by sea, land (road and rail) or air, which are all growing rapidly.⁵ The strong growth in freight and passenger traffic naturally results in growth in the number of species introduced beyond their natural range. And climate breakdown is removing thermal

1 Ruckelshaus, M. H., Jackson, S. T., Mooney, H. A., Jacobs, K. L., Kassam, K. A. S., Arroyo, M. T., ... & Ouyang, Z. (2020). The IPBES global assessment: pathways to action. *Trends in Ecology & Evolution*, 35(5), 407-414.

2 Haubrock, P.J., Everts, T., Abreo, N.A.S., Bojko, J., Deklerck, V., et al. (2026), The impacts of biological invasions. *Biol Rev.* <https://doi.org/10.1002/brv.70124>.

3 IPBES (2023). Summary for Policymakers of the Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Roy, H. E., Pauchard, A., Stoett, P., Renard Truong, T., Bacher, S., Galil, B. S., Hulme, P. E., Ikeda, T., Sankaran, et al. (eds.). IPBES secretariat, Bonn, Germany. <https://doi.org/10.5281/zenodo.7430692>.

4 Seebens, H., Meyerson, L. A., Richardson, D. M., Lenzner, B., Tricarico, E., Courchamp, F., ... & Pyšek, P. (2025). Biological invasions: a global assessment of geographic distributions, long-term trends, and data gaps. *Biological Reviews*, 100(6), 2542-2583.

5 Turbelin, A. J., Diagne, C., Hudgins, E. J., Moodley, D., Kourantidou, M., Novoa, A., Haubrock, P.J., Bernery, C., Gozlan, R.E., Franics, R.A. & Courchamp, F. (2022). Introduction pathways of economically costly invasive alien species. *Biological Invasions*, 24(7), 2061-2079.



barriers that previously limited the establishment and expansion of introduced species, in turn encouraging new introductions that become invasions.⁶

From Asian hornets in France to rabbits in Australia, Japanese knotweed in North America to brown tree snakes on Guam and Nile perch in Africa, there are countless examples showing the diversity and impacts of invasive alien species, and the range of regions invaded. Recent global summaries provide clear proof that exotic micro-organisms, fungi, plants and animals have been introduced to every part of the world, including Antarctica and the most far-flung remote islands.^{1,3}

Biological invasions are considered one of the most serious drivers for loss of biodiversity and damage to ecosystems. They are involved in 60% of plant and animal extinctions recorded globally

BIOLOGICAL INVASIONS AND SOCIO-ECOLOGICAL SYSTEMS

In its most recent report, the IPBES puts forward a standardized classification for the impacts of biological invasions, encompassing threats to nature, nature's contributions to people, and quality of life.³ Health impacts can be considered to cut across all these different categories, as the concept of health is now broader and more inclusive, no longer limited to human health alone. This approach, often referred to as One Health, highlights the close interdependence between the health of the various components within our socio-ecological systems: humans, animals, plants, and their environments. In this framework,

biological invasions would appear to be a major source of multiple health risks.

ECOSYSTEMS DISTURBED, BIODIVERSITY ALTERED

Biological invasions are considered one of the most serious drivers for loss of biodiversity and damage to ecosystems. They are involved in 60% of plant and animal extinctions recorded globally. In 16% of cases, invasions are in fact the sole cause of species disappearance, particularly on islands, and over 1,200 local extinctions as a result of invasions have already been documented. However, species extinction is simply the manifestation of the most irreversible of a set of 19 types of ecological impacts, running from physiological modifications affecting individuals to genetic annihilation via hybridization right up to complete ecosystem impairment.⁷

Biological invasions also lead to behavioral changes in native individuals, the natural range of native species, and even physical changes to habitat. Originally from South America, coypu alter the structure of river banks in France. The dense, shallow roots of the Miconia tree (also called Green Cancer) cause landslides on Tahiti, where it covers 60-70% of the island. And the yellow crazy ant destroys populations of forest-floor land crabs on Kiritimati, leading to a complete change in forest type. Invasions also create changes in water quality, such as the mussel invasion of the American Great Lakes, and soil composition (invasive earthworms in North America alter the nature of the soil and consequently the make-up of plant species that grow in it). Furthermore, invasions can modify natural



Young Asian hornet exiting its cocoon.
© Dominique Fenot

⁶ Thielges, D. W., Conn, D. B., Cuthbert, R. N., Dunn, A. M., Jolma, E. R., Hopkins, M. C., ... & Kočovský, P. M. (2025). Integrating climate change, biological invasions, and infectious wildlife diseases. *Frontiers in Ecology and the Environment*, 23(6), e2849.

⁷ Carneiro, L., Leroy, B., Capinha, C., Bradshaw, C. J., Bertolino, S., Catford, J. A., ... & Courchamp, F. (2025). Typology of the ecological impacts of biological invasions. *Trends in Ecology & Evolution*, 40(6), 563-574.



cycles for nutrients, water and fire. Rats kill seabirds on islands they invade, causing a fall in nitrogen from guano that fertilizes waters around coral reefs, whilst cogongrass (or speargrass) creates highly combustible ground cover that increases the frequency and intensity of fires in southeast Asia.

MULTIPLE PUBLIC HEALTH CHALLENGES

In addition to ecological disruption, biological invasions also pose real public health challenges. By altering interactions between species, habitats and environmental conditions, they create contexts favorable to emerging or increased health risks, with direct impacts on human and animal populations.

Transmission of pathogenic agents.⁸ Certain invasive alien species play a central role in the circulation of infectious agents.⁹ They can act as “biological reservoirs” providing long-term hosts to pathogens (viruses, bacteria or parasites) without necessarily developing any pathologies; “intermediate hosts” vital to the lifecycle of certain parasites; “vectors” able to transmit a pathogenic agent from host to host, usually by stinging; or “amplifiers” that increase pathogenic circulation (for example, by altering habitats) without directly transmitting them. There are countless well-known examples of each of these situations, but the most emblematic is probably the tiger mosquito: native to southeast Asia, it has spread around the world thanks to climate change and human influence on habitat. It can transmit viruses responsible for diseases such as dengue fever, chikungunya and yellow fever to humans.

The most emblematic is probably the tiger mosquito: native to southeast Asia, it has spread around the world [...]. It can transmit viruses responsible for diseases such as dengue fever, chikungunya and yellow fever to humans

Physical and physiological harms. Biological invasions can also impact human health via non-infectious mechanisms.⁷ Certain species produce potentially fatal toxins, such as sunfish that are invasive in the Mediterranean and can cause severe tetrodotoxin poisoning if eaten. Others can trigger severe allergic reactions. Common ragweed, native to North America, produces pollen that is a strong allergen and impacts 33 million people in Europe every year, aggravating asthma and respiratory illnesses. This could rise to as many as

77 million people by 2050 as climate change increases the plant's range. Physical injuries are another potential health impact. Fire ants, native to South America and recently detected in Europe, have painful stings that can trigger a severe allergic reaction or even anaphylactic shock. It is estimated that over 14 million people are stung each year in the USA, with several hundred thousand requiring medical treatment.

Food insecurity. Biological invasions can impact the availability, accessibility and quality of food resources.¹⁰ Certain invasive alien species directly damage farm crops, food stores, and fish stocks, whereas others act as rodents or vectors for diseases in cultivated plants. These impacts lead to reduced yields, greater instability in productive systems and, in the longer term, a reduction in the diversity of food resources. This disruption can also increase dependency on chemical inputs, with indirect knock-on effects on human and environmental health, as well as increasing vulnerability among the most exposed communities, particularly in places already facing severe socio-economic disadvantages. The fall armyworm perfectly symbolizes these challenges. Native to the Americas, it took less than five years for this pest insect to spread to over 80 countries in Africa, Asia and Oceania where it attacks more than 350 plant species, including staples such as maize, sorghum and rice. Its spread directly threatens food security for over 100 million people.

Mental health and wellbeing. Finally, where invasions cause lasting change to local land uses, resources or means of subsistence, they can generate stress, anxiety, or a sense of insecurity and loss of control.¹¹ The water primrose is a typical example. Native to South America, this aquatic plant is invading countless bodies of water and wetlands in Europe. Ecological impacts notwithstanding, the plant's dense proliferation prevents recreational activities such as fishing and swimming, profoundly alters the landscape, and modifies the relationship between residents and their environment. For some people, these transformations bring a feeling of powerlessness and a diminishing of ties with their local area. Although as-yet insufficiently studied, psychological factors are nonetheless a real part of the challenges to public health posed by biological invasions, underlining the need for an integrated approach to health.

8 The scientific community continues to debate whether certain pathogenic agents should be classified as invasive alien species. The debate raises various difficult questions, particularly regarding how to define an organism as exotic, determining the natural range of a pathogen that circulates freely between several hosts, and whether to classify a virus as a living organism.

9 Mahon, M. B., Sack, A., Aleuy, O. A., Barbera, C., Brown, E., Buelow, H., ... & Rohr, J. R. (2024). A meta-analysis on global change drivers and the risk of infectious disease. *Nature*, 629(8013), 830-836.

10 Lenzner, B., García-Rodríguez, A., Colling, G., Dullinger, S., Fugger, J., Glaser, M., ... & Essl, F. (2024). The neglected importance of managing biological invasions for sustainable development. *People and Nature*, 6(5), 1804-1811.

11 Jones, B. A. (2017). Invasive species impacts on human well-being using the life satisfaction index. *Ecological Economics*, 134, 250-257.





Imported red fire ant.
© Aoyama Y

FINANCIAL COST AS A UNIVERSAL METRIC

Despite the scale of the impacts of biological invasions, the phenomenon remains largely overlooked on the international political level. Using financial cost as a means of alerting the general public and policymakers provides a concrete and universal unit of measure: impacts become tangible, instantly understandable and comparable when expressed in monetary terms. This is the reasoning behind the creation of the InvaCost international research network.¹² The consortium of over 100 scientists works on an evolving public database that compiles thousands of estimates of the financial cost of biological invasions. Using a standardized methodology, InvaCost makes it possible to analyze costs on different scales: regional, taxonomical and social. It should be stressed that these costs do not represent a category of impacts in their own right. Instead, they represent the quantified translation of certain ecological, health and social harmful effects (agricultural losses, healthcare costs, damage to infrastructure, etc.), and the public or private expenditure committed to preventing, managing or attenuating biological invasions.

Their work has produced striking results. The cost exceeded 423 billion dollars in 2019 alone, over 80 times the combined budgets of the World Health Organization and the United Nations for the same period. More worryingly, the costs are growing exponentially, rising fourfold each decade. Despite these eye-popping figures, today's

estimates are still under-evaluated and represent the tip of the iceberg of the true financial cost of biological invasions around the world.

WHAT ARE THE POSSIBLE SOLUTIONS?

The IPBES proposes an integrated governance framework for effective management of biological invasions.¹³ The framework identifies three complementary actions: managing introduction and propagation pathways, managing invasive alien species themselves, and protecting or restoring invaded ecosystems. The literature all reaches the same clear conclusion: prevention is the most efficient and cost-effective strategy for combating biological invasions. Biosecurity measures based on an analysis of risks before, during and after an organism is introduced make it possible to intercept exotic species before they become durably established. Countries such as New Zealand and Australia have strict biosecurity protocols that apply to tourists and international trade equally. Although seemingly costly, these measures represent a far lower investment than the sums involved in the long-term management of established invasions. The cost of inaction during the several years it usually takes for a governance system to design and implement a project to combat an invasion can run to millions of dollars, as shown by a recent study of the tiger mosquito invasion.¹⁴

¹³ IPBES 2023, Summary for policymakers of the Thematic Assessment Report of Invasive Alien Species and their Control, figure SPM.3.

¹⁴ Ahmed, D.A., Hudgins, E.J., Cuthbert, R.N., Kourantidou, M., Diagne, C., Haubrock, P.J., Leung, B., Liu, C., Leroy, B., Petrovskii, S., Beidas, A., Courchamp, F. 2022. Managing biological invasions: the cost of inaction. Biological Invasions. 10.1007/s10530-022-02755-0.

¹² <https://invacost.fr/en/accueil/>



To take fire ants as an example: they wreak havoc in Australia and North America, with their very painful bites causing hundreds of thousands of Americans to seek medical treatment every year. It is estimated that combatting the ants costs several billion dollars annually. Invasive colonies have already been identified by the public on three occasions in New Zealand thanks to awareness-raising programs, and they were successfully destroyed in a matter of days. They were identified for the first time in Europe a few years ago (2022 in Sicily), but the lack of preventive measures, public awareness, and emergency response plans means invasive colonies are currently continuing to spread.

The literature all reaches the same clear conclusion: prevention is the most efficient and cost-effective strategy for combating biological invasions

Where prevention fails, early detection and rapid response become critical. At a more advanced stage, countermeasures are generally limited to confinement and efforts to control the population or slow the invasion, with variable results and far higher costs. Although a very large number of programs to eliminate invasive alien species have been run successfully around the world, they have almost without exception taken place on islands with a clearly defined land mass, often relatively simplified ecosystems, and relatively low human population. A renowned counter-example is the spectacularly effective eradication of the coypu in the 1980s from the whole of Great Britain via a mass trapping program carried out on a vast spatial and temporal scale. This shows that ambitious programs can be run successfully even under theoretically suboptimal conditions.

Restoring degraded ecosystems and boosting their resilience is another vital measure for limiting the health and financial impacts of biological invasions. Combating biological invasions also requires sustained effort in terms of education and awareness-raising. Teaching economic actors, policymakers and the general

public about the risks associated with the introduction of exotic species is the pre-requisite for taking effective action. However, current regulatory frameworks are still largely incapable of tackling the rapid rise in biological invasions.

Stricter regulations, rapid updates to lists of at-risk species and the adoption of more proactive approaches such as white lists, where only species proven to

be non-problematic are permitted entry to a territory, are all promising avenues for the future. And since biological invasions recognize no borders, integrated governance and stronger international cooperation are indispensable. This means that support for countries with limited prevention and management capacities is a priority in developing efficient responses to what is a global threat.

CONCLUSION

Biological invasions currently represent a major threat to the health of socio-ecological systems and, by definition, human wellbeing. Their impacts, whether on ecology, health or the economy, are multiple, interconnected and often underestimated. While monetizing these impacts can render the phenomenon more tangible, it does not alone reflect the true scale of the multiple disturbances caused. Faced with the increasing number of biological invasions in a time of global change, the challenge is more than simply scientific, it is also profoundly societal and cultural. Preventing introductions, acting fast, restoring the integrity of ecosystems, and bolstering international cooperation are all vital measures for limiting the associated health risks. Better understanding and communication about these challenges is essential to lasting protection for human, animal and environmental health in today's world.

About the authors

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Franck Courchamp is an ecologist and research director at the National Center for Scientific Research (CNRS) who studies the effects of human activities on biodiversity, with a special focus on biological invasions. He works primarily on macro-ecological, broad spatial and taxonomic scales, for example, looking at all invasive animal species in a particular continent. He has spent several years creating summaries of the ecological and financial impacts of biological invasions. He heads the AXA Research Chair on Invasion Biology at Université Paris Saclay.



The extent of the problems caused by invasive alien species

Extinctions

Contributed to
60%

Invasive alien species have contributed solely or alongside other drivers of change to 60% of recorded **global extinctions**, of which 90% occurred on islands^a

Economic cost

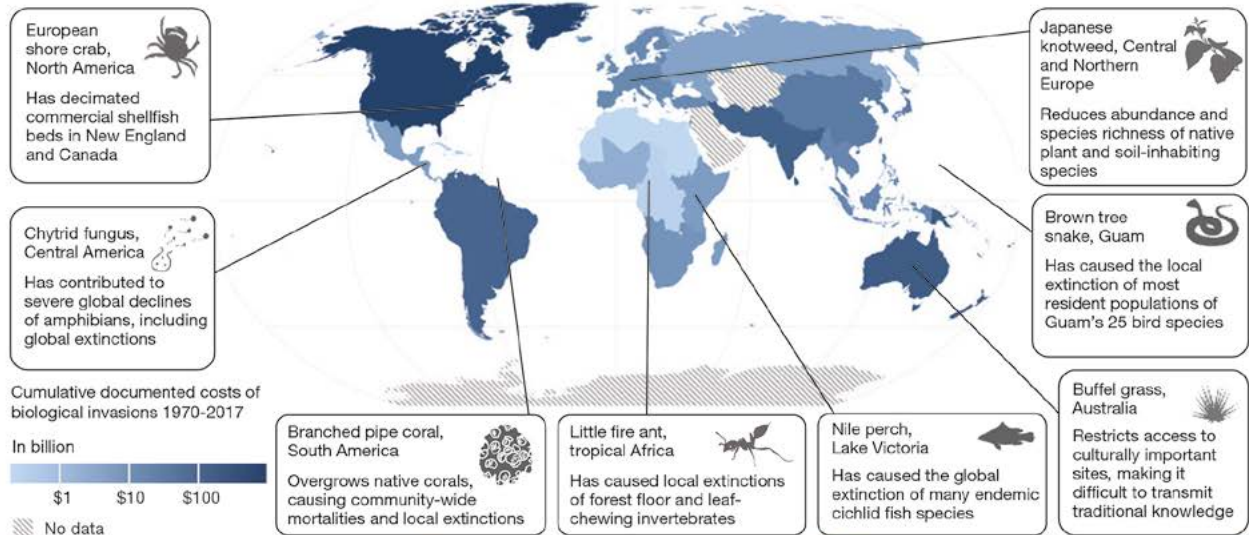
X 4
every decade

The **economic cost** of biological invasions has increased fourfold every decade^b

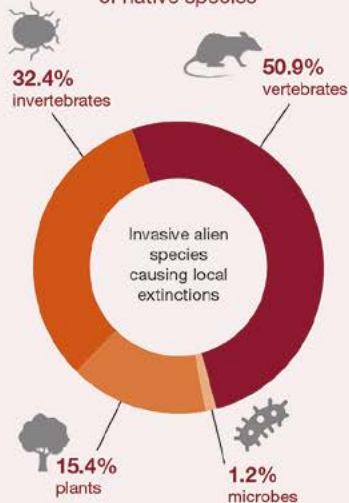
Good quality of life

85%

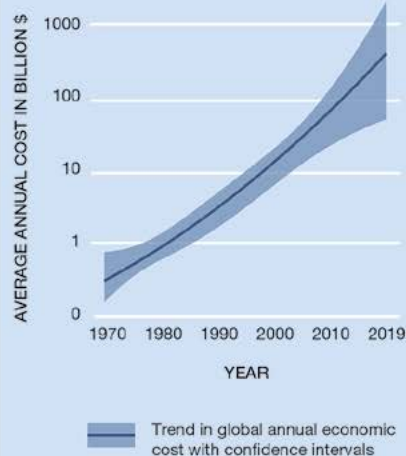
Invasive alien species have a negative impact on **good quality of life** in 85% of cases^c



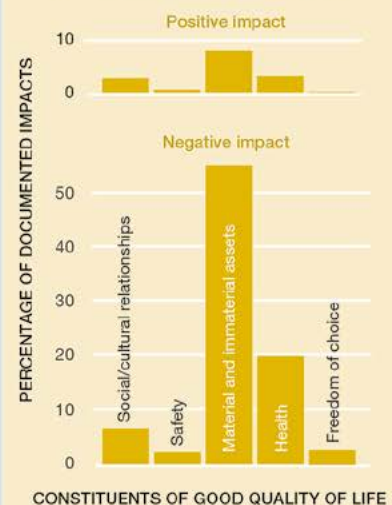
218 invasive alien species have caused 1,215 **local extinctions** of native species



In 2019, the estimated global annual **economic cost** of biological invasions was \$423 billion



Known impact of invasive alien species on **good quality of life**



Illustrative examples of the impacts of invasive alien species on native species (red, lefthand column), the economy (blue, central column) and quality of life (yellow, righthand column). The map in the center shows the documented cumulative economic cost of invasive alien species per IPBES subregion from 1970 to 2017 (IPBES¹³, 2023).

Community-Based Biodiversity Conservation in Africa:

Maximizing Rural Development Benefits While Minimizing Infectious Disease Risks

Professor Gerard Killeen

AXA Research Chair in Applied Pathogen Ecology, University College Cork, Republic of Ireland

Most of the world's biological carbon sequestration capacity and surviving biodiversity lies in the forests, woodlands, grasslands, and floodplains of low and middle-income tropical countries.¹ Unfortunately, the ongoing degradation of these exceptionally biodiverse natural ecosystems has accelerated the emergence of novel pathogens that threaten us all.² The rural communities living at the fringes of these biodiverse areas, where the risks of malaria, zoonoses and emerging infections are greatly exacerbated, are also among the most socioeconomically disadvantaged in the world.³ "Fortress conservation" strategies originating from the colonial era, which protect natural areas by rigorously excluding people from them, have often denied communities any meaningful benefit from the biodiversity they live alongside, while nevertheless exposing them to dangerous wild animals and infectious diseases.

In contrast, several success stories of community-based conservation schemes across Africa, based on tourism and climate finance, and our own recent experiences working with a community-run Wildlife Management Area in southern Tanzania point the way forward.⁴ They illustrate how devolved conservation initiatives may enable rural African communities to simultaneously tackle extreme local poverty and local infectious disease burden, while at the same time protecting the whole world against pandemics, climate change and loss of our collective natural heritage.

INTRODUCTION

Most of us from high income countries who primarily interact with spectacular tropical ecosystems through our televisions, tend to think of biodiversity in overwhelmingly positive terms. It looks fabulous, stimulates our imaginations and inspires us to protect our planet while there is still so much worth saving. Beyond the obvious appeal to our innate biophilia, the great forests, swamps, woodlands and grasslands scattered around the warm girdle of our world also provide us with invaluable ecosystem services.

However, living with tropical biodiversity is associated with a diversity of hazards, especially on the continent we all originate from. Africa is not only home to most of the world's surviving large mammals, including our nearest living relatives, but also some extraordinarily efficient malaria vector mosquitoes that have evolved along with us for over a million years. It's often hard to live with African biodiversity on a resident basis when it destroys your crops, tramples your neighbourhood, threatens to eat you, kills your livestock or makes you ill.

¹ Strassburg *et al.* (2020) Global priority areas for ecosystem restoration. *Nature*. 586:724-9. <https://doi.org/10.1038/s41586-020-2784-9>.

² Wilkinson *et al.* (2018) Habitat fragmentation, biodiversity loss and the risk of novel infectious disease emergence. *J R Soc Interface*. 15: 20180403. <https://doi.org/10.1098/rsif.2018.0403>; Mahon *et al.* (2024) A meta-analysis on global change drivers and the risk of infectious disease. *Nature*. 629:830-6. <https://doi.org/10.1038/s41586-024-07380-6>; Schmeller, D.S., Courchamp, F. & Killeen, G. Biodiversity loss, emerging pathogens and human health risks. *Biodivers Conserv* 29, 3095–3102 (2020). <https://doi.org/10.1007/s10531-020-02021-6>.

³ Sokolow *et al.* (2022) Ecological and socioeconomic factors associated with the human burden of environmentally mediated pathogens: a global analysis. *Lancet Planet Health*. 6:e870-9. [https://doi.org/10.1016/s2542-5196\(22\)00248-0](https://doi.org/10.1016/s2542-5196(22)00248-0).

⁴ Dressler *et al.* (2010) From hope to crisis and back again? A critical history of the global CBNRM narrative. *Environmental Conservation*. 37: 5-15. <https://doi.org/10.1017/S0376892910000044>; Brooks, Waylen & Mulder (2013). Assessing community-based conservation projects: A systematic review and multilevel analysis of attitudinal, behavioral, ecological, and economic outcomes. *Environmental Evidence*. 2: 2. <https://doi.org/10.1186/2047-2382-2-2>.





Examples of tree-house platforms built above rice fields, where farmers sleep to protect themselves against large mammals but are vulnerable to mosquitoes due to the impossibility of using bed nets⁵.

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THE CHALLENGES OF LIVING WITH BIODIVERSITY AND ZONOTIC ILLNESSES

Although the most readily perceived dangers in tropical ecosystems are visibly obvious, ranging in size from venomous scorpions to large carnivores to even larger herbivores, the biggest threats are either inconspicuous or outright invisible. Although each different animal species carries its own set of viruses, parasites and pathogenic bacteria, many of these can readily infect human beings either directly, or via the domesticated animals so many of us necessarily live in close contact with.⁶ Such zoonoses, meaning infection of humans that originate from animals, are often highly virulent, like bird flu or rabies.

For those of us living in temperate regions with relatively modest biodiversity and strong public health systems, examples we might have heard of include bovine tuberculosis, Lyme's disease (transmitted by ticks) or intestinal worms. Zoonoses are now relatively rare in

Haemorrhagic fevers typically occur in places where humanity is gnawing away at natural ecosystems in an unregulated manner

high income countries because our interactions with animals are so limited and carefully managed. Indeed, the remaining occasional cases of previously common zoonoses that do occur in wealthy temperate regions are often linked to livelihoods or pastimes, such as livestock rearing, pet ownership or hiking, that involve obvious exposure to animals, their excreta or the arthropods that feed on them.

In poorer tropical countries, however, zoonoses commonly arise from widespread contact with domesticated and feral animals, poor sanitation, limited health services and proliferation of diverse invertebrates that act as “bridge vectors” by ferrying unpleasant infections from one host species to another.⁴ The latter issue is particularly troublesome in the tropics because high temperatures and invertebrate species richness combine to facilitate robust transmission of correspondingly biodiverse vector-borne diseases. Rather than merely mechanically carrying pathogens around as passive cargo, most of these mosquitoes, ticks and snails act as their intermediate or even primary hosts, in which they systematically multiply before onward transmission to the next victim. All these invertebrate vectors are cold-blooded, so the process of pathogen incubation within their bodies relies on high ambient temperatures, making warm tropical weather as much a curse as a blessing.

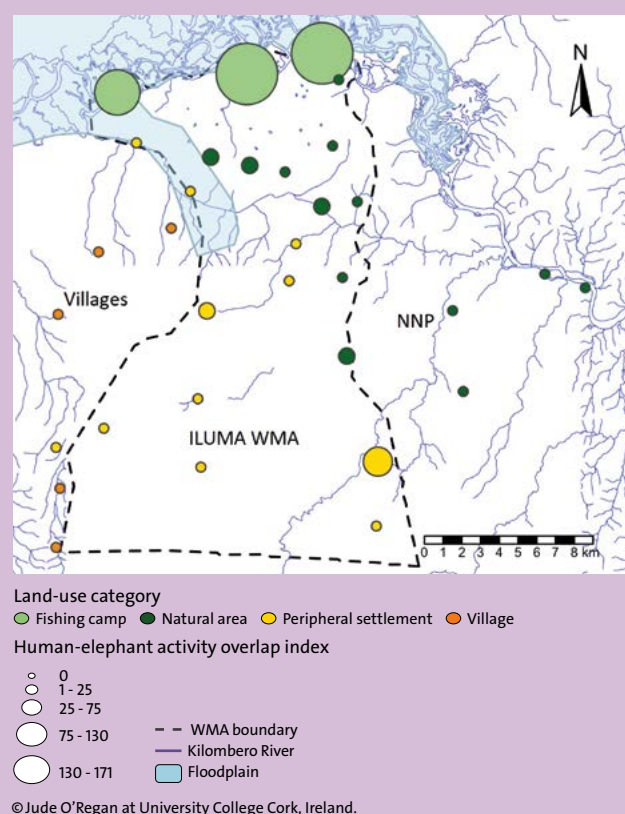
Most people across the tropics live in heavily converted landscapes, like settlements and farms where they are largely exposed to well-known pathogens of domesticated animals, for which treatment and control interventions are usually available. However, people who live in or near well-conserved natural tropical ecosystems, may sometimes acquire previously unknown pathogens from any of the diverse wild birds and mammals living nearby.⁶ For example, some of the fishing communities we work with in southern Tanzania, who act as resident custodians for the beautiful riverbank gallery forests their villages are sited within,⁷ share their lives with over 400 different birds and at least 40 readily identifiable mammals, as well as innumerable species of rodents and bats that regularly enter their homes in search of food and shelter.

⁵ Kavishe et al. (2025) Persistence of residual *Anopheles gambiae* populations associated with frontier human settlements and nocturnal livelihood-related activities at the fringes of a large conservation area in southern Tanzania. bioRxiv. 2025:2025.10.24.684313. <https://doi.org/10.1101/2025.10.24.684313>.

⁶ Keesing et al. (2010) Impacts of biodiversity on the emergence and transmission of infectious diseases. *Nature*. 468: 647-52. <https://doi.org/10.1038/nature09575>.

⁷ Duggan et al. (2026) An effective model for community-based conservation around authorised fishing settlements inside a devolved Wildlife Management Area in southern Tanzania. *Conserv Sci Practice*, In press; <https://doi.org/10.1111/csp2.70290>.

Map of overlapping elephant and human activities in and around the Ifakara-Lupiro-Man'gula (ILUMA) Wildlife Management Area (WMA) in southern Tanzania, illustrating how the only three authorized fishing camps along the Kilombero River in the north act as hotspots for risky encounters



The fully authorized and judiciously regulated fishing village is sited downstream from the largest inland delta in east Africa, where Rift Valley Fever is a remarkably common zoonosis among cattle herders living along the fringes of the Kilombero Valley.⁸ While the exact wild mammal species that act as reservoir hosts for Rift Valley Fever remain to be identified, it is clear that this virus spills over into livestock wherever they mingle with wildlife during floods that allow particular types of *Aedes* mosquitoes to breed and start moving it around between hosts.⁹ While humans do sometimes acquire this quite severe infection directly from mosquitoes,

Perhaps the most encouraging innovation is the growing number of community-based conservation initiatives successfully tapping into global climate finance

they usually do so through routine exposure to livestock body fluids like milk or blood.¹⁰ The epidemiology of Rift Valley Fever illustrates nicely how an important zoonosis can exhibit quite distinct transmission routes through wildlife, livestock and people that all link up right at the most blurred interfaces between humanity and wilderness,⁹ causing sporadic surges of illness that can be lethal for humans, and have devastating economic consequences by decimating livestock herds: over 100,000 sheep died in the 1951 South African RVF outbreak, for example.¹⁰

In similarly biodiversity-rich forests of neighbouring countries to the west and northwest, the most dangerous pathogens of all lurk within the stunning array of bat species that migrate seasonally around Africa each year: filoviruses like Ebola and Marburg cause catastrophic internal and external bleeding that usually ends in death without decisive medical intervention. Major outbreaks of such haemorrhagic fevers typically occur in places where humanity is gnawing away at natural ecosystems in an unregulated manner, forcing people and animals into unusually close contact.¹¹ Bats displaced from disturbed forests often find new homes roosting under people's roofs and feeding on their fruit trees, creating obvious opportunities for exposure to dung and saliva. While the same bats also visit Tanzania, there had never been an Ebola or Marburg outbreak there until very recently because spillover transmission tends to occur where they settle down to give birth.¹² Newborn bat pups lack any prior exposure or acquired immunity to these viruses, so they shed much greater numbers of virus particles than mature adults. Disturbingly, we have suddenly started experiencing outbreaks of Marburg virus in northwest Tanzania over recent years as climate and bat migrations now start to shift. Tanzania and its neighbours know from

experience how to decisively contain and eliminate haemorrhagic fever outbreaks but that's an obligation those of us living in lower biodiversity temperate climates are lucky to be spared. Next time you hear of an Ebola or Marburg outbreak somewhere in Africa, just remember that those countries are paying the price for

living with the biodiversity we all treasure as part of our collective natural heritage and global ecosystem services.

8 Sumaye *et al.* (2015) Inter-epidemic acquisition of Rift Valley fever virus in humans in Tanzania. *PLoS Negl Trop Dis.* 2015;9(2):e0003536. <https://doi.org/10.1371/journal.pntd.0003536>.

9 Walsh, de Smalen & Mor (2017) Wetlands, wild Bovidae species richness and sheep density delineate risk of Rift Valley fever outbreaks in the African continent and Arabian Peninsula. *PLoS Negl Trop Dis.* 11:e0005756. <https://doi.org/10.1371/journal.pntd.0005756>.

10 Nanyingi *et al.* (2015) A systematic review of Rift Valley Fever epidemiology 1931–2014. *Infect Ecol Epidemiology.* 5:28024. <https://doi.org/10.3402/iee.v5.28024>.

11 Wilkinson *et al.* (2018) Habitat fragmentation, biodiversity loss and the risk of novel infectious disease emergence. *J R Soc Interface.* 15: 20180403. <https://doi.org/10.1098/rsif.2018.0403>.

12 Reed Hranac *et al.* (2019) Predicting Ebola virus disease risk and the role of African bat birthing. *Epidemics.* 29:100366. doi: <https://doi.org/10.1016/j.epidem.2019.100366>.





The authorized fishing camp of Mikeregembe, the easternmost of the three elephant-human encounter risk hot spots in the above map of the Ifakara-Lupiro-Man'gula (ILUMA) Wildlife Management Area (WMA) in southern Tanzania.
© Gerard Killeen

However, dangerously close contact between diverse animal species can also occur far away from inappropriately exploited natural ecosystems, in the urban wet markets where exotic animals are so often trafficked. As we know from COVID-19,¹³ viruses given the opportunity to bounce around between many different mammalian host species and then into large, high density human populations can rapidly spread beyond local outbreaks, to cause regional epidemics and then global pandemics. No harm would have come to anyone if the trafficked animals involved had simply been left undisturbed in their natural habitats. Again, the lesson to be learned is not that biodiversity *per se* is a problem but rather how we manage our relationship with it. We need to respect the natural hard boundaries between species that have had negligible contact with each other over the millennia before we started flippantly mixing and matching diverse pathogens and host species in such a dangerously unmanaged way.

RE-ENFORCING NATURAL BOUNDARIES BETWEEN ANIMAL SPECIES AND THEIR PATHOGENS THROUGH EFFECTIVE ECOSYSTEM CONSERVATION

It is therefore essential that biodiversity-rich conservation areas are not only delineated on maps but also rigorously protected in practice. In Africa, risks of novel pathogen emergence have been clearly mapped out onto the badly frayed edges of threatened natural forest ecosystems, rather than the fully intact depths of those spectacularly biodiverse jungles.¹¹ One quite virulent zoonosis that accounts for about a quarter of all fevers across tropical

Asia,¹⁴ is so closely associated with patchy degradation of forests into scrubland mosaics that it is named accordingly: scrub typhus is caused by a rickettsial bacterium, for which rodent reservoir hosts and chigger mites that act as vectors proliferate in mixed vegetation cover, especially patchworks of forest, thicket, woodland and grass.¹⁵ The diverse menagerie that spawned COVID-19 were brought together in Wuhan from scattered wilderness areas far away to the south, which clearly could have been better protected against poachers and traffickers.

Patrolling and protecting natural ecosystems is expensive, so all conservation areas need sufficient income to be sustainable. Sadly, most of Tanzania's 21 excellent national parks receive too few visitors to break even, so those losses are necessarily borne by national taxpayers. While Tanzania has made great strides towards attracting more tourists, it will still take many years before they all become consistently self-sufficient in financial terms. And even though they collectively encompass almost 100,000 km² of protected land, that is still not enough to conserve entire functional ecosystems for viable populations of large mammals that may occur at very low densities and/or migrate over vast distances.

Tanzania therefore wraps the fringes of its great parks and reserves with other kinds of conservation areas, an increasing number of which are now managed in a devolved manner by local communities. Tanzania has authorized 22 community-based authorities to run Wildlife Management Areas (WMAs), using an excellent

¹³ Worobey *et al.* (2021) Dissecting the early COVID-19 cases in Wuhan. *Science*. 374:1202-4. <https://doi.org/10.1126/science.abm4454>; Xiao *et al.* (2021) Animal sales from Wuhan wet markets immediately prior to the COVID-19 pandemic <https://doi.org/10.1038/s41598-021-91470-2>.

¹⁴ Dasgupta *et al.* Global seroprevalence of scrub typhus: a systematic review and meta-analysis. *Sci Rep*. 2024 May 13;14(1):10895. <https://doi.org/10.1038/s41598-024-61555-9>.

¹⁵ Han *et al.* Current and Future Projection of Scrub Typhus Risk Related to Land Use Change in China. *Geohealth*. 2025 Sep 14;9(9):e2024GH001203. <https://doi.org/10.1029/2024gh001203>.





The pangolin is the most trafficked wild animal in the world and the intermediate host through which bat beta-coronaviruses are thought to have evolved into COVID-19¹⁶ in and en route to the cramped, inhumane conditions of the Hunan wet market in Wuhan.¹³ This photograph is of an Indian pangolin (*Manis crassicaudata*) rescued from the live animal trade in western Pakistan.¹⁷

© Dr. Sayantani M. Basak at University College Cork, Ireland and Dr. Tariq Ahmad at Northeast Forestry University, China

legal framework that democratically empowers local people as owners of such decentralized conservation initiatives, while also maintaining essential government oversight and support.¹⁸ These locally run conservation areas are intended to act as buffer zones for the neighbouring large parks and reserves, while also allowing the communities who collectively contributed their village lands to leverage socioeconomic benefits from the biodiversity they commit to protect. Some of these WMAs, like Burunge, have already achieved great success based on conventional tourism as their primary source of income, delivering net surpluses that pay for improved community services through schools, clinics and co-operatives.¹⁹ Most, however, have struggled to leverage sufficient income,²⁰ which is why new income streams are now being developed, the most exciting of which is climate finance (eg. <https://carbontanzania.com/> and <https://reforestafrica.com/>).

16 Yang *et al.* (2023) The species coalescent indicates possible bat and pangolin origins of the COVID-19 pandemic. *Sci Rep* 13: 5571. <https://doi.org/10.1038/s41598-023-32622-4>.

17 Ahmad *et al.* (2026) Exploring Habitat Preferences, Suitability, and Illegal Trade Routes of Indian Pangolins in Western Pakistan: Implications for Conservation. *Ecology and Evolution* 16: e72610. <https://doi.org/10.1002/ece3.72610>.

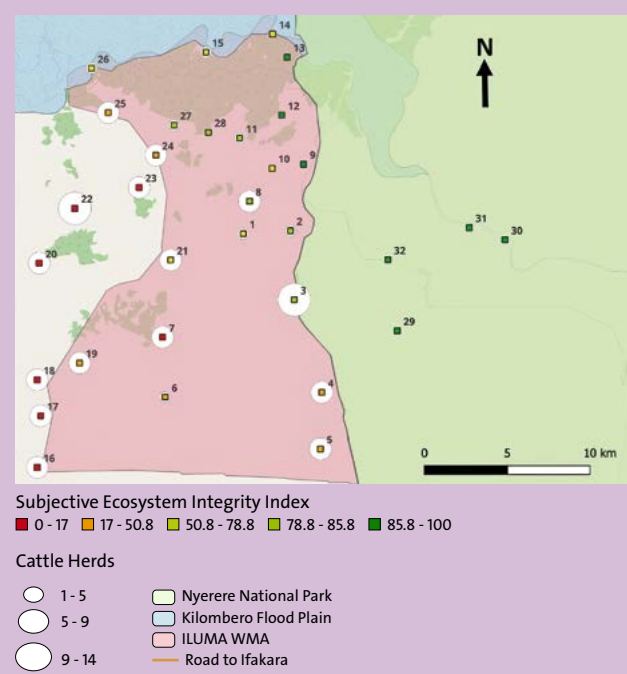
18 Wilfred (2010) Towards sustainable Wildlife Management Areas in Tanzania. *Trop Conserv Sci.* 3:103-16. <https://doi.org/10.1177/194008291000300102>; Government of Tanzania (2023) National Wildlife Management Area Strategy (2023-2033).

19 Kisingo & Kideghesho (2020) Community Governance of Wildlife Resources: Implications for Conservation, Livelihood, and Improvement in Democratic Space. In: Durrant *et al.* (eds). *Protected Areas in Northern Tanzania: Local Communities, Land Use Change, and Management Challenges*. Cham: Springer International Publishing; p. 113-20.

20 Bluwstein *et al.* (2018) A quasi-experimental study of impacts of Tanzania's wildlife management areas on rural livelihoods and wealth. *Scientific Data.* 5: 180087. <https://doi.org/10.1038/sdata.2018.87>.

Our own experiences with the Ifakara-Lupiro-Mang'ula (ILUMA) Wildlife Management Area clearly illustrate how underdeveloped business models and inadequate income streams result in rampant encroachment²¹ and obvious exacerbation of zoonotic disease risks. Without sufficient income to pay for frequent patrols by Village Game Scouts, illegal cattle herding deep within supposedly protected forest areas is common²² and this is exactly where hot spots of Rift Valley Fever transmission occur in close association with this specific livelihood.⁹

Unauthorized cattle herding and associated impact upon natural ecosystem integrity in the Ifakara-Lupiro-Mang'ula (ILUMA) Wildlife Management Area adjacent to Nyerere National Park⁷



Of particular concern is not only where such unauthorized encroachment occurs, but also the way in which those involved live so fully exposed to all the rich biodiversity around them, a known risk factor of zoonotic illness in such communities.²³ While legal visitors to the WMA typically wear boots, sleep in tents and bring enough equipment with them to maintain good camp hygiene,

21 Tarimo *et al.* (2025) The Role of Resident Custodian Communities in Devolved Forest Conservation: Lessons from a retrospective, mixed-method observational study of the Ifakara-Lupiro-Mang'ula Wildlife Management Area in Southern Tanzania. <https://doi.org/10.1101/2025.10.20.683348>.

22 Tarimo *et al.* (2025) Stakeholder perspectives on the effectiveness of the Ifakara-Lupiro-Mang'ula wildlife management area in Southern Tanzania. *Environmental Challenges.* 20:101214. <https://doi.org/10.1016/j.envc.2025.101214>.

23 Salerno *et al.* (2017) Human-Wildlife Interactions Predict Febrile Illness in Park Landscapes of Western Uganda. *Ecohealth.* 14: 675-90. <https://doi.org/10.1007/s10393-017-1286-1>; Sokolow *et al.* (2022) Ecological and socioeconomic factors associated with the human burden of environmentally mediated pathogens: a global analysis. *Lancet Planet Health.* 6: e870-9. [https://doi.org/10.1016/s2542-5196\(22\)00248-0](https://doi.org/10.1016/s2542-5196(22)00248-0).



secretive charcoal burners, meat poachers and timber harvesters never bring anything that they cannot afford to leave behind at the first sign of trouble with the law. Their covert camps are therefore minimalistic, leaving them badly exposed to the natural forest fauna, ranging from rodents scurrying over their utensils and nibbling at their food, to bats roosting right over them as they sleep, not to mention all the mosquitoes and large carnivores that can attack them while they sleep.



Minimalist covert camps that unauthorized charcoal burners, meat poachers and timber harvesters sleep in when they encroach on poorly protected conservation areas like the ILUMA WMA.
© Gerard Killeen

EMERGING EXAMPLES OF SUCCESS THAT EMPOWER LOCAL COMMUNITIES, PROTECT BIODIVERSITY, MITIGATE AGAINST CLIMATE CHANGE AND PROTECT US ALL AGAINST PANDEMICS

Fortunately, most of these risks can be robustly mitigated with emerging solutions to not only fund the routine enforcement of the conservation regulations but also the socioeconomic development processes that incentivize communities and protect them against such health risks. While some WMAs have made a success out of conventional photographic, hunting and fishing tourism, perhaps the most encouraging innovation is the growing number of community-based conservation initiatives successfully tapping into global climate finance. If you would like to mitigate your carbon footprint in a constructive way, The *Carbon Tanzania* and *Reforest Africa* websites provide many opportunities to contribute to the protection of forests that might otherwise disappear, while simultaneously investing in the socioeconomic empowerment of some highly disadvantaged rural African communities.

Taking the communities that have accessed the global carbon finance market through Carbon Tanzania as just one particularly heart-warming example, ongoing agreements protect the stunning ancestral homelands of Hadza hunter-gatherers and Datooga pastoralists living around the Lake Eyasi, as well as those of Masai herders living around the Makame WMA, also in the northern Rift Valley. In much wetter parts of the south with even better carbon sequestration capacity, the rich forests of the Ntakata Mountains provide a safe home for hundreds of endangered eastern chimpanzees, and pay for a variety of new community services, notably universal health insurance coverage. We are also encouraged that the ILUMA WMA we have been working closely with have, with invaluable support from *Reforest Africa*, now agreed to a forest restoration investment project with the carbon credits trading company Lasting Forest Solutions, aiming to help this exciting community-led venture access international carbon finance within the next five years.

CONCLUSION

These initiatives also provide high quality employment for hundreds of village game scouts and other conservation personnel, who simultaneously protect these amazing ecosystems against encroachment and would-be encroachers against unsafe exposure to the most dangerous side of biodiversity. By supporting such community-led enforcement of locally tailored conservation regulations, we can not only protect exceptionally biodiverse landscapes and boost socioeconomic development where it is needed most, but we also greatly attenuate the risks of both local zoonotic outbreaks and global pandemics of novel pathogens. By expressing our solidarity with the local communities who care for tropical biodiversity in remarkably modest financial terms, we can simultaneously protect them against local zoonotic disease burden and ourselves against emerging infections that threaten everyone on the planet.

About the author

Over the last six years, **Professor Gerard Killeen** and his team have explored how the behavioural ecology of African malaria vector mosquitoes allows them to entirely evade contact with pesticides by feeding on wild animals and breeding far away from people, agriculture and livestock, potentially enabling much more sustainable strategies for managing the evolution of arthropod resistance against those life-saving active ingredients. During this fundamental study of vector ecology, he and his team worked closely with a Wildlife Management Area in southern Tanzania, to support the stakeholder communities in this locally led initiative as they strive to deliver on its key conservation and rural development goals.



Birds as Sentinels: Emerging Avian Diseases in a Biodiversity Crisis

Tamara Szentivanyi: Research fellow at the HUN-REN Centre for Ecological Research, Vácrátót and at the Institute of Metagenomics, University of Debrecen, in Hungary

Birds have always played a key role – historically as messengers, and today as indicators of environmental change. Across Europe, the occurrence of avian-borne pathogens, such as the West Nile Virus (WNV), the Usutu Virus (USUV), and various avian flu viruses (AIVs) is increasing, revealing an alarming trend. These pathogens mainly circulate in birds, at times causing severe disease, while only occasionally infecting humans and other mammals, usually with mild symptoms. As habitats fragment and biodiversity declines, natural barriers to pathogen emergence weaken.

WEST NILE VIRUS (WNV) AND USUTU VIRUS (USUV): MOVEMENT THROUGH BIRDS AND MOSQUITO VECTORS

WNV, a mosquito-borne disease, is among the most widespread avian pathogens. It spreads with birds along migratory routes and is now established across Europe. Outbreaks are rising in birds, horses and human populations. In 2025, 1,112 human cases were reported in 14 European countries – mainly Italy, Greece and France – alongside 359 bird outbreaks.¹ Species like blackbirds, magpies, and raptors act as pathogen reservoirs,² while mosquitoes, particularly the common house mosquito (*Culex pipiens*), are vectors, transmitting the pathogen between hosts. Most human infections are asymptomatic, but severe neurological cases and fatalities occur, especially during heatwaves and rainfalls, that favor mosquito development. Hundreds of human infections are

reported annually in Europe, with a sharp rise in recent years: 709-1,400 cases per year from 2022-2024, compared with fewer than 300 from 2010-2017 and only sporadic cases in the early 2000s.¹

USUV emerged in 1996 in Italy and has since spread across Central and Western Europe,³ with blackbirds as key drivers. While human disease is rare, periodic bird die-offs act as an eco-epidemiological alarm.

AVIAN INFLUENZA: WHEN MIGRATORY BIRDS MEET THREATENED ECOSYSTEMS

Wild migratory birds are also natural reservoirs of avian influenza viruses (AIVs), including the highly pathogenic H5N1 and H5N8. In 2025, outbreaks were reported in 29 European countries, with waterfowl and common cranes particularly affected. In Germany, an estimated 20,000 cranes died.⁴ Although many infections are asymptomatic, outbreaks can cause major bird die-offs and spill over to poultry, livestock (e.g., cattle or mink), and humans, with serious health and economic impacts, including the culling of millions of poultry each year and over 70 human cases with several deaths worldwide.⁵ AIV outbreaks have also grown in frequency and intensity in recent years. Between September and November 2025, wild bird outbreaks

Biodiversity loss further complicates disease dynamics by disrupting the natural balance between hosts, vectors, and pathogens

¹ European Centre for Disease Prevention and Control (ECDC). West Nile virus infection. <https://www.ecdc.europa.eu/en/west-nile-virus-infection>.

² The pathogen is normally found, maintained and can multiply in these animals.

³ Engel, D., Jöst, H., Wink, M., Böstler, J., Bosch, S., Garigliany, M. M., ... & Schmidt-Chanasit, J. (2016). Reconstruction of the evolutionary history and dispersal of Usutu virus, a neglected emerging arbovirus in Europe and Africa. *MBio*, 7(1), 10-1128.

⁴ Günther, A. et al. (2025). High pathogenicity avian influenza virus H5N1 (clade 2.3.4.4b) drives mass mortality in Eurasian crane (*Grus grus*) populations in Germany, 2025. *Biorxiv*, Preprint. <https://www.biorxiv.org/content/10.64898/2025.12.08.692485v1>.

⁵ World Organisation for Animal Health (WOAH). Avian Influenza. <https://www.woah.org/en/disease/avian-influenza/>.



were six times higher than in 2024 and twelve times higher than in 2023, while domestic bird outbreaks were comparable to 2024 and 2022 levels, yet five times higher than in 2023 and nearly twice 2021 levels.¹

These increases reflect shifting environmental conditions – from habitat and biodiversity loss to altered migration routes – disrupting natural disease dynamics. Evidence shows that wetland habitat loss along migratory flyways can concentrate waterfowl at fewer stopover sites, increasing contact rates, AIV transmission and outbreak risks.⁶ As boundaries between wildlife, livestock, and human health blur, addressing the ecological drivers of disease emergence becomes urgent.

THE ECOLOGICAL BUFFER: HOW BIODIVERSITY REDUCES PATHOGEN RISK

Europe's position along major migratory flyways, connecting it with Africa and Asia, allows an exchange of tropical and temperate climate pathogens, including avian influenza and West Nile Virus.

Biodiversity loss further complicates disease dynamics by disrupting the natural balance between hosts, vectors, and pathogens. For instance, greater avian host diversity is linked to lower human WNV incidence⁷ and greater non-passerine bird diversity (e.g., woodpeckers) is associated with lower WNV infection rates in mosquitoes and humans.⁸ In biodiversity-rich environments, the “dilution effect”

Global spread of highly pathogenic avian influenza (brown) and West Nile Virus (red) in relation to Europe



Source: Created via BioRender (biorender.com) by Tamara Szentivanyi

reduces the likelihood a pathogen finds a competent host. When biodiversity declines, buffering, incompetent reservoir species disappear, leaving a few generalists (e.g., house sparrows, blackbirds, or feral pigeons) that thrive in disturbed habitats and can efficiently transmit certain diseases.⁹

Species-poor environments, often dominated by a few common species – like dense poultry facilities or urban areas – help pathogen amplification, increase vector abundance, and bring wildlife, livestock, and humans into closer contact, raising spillover risk. As biodiversity declines, outbreak emergence becomes an increasingly expected outcome.

6 Yin, S. et al. (2022). *Habitat loss exacerbates pathogen spread: An agent-based model of avian influenza infection in migratory waterfowl*. PLOS Computational Biology, 18(8), e1009577. <https://doi.org/10.1371/journal.pcbi.1009577>.

7 Swaddle, J. P., & Calos, S. E. (2008). *Increased Avian Diversity Is Associated with Lower Incidence of Human West Nile Infection: Observation of the Dilution Effect*. PLOS ONE, 3(6), e2488.

8 Ezenwa, V. O. et al. (2006). *Avian diversity and West Nile virus: testing associations between biodiversity and infectious disease*. Proceedings of the Royal Society B: Biological Sciences, 273(1582), 109–117.

9 Keesing, F., & Ostfeld, R. S. (2021). *Impacts of biodiversity and biodiversity loss on zoonotic diseases*. Proceedings of the National Academy of Sciences, 118(17), e2023540118.

HUMAN HEALTH AND THE COST OF ERODED BIODIVERSITY

The human health burden of avian-associated diseases is hard to measure but the trend is clear. Zoonoses outbreaks raise healthcare costs and reduce productivity in people and agriculture, driven by workforce absenteeism and mass livestock and poultry culling, which sharply decreases outputs and requires greater investment in surveillance and vector control.¹⁰ Besides, wildlife-associated pathogen emergence highlights the tight link between human and ecosystem health.

Early detection of avian pathogens in wild bird populations can enable rapid action to limit their spread and reduce the risk of transmission to humans. A well-documented example comes from the emergence of WNV in the United States around 1999-2000. Reports of dead crows revealed the presence of the virus and urged intensified surveillance, mosquito control, and public education on personal protection. Due to these measures, WNV-positive birds were detected more than three months before the first human cases, providing a valuable window for intervention.¹¹

Policies must integrate biodiversity conservation, pathogen surveillance, and public health into a unified One Health strategy.¹² Protecting natural

habitats helps preserve avian diversity and reduce outbreaks. Protected wetlands such as Ramsar sites are associated with lower risks of avian influenza outbreaks, likely because they separate wild waterfowl from human-dominated areas and buffer spillover into domestic environments.¹³

One Health surveillance – monitoring wildlife, livestock, and humans together – allows early detection of avian pathogen circulation before it becomes a public health crisis. Examples include testing migratory waterfowl for AIV, monitoring sick horses, and screening poultry workers or nearby residents for early exposure. Investing in biodiversity protection, species conservation, and sustainable urban planning is increasingly viewed as a preventive effort to improve human health globally. Prioritizing umbrella species – whose protection indirectly benefits multiple co-occurring species and entire habitats, such as migratory waterfowl or wetland-dependent birds – can help mitigate outbreaks by preserving habitat integrity and bird community diversity, thereby reducing crowding and pathogen spillover risk.

If we fail to act now, the cost to public health will be far greater tomorrow. Birds carry the message that biodiversity loss threatens human health, reinforcing the need for proactive conservation.

¹⁰ Bernstein, A. S., Ando, A. W., Loch-Temzelides, T., Vale, M. M., Li, B. V., Li, H., ... & Dobson, A. P. (2022). *The costs and benefits of primary prevention of zoonotic pandemics*. *Science Advances*, 8(5), eabl4183.

¹¹ Eidson, M., Kramer, L., Stone, W., Hagiwara, Y., Schmit, K., & New York State West Nile Virus Avian Surveillance Team. (2001). *Dead bird surveillance as an early warning system for West Nile virus*. *Emerging infectious diseases*, 7(4), 631.

¹² Cunningham, A. A., Daszak, P., & Wood, J. L. (2017). *One Health, emerging infectious diseases and wildlife: two decades of progress?* *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372(1725), 20160167.

¹³ Wu, T., Perrings, C., Shang, C., Collins, J. P., Daszak, P., Kinzig, A., & Minter, B. A. (2020). *Protection of wetlands as a strategy for reducing the spread of avian influenza from migratory waterfowl*. *Ambio*, 49(4), 939–949.

About the author

Dr. Szentivanyi earned her PhD in 2020 from the University of Lausanne, Switzerland where she studied the ecology and evolution of bats and their associated pathogens and parasites. She is currently a research fellow at the HUN-REN Centre for Ecological Research and the Institute of Metagenomics, University of Debrecen, Hungary. Her work focuses on mosquito-borne diseases, including exploring how ecological and environmental factors, along with climate change, shape the link between arboviruses and birds, supported by the AXA Fellowship. Her institutes investigate a wide range of ecological and environmental issues related to human and ecosystem health.





Monitoring and surveillance of bird health and avian-associated pathogens provides crucial insights into interspecies disease dynamics and early warning of emerging threats.
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3

Solutions for Preserving Biodiversity and Protecting Health



The unbreakable ties between ecosystem stability and human health mean that simply noting the damage is not enough: we need to take action to restore the living world. Preserving biodiversity requires coordinated action at every level underpinned by growing public awareness. In France, mobilization against the proposed Duplomb Act, which sought to overturn the ban on acetamiprid, a pesticide banned in France since 2018, showed that there is now a better understanding of the risks that harming pollinator populations poses to human health and food security, revealing a shift in the public debate surrounding biodiversity and the degree to which humanity depends on it.

Despite the overall failure of the Aichi Biodiversity Targets, there has been some progress in terms of protection for ecosystems and biodiversity. The Secretariat of the Convention on Biological Diversity highlighted certain areas of progress in 2020, including the success of various fishery policies in restoring fish stocks, a fall in the number of species becoming extinct, and an increase in the amount of information and data on biodiversity available to the public.¹ This shows that it is possible to tackle biodiversity erosion, provided that remediation measures and actions to reduce anthropic pressures are taken. Integrated responses rolled out simultaneously at individual, local, national, and global levels can generate substantial benefits in terms of protecting health and the living world. The third section of the report explores actions taken at different levels – institutional, global and local – to mobilize and reverse current trajectories surrounding ecosystem erosion.

Henri Bourgeois-Costa and **Pierre Mienville** offer an ocean-based perspective on the One Health concept, emphasizing the fundamental interdependence between human health and the health of marine ecosystems. He underscores the critical need to fully integrate this interconnection into biodiversity conservation and public health strategies, grounded in a science-based and non-anthropocentric approach.

Using the Veolia example, **Sébastien Daziano**, **Tiphaine Déas** and **Jean-Pierre Maugendre** analyze how embedding biodiversity into industrial practices helps combine operational performance with restoring ecosystems. By leveraging local actions and nature-based solutions, Veolia transforms its industrial sites into havens for the natural world, places that encourage the reappearance and protection of native species. This approach underscores the ability of structured local actions to generate measurable environmental, social, and health benefits.

Mobilizing private funding for nature restoration is key to achieving international biodiversity and climate goals. Using the example of the "Restore" insurance product developed by AXA and SCOR, **Aurélie Fallon Saint-Lô** highlights the importance of innovative insurance solutions as a key lever for securing investments in nature restoration.

In addition to actions undertaken by economic actors, rethinking frameworks for public action is crucial to erecting effective health barriers. **Benjamin Roche**

and **Audrey Arnal** analyze interactions between international institutional frameworks and local and national strategies for combating zoonotic diseases, demonstrating how conserving biodiversity is a lever for protecting public health in its own right. Ecological research, multi-actor governance, and community participation, as in Mexico and Costa Rica, are all necessary tools for designing coherent responses, global to local, and delivering a lasting boost to health resilience.

Next, establishing effective strategic plans requires both public and private initiatives to ensure they have in-depth understanding of the links between biodiversity erosion and human health. **David Nogués Bravo** points to the central role of integrated biodiversity-health indicators to inform decisions likely to simultaneously impact ecosystems and health. He demonstrates that their absence makes it impossible to anticipate health benefits as well as emerging risks relating to the natural world. He emphasizes that the development of these metrics requires interdisciplinary expertise, improved data integration, and unwavering institutional backing for a systemic approach.

Given the environmental and health shortcomings of intensive farming models, new areas of innovation now offer credible alternatives. **Johan Rodriguez-Melo**, **Soledad Traubenik** and **Federico Ariel** describe new RNA biotechnologies that reduce pesticide use without compromising agronomic efficiency. Based on targeted biological mechanisms with low environmental persistence, these solutions illustrate how scientific innovations can lessen pressure on biodiversity while helping to protect human health and supporting the transition to more sustainable agricultural systems.

Finally, the long-term future of every strategy for preserving biodiversity is conditioned on buy-in from the general public. For **Véronique Andrieux**, inappropriate messaging, seen as too alarmist or overly technical, hinders mobilization despite massive publicity given to environmental warnings. She highlights the role health can play as a unifying narrative that can make ecological issues seem more real. For **Afnan Agramont**, public ownership of environmental data is a key issue, particularly in terms of ensuring people can grasp and measure environmental harm. Producing knowledge at the local level, as illustrated by citizen science initiatives in Bolivia and Kenya, makes it possible to describe these dynamics more precisely, and to document interactions between biodiversity, health, and living conditions.

¹ Secretariat of the Convention on Biological Diversity (2020) Global Biodiversity Outlook 5 – Summary for Policymakers, p.4-5. <https://www.cbd.int/gbo/gbo5/publication/gbo-5-spm-en.pdf>



One Health from an Ocean Perspective: Protecting Living Beings to Protect Ourselves

Henri Bourgeois-Costa: Head of Public Affairs for the Tara Ocean Foundation

Pierre Mienville: Advocacy Officer for the Tara Ocean Foundation

The United Nations General Assembly took a decisive step in 2023 with the formal recognition of the One Health concept.¹ Acknowledging the advances and limits of scientific understanding of ecosystems, UN bodies called for the concept to be translated into concrete policy actions,² stating that *“the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and interdependent.”*³

Mindful of the growing focus on this conceptual framework and the increasing number of overly simplistic interpretations, the Tara Ocean Foundation, with its track record of scientific expeditions stretching back more than 20 years, seeks to explore the reality of the approach through the prism of ocean sciences and reveal its full depth and complexity.

A HEALTHY OCEAN IS AN INDISPUTABLE PREREQUISITE FOR THE CONTINUED HEALTH OF OUR SPECIES

Oceans play an important role in the main physical-chemical cycles (water, carbon, etc.) that regulate the biosphere equilibrium marine organisms depend on. They interact with the environment and with each other, producing biomass and accounting for a major source of oxygen production. Conditions vital to human life depend to a great extent on this marine ecosystem and its relative stability.⁴ This means that a “healthy” ocean can be defined, from the human viewpoint, as the stability of the physical and chemical conditions needed to maintain the biological communities to which humans also belong.

In other words, an equilibrium that is beneficial to all living organisms, preserving species-specific and genetic diversity, the richness of their interactions, and the conditions needed to ensure freedom from human intervention. The 15 expeditions conducted by the Tara Ocean Foundation and its partners from laboratories and academic research institutes have improved our knowledge of oceanic biodiversity and environmental change. They have highlighted the fundamental role the marine microbiome (set of microbial communities) plays in ocean processes. Microscopic organisms represent over two thirds of total biomass in the oceans,⁵ performing almost as much photosynthesis as land-based plants, and are central to the global carbon cycle. They also act as the primary producer in marine food webs;⁶ fish are the main source of protein for around one billion people.⁷

Countless instances of erosion of physical-chemical conditions (climate heating, pollution, acidification, etc.) and of the living world (overfishing, division of populations, etc.) threaten these equilibria. This shows how the ocean has become a bellwether both for direct threats and land threats, some of which accumulate there. And an ocean in “poor” health undermines human health.⁸ The truth is that some activities alleged to be beneficial to the human species (certain fishery practices, industrial mining activities, etc.) actually erode the planet’s livability⁹ for our species – and many others besides.

1 Resolution 77/275 of February 24, 2023 adopted by the United Nations General Assembly on the Scope, modalities, format and organization of the High-Level Meeting on Pandemic Prevention, Preparedness and Response. <https://doi.org/10.1016/j.cell.2019.11.018>.

2 Quadripartite call to action for One Health for a safer world. Joint press release from the Food and Agriculture Organization of the United Nations (FAO), United Nations Environment Programme (UNEP), World Health Organization (WHO), and World Organisation for Animal Health (WOAH); March 27, 2023, Rome/Paris/Geneva/Nairobi. <https://www.fao.org/newsroom/detail/quadripartite-call-to-action-for-one-health-for-a-safer-world/en>.

3 Definition in *One Health Definitions and Principles*, published by the One Health High-Level Expert Panel, July 24, 2023. <https://cdn.who.int/media/docs/default-source/one-health/ohhlep/one-health-definition-and-principles-translations.pdf>.

4 IPCC (2019). *Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, et al. (eds.)]. Cambridge University Press. <https://www.ipcc.ch/srocc/>

5 Bar-On, Y. & Milo, R., (2019). *The biomass composition of the oceans: a blueprint of our blue planet*. Cell, 179, 1451–1454. <https://doi.org/10.1016/j.cell.2019.11.018>.

6 Tara Ocean Foundation, Tara Oceans, European Molecular Biology Laboratory (EMBL), et al. (2022) *Priorities for ocean microbiome research*. Nature Microbiology 7, 937–947. <https://doi.org/10.1038/s41564-022-01145-5>.

7 United Nations, Department of Economic and Social Affairs - Sustainable Development, Oceans and Seas. <https://sdgs.un.org/topics/oceans-and-seas>.

8 See, among others: Richardson, K., et al. (2023). *Earth beyond seven of nine planetary boundaries*. Science Advances, 9(37); <https://doi.org/10.1126/sciadv.adh2458>. Landrigan, P. J., et al. (2020). *Human Health and Ocean Pollution*. Annals of Global Health, 86(1), 151. (The Monaco Commission). <https://doi.org/10.5334/aogh.2831>.

9 See, among others: IPBES (2019). Brondizio, E. S., et al. (eds.) *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services*. https://files.ipbes.net/ipbes-web-prod-public-files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf; and IPBES (2020) on structural links between biodiversity loss and global health risks. <https://files.ipbes.net/ipbes-web-prod-public-files/2020-11/20201028%20IPBES%20Pandemics%20Workshop%20Report%20Plain%20Text%20Final.pdf>.



Accepting the existence of One Health entails (re)locating humans in their rightful place: not central, but within a living fabric that they depend on. The idea of asymmetric dependency follows on from this definition. Human health depends on the health of ecosystems, but the reverse does not apply: the ocean's health is not dependent on people being in good health, it depends on our capacity to stop harming it.

This means that harming ecosystems harms the human species because the damage we cause erodes the conditions our existence depends on. Conversely, taking care of the living world we are a part of contributes to improving our health. Given this fact, solving the systemic crisis afflicting our shared health has to involve giving ourselves the right tools for the job: tools to protect ecosystems. Without them, our chances of success are compromised.

These insights oblige us to move beyond an anthropocentric mindset and take responsibility for all living beings.

ACTING TO PRESERVE OUR COMMON HEALTH

The One Health Joint Plan of Action sets out a sustainable pathway compatible with the balances of the living world,¹⁰ calling not just for reactions to crises but for transformative change in how we produce, take preventive measures, and make decisions.

The Tara Ocean Foundation is convinced that a pragmatic One Health strategy has to establish quantified, time-limited and binding targets for reducing impacts. It could be based on the principles of prevention (reducing risks with a scientifically proven causal link to adverse health

The Tara Ocean Foundation champions a science-based vision in which protecting the ocean means protecting our physical health



Tara, a schooner and floating laboratory, with the Tara Ocean Foundation's new drifting Arctic scientific base, Tara Polar Station.
© Valentin Lauféron - Tara Ocean Foundation

impacts) and precaution (reducing risks in fields where the science identifies cause for concern), backed by robust international¹¹ and national¹² legal frameworks.

Implementing this pathway will require overcoming a number of obstacles:

- **Agreeing on a non-reductive approach to One Health**

Many of the approaches to the One Health concept are not science-based, often leading to excessive anthropocentrism which views human health in opposition to the rest of the living world, negating the very essence of One Health. Taking scientific knowledge as the starting point makes it possible to grasp the One Health concept in its full complexity. Sharing this vision paves the way to the cooperation vital to solving problems that no single administration can manage by itself. This will require time, data sharing, decompartmentalized governance, and shared objectives.

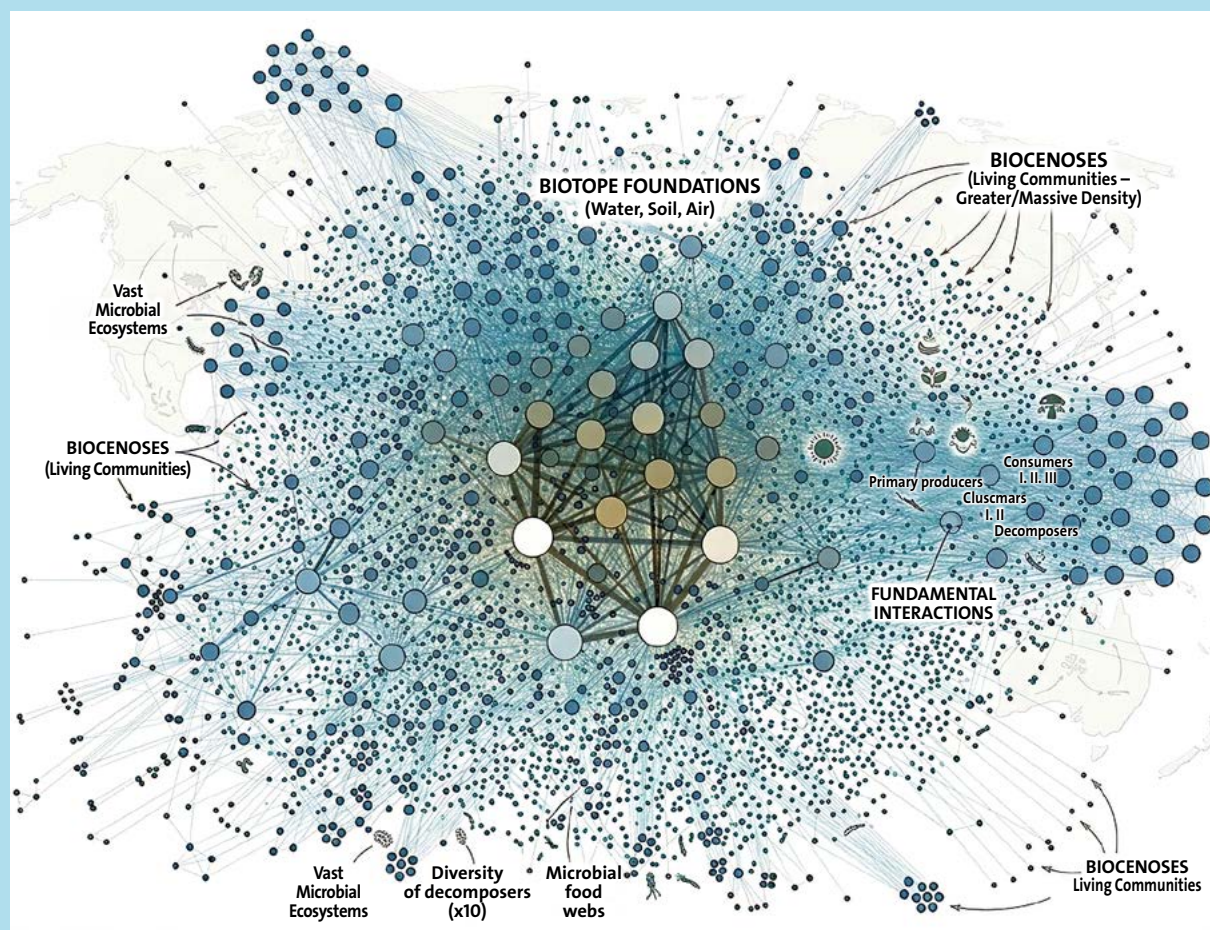
¹⁰ FAO, UNEP, WHO, and WOA. 2022. *One Health Joint Plan of Action (2022-2026). Working together for the health of humans, animals, plants and the environment.* Rome. <https://www.who.int/publications/i/item/9789240059139>.

¹¹ United Nations General Assembly, *Rio Declaration on Environment and Development*, 1992, A/CONF.151/26. <https://digitallibrary.un.org/record/141565?ln=fr&v=pdf>.

¹² In France, for example, the precautionary principle has a constitutional role, included in Article 5 of the Environment Charter since 2005.



Vastness of biosphere interrelations



Our health lies somewhere at the intersection of inter-relations between ecological communities and their biotopes.

- **Advancing a culture of precaution**

How the living world operates remains largely a mystery to us.¹³ We only know about 15% of the species living in the world's oceans.¹⁴ Claiming to govern a world we know so little about demands a large measure of precaution.

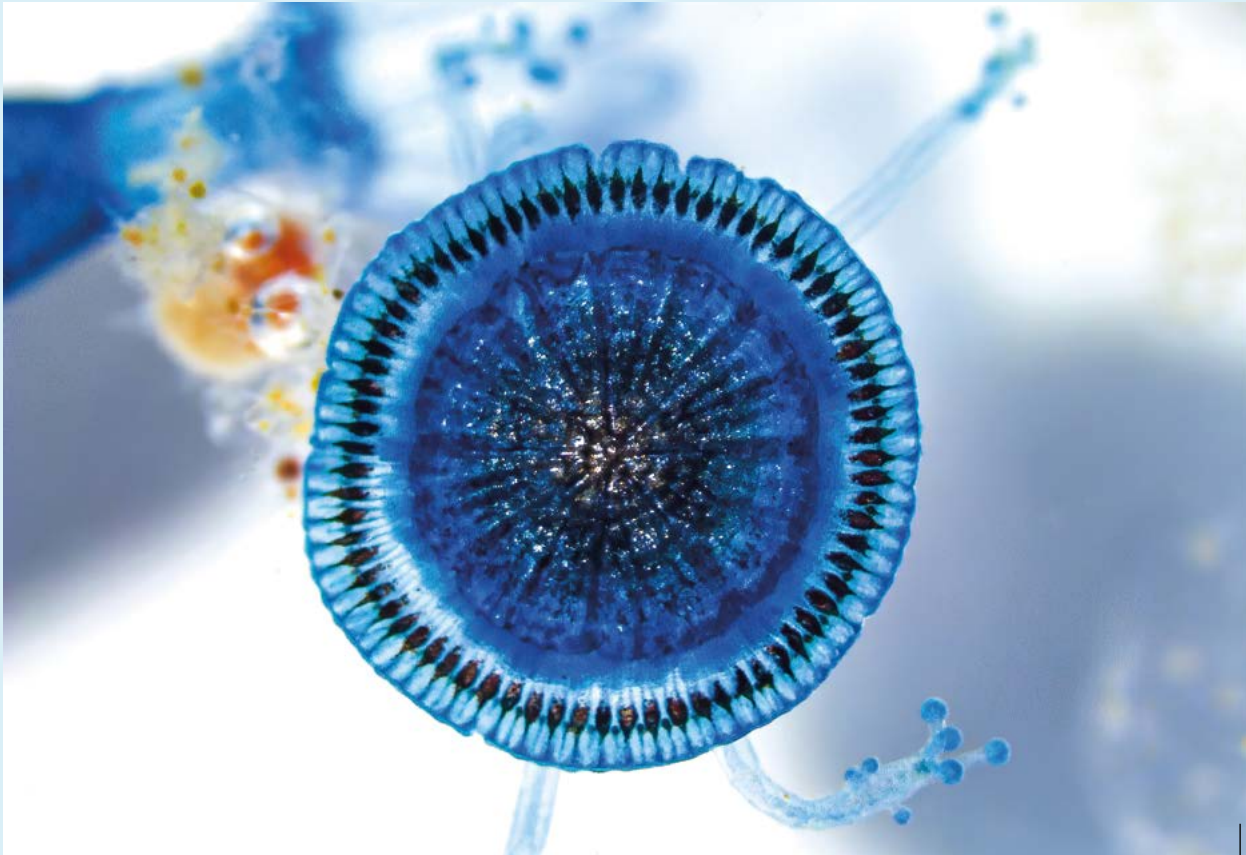
¹³ In 2026, approximately 242,000 marine species were listed in the *World Register of Marine Species (WoRMS)*. See Appeltans, W., et al. (2012). *The Magnitude of Global Marine Species Diversity*. *Current Biology*, 22(23), 2189-2202. <https://doi.org/10.1016/j.cub.2012.09.036>.

¹⁴ Average of studies by Mora et al. (2011), <https://doi.org/10.1371/journal.pbio.1001127> published in *PLOS Biology*, source for the top-end estimate of 2.2 million marine species. The authors used a statistical method based on taxonomy (the rate at which we discover new families and genera to predict the number of remaining species), and on work by Appeltans et al. (2012), <https://doi.org/10.1016/j.cub.2012.09.036>, published in *Current Biology*, positing a more conservative range between 0.7 and 1 million species. The study involved dozens of experts per taxonomic group (fish, molluscs, etc.) to estimate the number still to discover in each category.

- **Implementing concrete policy transformations**

A fit-for-purpose strategy must combine prevention, precaution, combatting plastic and chemical pollution, reducing fossil fuel emissions, rewilding habitats, limiting destructive extractive activities, greater vigilance, the polluter pays principle, and greater caution regarding geo-engineering. A One Health approach can only result in concrete choices, sometimes highly demanding, leading to a reinvention of our socio-economic models.





Plankton (Propita propita) observed by the schooner Tara off the coast of South Africa.
© Maëva Bardy - Tara Ocean Foundation.

CONCLUSION: PROTECTING LIVING BEINGS TO PROTECT OURSELVES

The environment must no longer be viewed as simply an external risk factor but as the cornerstone of our shared stability. The Tara Ocean Foundation champions a science-based vision in which protecting the ocean means protecting our physical, mental and social health, as well as the continuity of the great cycles of life. An approach that is at once scientific, political, and profoundly human.

One Health asks us to change our perspective. Health is not compartmentalized between hospitals, farms, fields and the ocean: it is a living reality, shared, fragile, and interdependent. Rather than simply preventing crises, we must choose a way of inhabiting the world that is more just, clear-sighted and methodical, informed by the conviction that protecting the living world means we are protecting ourselves.

About the authors

Henri Bourgeois-Costa is head of public affairs for the Tara Ocean Foundation, expert on the circular economy and plastic pollution and expert in ecosystem geography. He began his NGO career in 1997, acquiring expertise in water, biodiversity, and industrial environments (eco-design, plastics industry, and materials recovery). He has worked with the Tara Ocean Foundation since 2019, where he is responsible for circular economy advocacy, particularly for plastics and toxins, as well as international advocacy at UN bodies. The One Health concept is central to the work of the Tara Ocean Foundation, which explores the oceans so they can be better understood and protected.

Pierre Mienville is an advocacy officer for the Tara Ocean Foundation.

Real-World Illustration of A Business' Role in Protecting Biodiversity:

The Veolia Case

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The nature of its activities means Veolia, the world leader in environmental services, plays a role in protecting the environment and biodiversity through combating climate breakdown, pollution, and the overexploitation of resources. The Veolia Group is also committed to transforming the 2,000 industrial sites it operates worldwide into real reservoirs of biodiversity. It implements this approach through local action plans and, where appropriate, adopting nature-based solutions. This commitment is a further reflection of Veolia's deep local roots and serves as a powerful driver for dialogue with local stakeholders, making it possible to share analyses of the environmental and social benefits these types of action generate.

INTRODUCTION

The February 2026 IPBES Business and Biodiversity Assessment¹ emphasized that businesses are key actors in protecting nature owing to their ability to deliver corporate policies, innovations, and commitments across their value chains. They act to reduce their negative impacts but also to accelerate rollout of their positive-impact solutions designed to restore and regenerate the natural environment and implement nature-based solutions.

Veolia welcomed this conclusion enthusiastically, both in its role as global specialist in environmental protection solutions but also as a site operator striving to reduce to a minimum the local impacts the industrial facilities it manages may generate.

Combining these two types of actions creates the multiple forms of grassroots environmental and social value examined in this article.

VEOLIA'S COMMITMENT TO BIODIVERSITY IS INDISSOCIABLE FROM THE NATURE OF ITS ACTIVITIES, AND IS EMBEDDED IN ITS STRATEGY AND OPERATIONAL PRACTICES.

Veolia's activities help preserve natural environments by focusing on depolluting, decarbonizing, and regenerating. They directly reduce several of the factors behind biodiversity erosion identified by the IPBES (climate breakdown, pollution, overexploitation of resources) that result from the activities of its municipal and industrial customers. Collecting and treating waste limits the spread of pollutants into the soil and atmosphere, and treating wastewater ensures quality discharges that protect aquatic environments. Likewise, the development of district heating networks and the use of biomass from certified sources reduces carbon footprints, while recycling and reusing wastewater preserves natural resources and helps maintain flows in watercourses.

Industrial activities at Veolia-operated sites, hardly any of them owned by Veolia, may, however, have direct or indirect environmental impacts at the local level, but on a far smaller scale than those relating to the reduction of its customers' impacts. Controlling these local impacts forms part of the Veolia Group's environmental policy.

¹ The report's full title: Methodological assessment of the impact and dependence of business on biodiversity and nature's contributions to people <https://www.ipbes.net/business-impact>. IPBES, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, is "the IPCC for biodiversity".



For instance, a Veolia sewage plant treats wastewater prior to discharge into the environment, thereby avoiding pollution of rivers and groundwater. But operating the plant also generates local impacts such as soil sealing, night-time lighting, heavy plant traffic, and so on. The site is therefore required to take concrete measures such as differentiated management of its green spaces, limiting night-time lighting to protect local wildlife, etc.

Veolia's commitment to protecting the living world has been shaped by a number of key milestones. Veolia formalized its initial approach in 2015 when it aligned itself with France's national biodiversity strategy. The publication of its purpose in 2019 then embedded environmental protection into the company's articles of association. The same year, Veolia joined Act4nature international,² helping to transform these principles into firm timelines and quantified objectives aligned with international frameworks such as the Global Biodiversity Framework.

In concrete terms, Veolia is committed to:

- restoring and protecting by implementing custom action plans at 100% of sites offering the greatest ecological potential, with a target of completing $\geq 85\%$ of plans by 2027;
- transforming practices by generalizing environmentally friendly management and abandoning use of pesticides and herbicides at 95% of its sites;
- acting across its value chain, aiming for 100% traceability and certification for its supplies of wood biomass, ensuring zero impact on deforestation.

The Group's multifaceted performance approach includes a dedicated indicator for monitoring the rollout of action plans to attenuate biodiversity impacts at sensitive sites. To ensure buy-in at the highest level, this objective is supported by a sponsor on the Executive Committee, Sebastien Daziano.

The 154 sites identified around the world cover over 20,000 hectares. They were selected according to two criteria: environmental sensitivity and potential (proximity to protected areas, presence of endangered species), and potential pressures linked to operations (discharges, water intake, soil sealing).

Measuring the biodiversity footprint at these sensitive sites makes it possible to evaluate each plant's positive and negative local impacts, both direct and indirect.

The tool for analyzing the biodiversity footprint was designed collaboratively in 2019 by Veolia working with ecologists and lifecycle analysis experts. It is used to produce a qualitative and quantitative assessment of each site's local challenges. Comparative analysis looks at data from the industrial process (discharges, water intake, consumption) and the local environmental setting (characterization of surroundings, proximity to protected areas, presence of rare or endangered species).

Input from a local biodiversity expert is mandatory to help operational units measure on-site footprints. The ecologist also helps the site to draw up its action plans, defined to reflect the major challenges identified via the biodiversity footprint study. This process is guided by a list of predefined actions designed to reduce identified impacts and restore and preserve the natural environment. These actions (15 generic actions and various specific actions) seek to reduce impacts in terms of soil sealing and habitat fragmentation, preserving rare and endangered species, environmentally friendly management of green spaces, protection of water resources, combating invasive alien species, reducing light pollution, combating pollution and climate disruption, and raising awareness among stakeholders.

High standards for preserving biodiversity are applied at all other sites managed by the Group.

- Environmentally friendly management techniques, set out in a Green Spaces charter. This replaces traditional maintenance approaches with practices that respect biodiversity. It includes mandatory measures such as delayed mowing, establishment of wildlife havens (nest boxes, log piles, dry stone) and differentiated management of green spaces according to their uses.
- Veolia is committed to ending the use of pesticides, herbicides, fungicides, insecticides and biocides in the management of its green spaces. This requirement involves a shift to alternative mechanical or thermal methods and a change in aesthetic standards to better incorporate nature into industrial sites.

124,000 trees have been planted since January 2025. The project's ecological goals are not confined to planting trees: it also aims to improve water quality, promote greater biodiversity, and provide long-term capture of atmospheric carbon

² Act4nature international was launched by EpE (Businesses for the Environment) in 2018. Its 70+ members are French-owned or based in France. Corporate commitments are reviewed and approved by a multi-actor steering committee that includes environmental NGOs, business bodies (Medef, Afepe), academic partners, and public bodies (French Office for Biodiversity) <https://www.act4nature.com/en/>.



The rollout of all these actions is overseen by a network of over 50 biodiversity correspondents present across all business units in the Veolia Group. Annual updates are provided by Veolia in the Universal Registration Document, detailing progress in meeting its Act4nature International commitments.

Lastly, one of the Group's innovation program priorities is the development of nature-based solutions for managing the entire water cycle, such as artificial wetlands or biomonitoring solutions to analyze the state of ecosystems by measuring the presence of certain representative species. These solutions are incorporated as widely as possible into biodiversity protection plans and, of course, into the solutions Veolia proposes to potential customers.

ACTIONS ROLLED OUT ACROSS ALL OF THE GROUP'S ACTIVITIES AND IN EVERY PART OF THE WORLD WHERE IT OPERATES

In Latin America, Veolia has embedded biodiversity protection into the process of transforming all the landfill waste centers it manages in Colombia, such as the Antanas site (*see box*), into “environmental technology parks”, designed to be centers for decarbonization, decontamination, and resource regeneration. It has developed action plans for preserving plants and wildlife, including educating employees and subcontractors about protecting biodiversity, a total ban on the use of pesticides and herbicides, controlling invasive species, use of compost and organic fertilizer, and creating wildlife habitats to achieve harmony between the site's operations and its ecosystem. These actions have resulted in the restoration of close to 2,300 hectares, along with the protection for 663 animal species and 552 plant species. In Brazil, environmentally friendly management of the Ipéro landfill site near Sao Paulo, which manages waste from over a million residents, plays its part in restoring damaged ecosystems in the Mata Atlântica, one of the world's richest and most endangered biomes. When the site was created, it included creating an ecological corridor to the nearby protected forest.

In France, a wide range of actions have been implemented at treatment plants operated by the Greater Paris Water Authority (SEDIF) and located on the banks of rivers with major environmental challenges. The actions form part of the renewal of Veolia's contract, and are illustrated in the document published by SEDIF about the Choisy-le-Roi water treatment plant on the banks of the Seine.

Antanas environmental technology park, Colombia



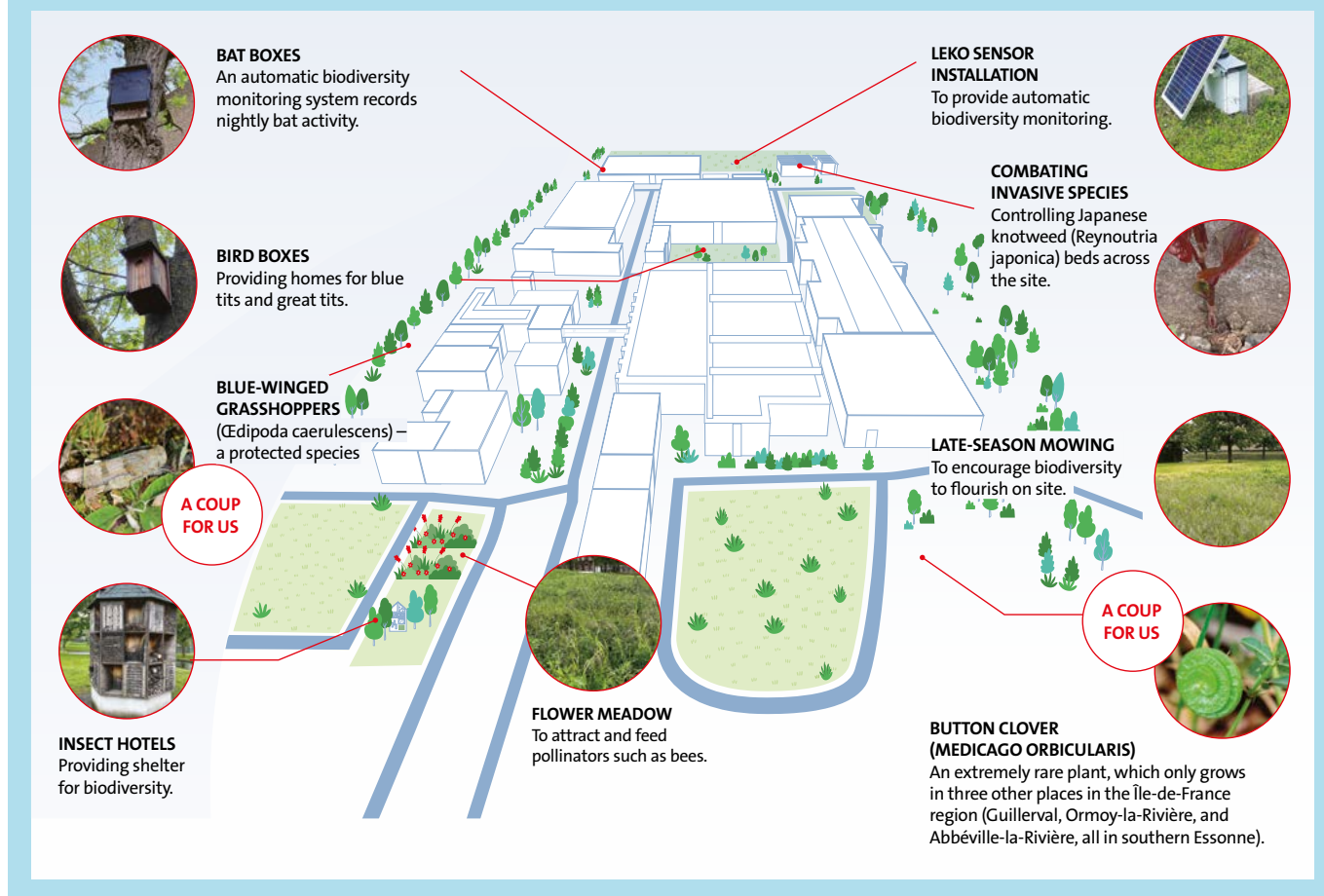
Located in the municipality of Pasto, this 100-hectare park at a waste landfill site has maintained three conservation zones since 2021, covering a total of 73 hectares. Creation of a plant nursery ensures availability of endemic species for replanting and reforestation (*Quercus humboldtii*, *Clusia spp*, *Panopsis spp*, etc.), with the gardens employing sustainable practices that make use of local plants. Three wildlife observation circuits offer an opportunity for participative scientific monitoring, and biological corridors link the site's forests to improve ecological connectivity. Specialist sensors have been installed to identify different species, and data from the sensors is used for advanced modelling that provides direct headcounts as well as automated audio recordings and learning algorithms. The site's managers raise awareness among employees and local people through visits, lectures, and active participation in initiatives designed to preserve biodiversity.

Launching plans to protect biodiversity is an inherently local action tied very closely to a specific place

For industrial sites, the rehabilitation of eight hectares of former wetlands, comprising 23 terraces, close to the Sinopec petrochemical plant in China is another example of biodiversity restoration. The initiative, led by Veolia in its role as manager of the site's water cycle, aims to optimize the quality of treated wastewater (60% of wastewater is now reused) prior to discharge into the environment. Each terrace has its own specific vegetation chosen for its purifying qualities. The rehabilitated wetland acts as an intermediary buffer prior to final discharge into the Niukouyu reservoir. Restoring the wetland included planting a 2.7-hectare phyto-remediation zone to improve water quality. The creation of different habitats and landscapes enriched local plant and wildlife, with over 140 bird species identified, including some on the IUCN extinction list, such as the northern lapwing and reed parrotbill, and the reappearance in the zone of nine species of fish indigenous to the Beijing region.



The Choisy-le-Roi plant is owned by the Syndicat des Eaux d'Île-de-France (SEDIF)



At Gum Springs in Arkansas, USA, a program was launched to plant 275 hectares close to a waste treatment center. 124,000 trees have been planted since January 2025. The project's ecological goals are not confined to planting trees: it also aims to improve water quality, promote greater biodiversity, and provide long-term capture of atmospheric carbon. The initiative's deep local roots and scientific character are noteworthy: foresters provide their expertise about local conditions, and academic teams actively monitor the return of wildlife, day and night.

THE LOCAL CHARACTER OF ACTIONS TO PROTECT BIODIVERSITY: NECESSARY PREREQUISITES AS WELL AS MAJOR OPPORTUNITIES

Launching plans to protect biodiversity is an inherently local action tied very closely to a specific place. In the context of a delegated management contract, in common with all actions relating to the life of the contract, it also

requires the facility owner (municipality or industrial company) and its operator to agree on how they view the targets to meet and resources to deploy. Equally, they must be mindful that restoring good ecological conditions is a long-term proposition, and that it will often take several years before any tangible progress can be seen.

Specifically, an action plan can sometimes lead to part of the available land being ring-fenced to create an environmental reserve to the detriment of other activities, through investments not initially provided for in the contract (replacing conventional lighting with LEDs to limit light pollution, which also benefits from a very high rate of return on investment, establishing nature-based solutions such as artificial wetlands, etc.), or alterations to operating practices (banning the use of biocides, despite their use sometimes being imposed by certain international contract requirements).



This highly local character also makes it hard to apply copy & paste principles to action plans. Although the industrial activities may be similar, the ecological challenge can differ very markedly from one site to another. A landfill center in Brazil might focus primarily on protecting the Mata Atlântica, whereas a similar site in France is more likely to want to restore degraded local environments (ponds, shrub and tree planting, reptile shelters, etc.).

Lastly, as with any local action, the role played by operators on the ground, under the responsibility of site managers, is essential: they will implement the identified actions by incorporating them into their operational practices, teach subcontractors about the new practices, and more generally serve as the link with local stakeholders interested in protecting the natural world.

In addition, opening sites to local visitors to show them the on-site changes made to preserve biodiversity is an excellent tool for illustrating the contribution our own activities – decarbonization, depollution, protecting resources – make to preserving the environment, while also helping to improve their local acceptability.

SCALING UP WITH AN APPROACH BASED ON SHARING ALL BENEFITS DERIVING FROM SOLUTIONS TO PRESERVE THE LIVING WORLD

We believe that the widespread adoption of biodiversity protection plans at industrial sites, as well as nature-based solutions such as the creation or restoration of wetlands, would be significantly encouraged by recognition of the complete set of environmental and social benefits that these actions produce. In Alicante, Spain, the Marjal city park was created to act as a floodable zone able to hold back runoff during periods of heavy rainfall.

It is now also universally appreciated as a leisure and walking facility, contributing to the attractiveness of the local district that used to be unpopular due to flooding. In France, the Plessis Gassot landfill center north of Paris forms an unexpectedly green area spanning several dozen hectares in surroundings characterized by intensive agriculture. The same applies to the planted discharge zone for Sinopec in China, which contributes to quality of life in a highly industrialized environment.

These examples show how a project initially designed to fill a single function generates multiple forms of value locally. It would be useful to detail this value, at least in qualitative terms, so that policymakers can understand it. A study launched by Veolia of listings of the co-benefits associated with a large number of biodiversity certification projects could certainly help toward this goal.⁴

About the authors

Sébastien Daziano is Veolia's Senior Vice President of Multifaceted Performance and Strategy and a member of the Executive Committee. He sponsors the depollution and biodiversity preservation objective included in the multifaceted performance approach Veolia has adopted to implement the principles set out in its purpose.³

Jean-Pierre Maugendre was head of the Nature and Biodiversity team at Veolia's Multifaceted Performance and Sustainable Development Department from January 2022 to January 2026. He is now Vice President of the department.

Tiphaine Déas is Biodiversity Engagement Manager at Veolia's Multifaceted Performance and Sustainable Development Department.

³ To find out more, visit <https://www.veolia.com/en/veolia-group/csr-multifaceted-performance>.

⁴ To find out more: Veolia Biodiversity Report (2024) <https://www.veolia.com/sites/g/files/dvc4206/files/document/2025/08/biodiversity-report-veolia-081925.pdf>.





Public and Institutional Policies:

Protecting Biodiversity to Prevent Zoonotic Disease, from Global to Local

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Preventing zoonotic diseases implies rethinking public policies at the interface between biodiversity, human health and socio-economic dynamics. As damage to ecosystems increases at-risk contact between wild animals, domestic animals and humans, a large number of international and regional initiatives show that biodiversity conservation can be an effective public health tool. This article analyzes how institutional frameworks – from the IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) to the OHHLEP (One Health High-Level Expert Panel), the Global Biodiversity Framework and programs such as PREZODE (PREventing ZOonotic Disease Emergence) and ZODIAC (ZOonotic Disease Integrated Action) – interact and reciprocally support national and local preventative strategies. Drawing on examples from the Caribbean and Latin America, it illustrates how ecological research, multi-actor governance and community participation make it possible to design coherent interventions, from global to local. The authors argue for integrated governance, where protections for the living world become a central pillar for resilience in public health.

INTRODUCTION

Recent health crises have underlined the central role that environmental degradation plays in the emergence of infectious diseases.¹ Loss of biodiversity alters ecological balances and increases the probability of transmission between wild animals, domestic animals and humans. Although these relationships are now scientifically well established, they remain unevenly integrated into public policies. Faced with this situation, international institutions and national governments are gradually developing new frameworks for actions in fields where biodiversity and health overlap. This article will examine how these frameworks – from global to local – guide preventive actions, using concrete examples of institutional mechanisms and regional programs.

DEVELOPING ONE HEALTH GLOBAL GOVERNANCE AND ITS IMPACT ON PUBLIC POLICIES

The emergence in academic circles of the One Health approach combining human, animal and environmental health dates back to the early 2000s.² While this approach has played a particularly important role in strengthening our understanding of emergence mechanisms³ the need to apply it to the development of so-called primary prevention strategies (i.e. by focusing on the causes of the emergence in animal populations rather than trying to prevent interhuman transmission⁴) only became clear during the SARS-CoV-2 pandemic in 2019.

In this context, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) played a determining role in the international recognition of the link between environmental degradation and the emergence of diseases. Its 2020 report on pandemic risks offered a major scientific basis for repositioning

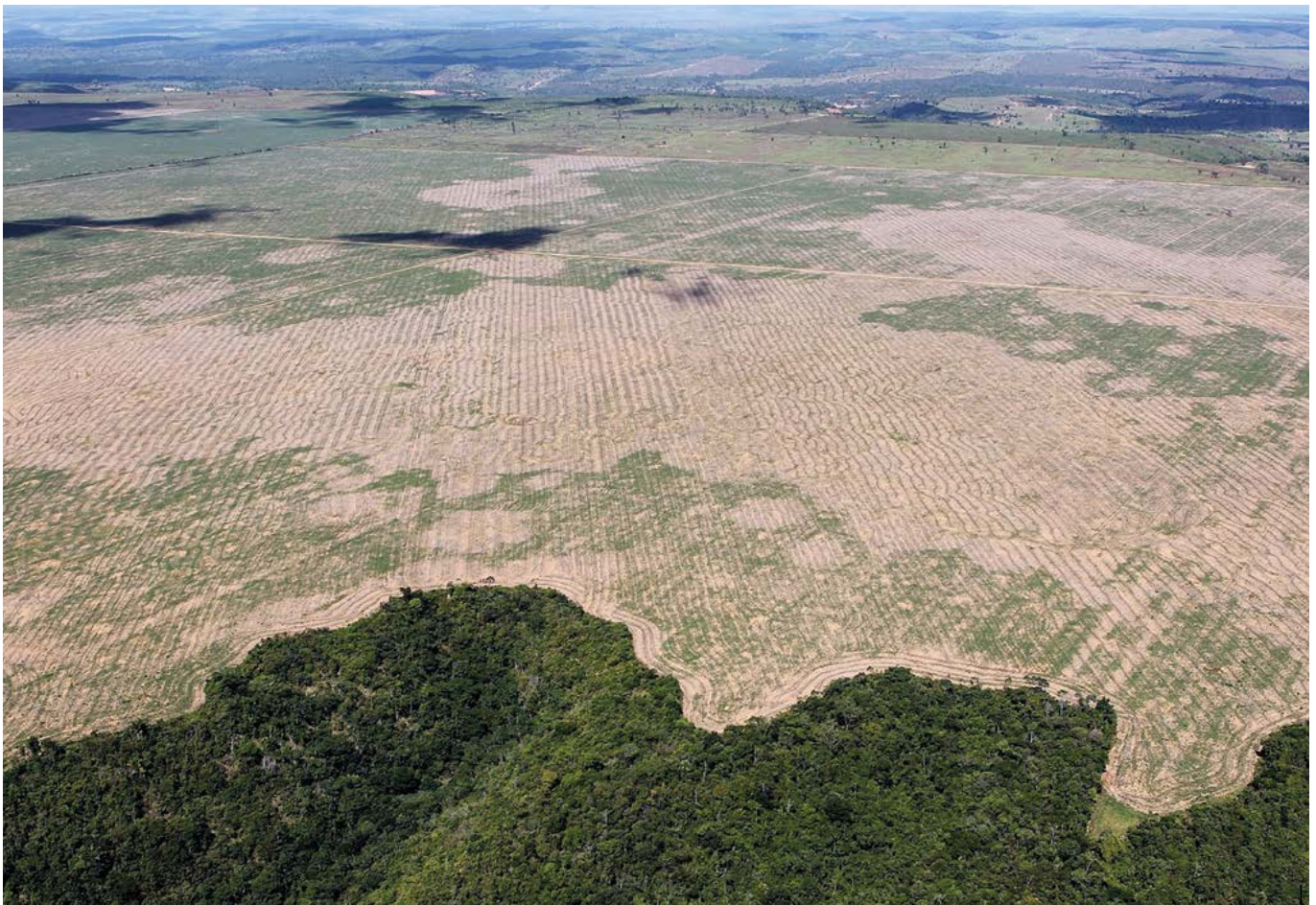
1 Jones, K. E., Patel, N. G., Levy, M. A., Storeygard, A., Balk, D., Gittleman, J. L., & Daszak, P. (2008). Global trends in emerging infectious diseases. *Nature*, 451(7181), 990–994. <https://doi.org/10.1038/nature06536>.

2 Daszak, P., Cunningham, A. A., & Hyatt, A. D. (2000). Emerging infectious diseases of wildlife—threats to biodiversity and human health. *Science*, 287(5452), 443–449. <https://doi.org/10.1126/science.287.5452.443>.

3 Plowright, R. K., Parrish, C. R., McCallum, H., Hudson, P. J., Ko, A. I., Graham, A. L., & Lloyd-Smith, J. O. (2017). Pathways to zoonotic spillover. *Nature Reviews Microbiology* 2017 15:8, 15(8), 502–510. <https://doi.org/10.1038/nrmicro.2017.45>.

4 Bernstein, A. S., Ando, A. W., Loch-Temzelides, T., Vale, M. M., Li, B. V., Li, H., et al. P. (2022). The costs and benefits of primary prevention of zoonotic pandemics. *Science Advances*, 8(5). <https://doi.org/10.1126/sciadv.abl4183>.





A natural landscape heavily impacted by human activity, characterized by the fragmentation of natural habitats and the conversion of ecosystems, in this case, due to the illegal logging and trade of timber within the Gurupi Biological Reserve and the Caru and Alto Turiaçu Indigenous Lands in the state of Maranhão. (2016) © Felipe Werneck/Ibama

prevention at the heart of public policies.⁵ In particular, it shows that zoonotic diseases represent around 70% of emerging infectious diseases and identifies several key anthropic factors for their emergence, with changes in land use (deforestation, habitat fragmentation, spread of agriculture, and urbanization) linked to over 30% of emergence events reported since the 1960s. These results highlight the central role of anthropic pressure on ecosystems in present-day zoonotic risk patterns. The report also suggests primary prevention measures, running from reducing environmental pressures to regulation of at-risk interfaces, in order to explicitly integrate health concerns into the management of ecosystems and territorial development planning. In a similar vein, the 2021 creation of OHHLEP (One Health High-Level Expert Panel) by the WHO (World Health Organization), FAO (Food and

Demonstrating the links between biodiversity and the emergence of epidemics made it possible to embed public health targets into national and international biodiversity protection strategies, thereby aligning ecosystem management with prevention of emerging risks

Agriculture Organization), WOA (World Organization for Animal Health formerly *Office International des Epizooties* (OIE)) and UNEP (United Nations Environment Programme) marked a key step on the road toward the One Health model of integrated global governance. It provides governments with harmonized recommendations on the prevention of zoonotic risks, sustainable regional planning and development, and intersectoral coordination.

Demonstrating the links between biodiversity and the emergence of epidemics made it possible to embed public health targets into national and international biodiversity protection strategies, thereby aligning ecosystem management with prevention of emerging risks. This approach acknowledges that conserving habitats, reducing fragmentation of natural environments, and sustainably regulating inter-species interactions has a direct influence on pathogen dynamics. By explicitly incorporating human

⁵ IPBES. (2020). *Workshop Report on Biodiversity and Pandemics of the Intergovernmental Platform on Biodiversity and Ecosystem Services*. 108.



health into biodiversity frameworks such as the Kunming-Montreal Global Biodiversity Framework, governments are able to steer their actions toward measures offering co-benefits: ecological rehabilitation that reduces at-risk contact, eco-epidemiological surveillance in sensitive zones, and regulating trade of wild animals. This process of inclusion transforms environmental policies into tools providing real public health benefits, allowing authorities to better anticipate threats and protect people.

Although this recognition has improved global awareness, its effective appropriation by governments remains highly variable. Some countries have acted proactively to address these links: Costa Rica has reinforced protection for its ecosystems and developed an eco-epidemiological surveillance approach structured around its network of protected areas,⁶ and Colombia is trialing a system of ecological such as the corridors⁷ *Corredor de Protección del Jaguar* in Guaviare, covering an area of around 496,000 hectares. Conversely, conservation policies in many parts of the world remain inadequately funded or disconnected from health concerns, which limits their impact. This patchy implementation underlines the need for capacity-building, better international support and more robust intersectoral coordination to translate these conceptual advances into effective prevention actions. Certain international initiatives such as PREZODE (PREventing ZOonotic Disease Emergence) and ZODIAC (ZOonotic Disease Integrated ACTion) show how biodiversity protection can become a public health instrument in its own right. These programs support the establishment of observatories in the field, integrated surveillance systems and participative approaches designed to reduce anthropic pressure on ecosystems, stabilize animal communities and limit conditions favorable to pathogens jumping to other species. They also provide scientific, technical, financial and institutional support: PREZODE – launched by France and co-steered by the IRD, Cirad (French Agricultural Research Centre for International Development) and INRAE (French National Research Institute for Agriculture, Food and Environment) – currently works with over 220 partner institutions in more than 50 countries and

Conservation is not simply an ecological obligation but also a strategic investment for regional public health, economic and social resilience

with around 30 national governments. It funds pilot projects (€50 million), contributing to the rollout of surveillance mechanisms, bolstering local capacity and structuring networks focused on research and prevention. ZODIAC, coordinated by the IAEA (International Atomic Energy Agency), supplies diagnostic tools, training for national laboratories and operational support for surveillance in over 150 countries (with an initial budget of €80 million). Initiatives such as these combine states, health agencies, researchers and actors in the field to bolster prevention at the source. By promoting habitat restoration, sustainable management of natural resources and farming practices compatible with ecosystem health, these initiatives help governments to develop public policies that stifle risks at the source rather than responding to them retrospectively. For the time being, the long-term impact of these initiatives is difficult to measure as they are still at the stage where the focus is on strengthening capacities and infrastructure. However, their scientific component is beginning to prove that conservation is not simply an ecological obligation but also a strategic investment for regional public health, economic and social resilience.

UNDERSTANDING LOCAL DYNAMICS IN ORDER TO CO-CONSTRUCT PREVENTION STRATEGIES: EXAMPLES FROM LATIN AMERICA AND THE CARIBBEAN

While major international initiatives such as PREZODE⁸ and ZODIAC seek to link policies for protecting biodiversity and public health at the global level, their success is predicated on granular knowledge of local ecological and social dynamics. This is because the relationship between biodiversity and the circulation of pathogens varies considerably depending on environmental contexts, animal species involved and human-wildlife interactions.

In this regard, several studies seek to characterize the relationships between biodiversity, viral circulation and human exposure in South American tropical ecosystems, notably via the projects PREACTS-ASAMCO (2024-2028, €3 million between Mexico, Costa Rica and Haiti, involving 15 researchers/students) and TRANSVI (2026-2028, €200k, involving 10 researchers/students). These projects are run jointly by local research institutions in Mexico, Costa Rica and Haiti and international teams, mostly from France, in close collaboration with the appropriate

6 Aguilar-Vargas F, Solorzano-Scott T, Baldi M, Barquero-Calvo E, et al. Passive epidemiological surveillance in wildlife in Costa Rica identifies pathogens of zoonotic and conservation importance. *PLoS One*. 2022 Sep 26;17(9):e0262063. <https://doi.org/10.1371/journal.pone.0262063>. PMID: 36155648; PMCID: PMC9512195 ; Brumberg H, Furey S, Bouffard MG, Mata Quirós MJ, et al. Increasing Forest Cover and Connectivity Both Inside and Outside of Protected Areas in Southwestern Costa Rica. *Remote Sensing*. 2024; 16(6):1088. <https://doi.org/10.3390/rs16061088>.

7 Sara Pineda-Zapata, Sergio González-Ávila, Dolores Armenteras, Tania Marisol González-Delgado, Alejandra Morán-Ordoñez, Mapping the way: identifying priority potential corridors for protected areas connectivity in Colombia, *Perspectives in Ecology and Conservation*, Volume 22, Issue 2, 2024, Pages 156-166, ISSN 2530-0644, <https://doi.org/10.1016/j.pecon.2024.02.003>.

8 PREZODE: preventing zoonotic disease emergence, Peyre, Marisa et al. *The Lancet*, Volume 397, Issue 10276, 792 – 793. [https://www.thelancet.com/journals/lancet/article/PIIS0140-6736\(21\)00265-8/fulltext](https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(21)00265-8/fulltext).





Capture and handling of a bird (*Melanerpes pygmaeus*) during fieldwork in a local community.
© Aarón Rodríguez Blanco

health and environmental authorities in each country. This research, part of the process of shifting the PREZODE initiative to an operational status, aims to document the ecological, behavioral and social conditions that favor or curb zoonotic transmission of viruses – in particular arbovirus (viruses carried by rodents and transmissible to humans by inhalation of contaminated droplets or contact with their excreta), hantavirus (viruses transmitted by hematophagous arthropods, primarily mosquitos and ticks), and coronavirus – in order to reinforce local prevention and surveillance capacities.

One of the central areas of study for the PREACTS-ASAMCO project involves analyzing, in areas of high biological diversity in each partner country, how changing land use (deforestation, expansion of agriculture and intensive livestock farming, as well as urbanization) impacts the composition of animal communities and, as a consequence, the circulation and transmission of pathogens. The approach combines ecological, virological and social data to evaluate the degree to which protecting biodiversity can act as a mechanism preventing the emergence of zoonotic diseases. The data reveals the

conditions under which the dilution effect⁹ manifests, and, conversely, those where habit fragmentation or loss of key species amplifies the risk of transmission. Initial results from this work shows, for example, that in some agricultural areas of the Yucatán, stripping out natural features from the landscape as a result of increasingly standardized land use linked to more intensive farming, for instance, favors the dominance of rodent species highly susceptible to carry certain viruses (arboviruses or hantaviruses), thereby increasing their circulation within animal populations (approximately 15%), which can have a knock-on impact on the risk of human exposure. These observations make it possible to identify the most at-risk types of landscape configurations and provide guidance for recommendations about the area's management.

⁹ The dilution effect refers to the hypothesis whereby strong biodiversity can lower the risk of transmission of certain pathogens. Where several host species coexist, including species with poor pathogen transmission competence, they dilute transmission by interrupting transmission chains or diverting contacts with vectors in the case of vector-borne diseases. Conversely, loss of biodiversity tends to favor species with greater competence, which can increase risk of infection among human populations.





A bat (*Artibeus jamaicensis*) captured in the Yucatan (Mexico) and handled with protective gloves during a field session as part of an epidemiological surveillance protocol aimed at detecting and monitoring viruses in wildlife.
© Audrey Arnal

A project called TRANSVI, financed by ANRS-MIE (an Inserm agency focused on emerging infectious diseases), adopts a more mechanism-focused approach centered on characterizing transmission chains between wild animals and humans in the Yucatán Peninsula (Mexico). By studying the genetic diversity of viruses circulating in bats and rodents, as well as forms of human exposure related to farming, domestic and professional practices, it seeks to improve understanding of emergence interfaces and ecological conditions that favor cross-transmission. By combining field observations with genetic analyses and behavioral approaches, the project offers enhanced insight into the ecological and evolutionary mechanisms that govern inter-species transmission of viruses. This knowledge is essential for designing ecosystem management strategies capable of delivering a long-term reduction in the risk of human transmission.

These consortiums embody a new way of thinking about environmental health governance, one that is cooperative, decentralized, and inclusive

In addition to fundamental research, it is also essential to co-construct long-term prevention strategies that reflect local realities, using participative mechanisms that make space for the knowledge and needs of the communities concerned. The sites studied are populated predominantly by rural communities, smallholders, livestock farmers and, in some instances, indigenous groups living close to natural habitats. These people predominantly require access to reliable information about risks, greater local surveillance capacities and the adoption of farming or livestock practices that limit at-risk interfaces. A project called FOCUS (2026-2029, €600 000, 15 researchers/students, financed by the Mexican ministry for research, SECIHTI) examines this aspect in greater detail: it gets actors from health, environment and civil society sectors involved in developing local capacities for the prevention of zoonotic diseases. The aim is to transform scientific results into concrete tools for action by incorporating management of ecosystems and public health into a shared One Health approach.

These programs highlight the fact that the prevention of emerging diseases cannot be handled in isolation from environmental and social justice. The participation of rural communities, local universities and NGOs is essential to embedding prevention in local areas and bolstering resilience in the face of global changes. In Latin America, socio-economic conditions are marked by heavy dependency on natural resources, coupled with great cultural diversity: recognizing local knowledge and leveraging community dynamics thus appear to be indispensable conditions for any lasting actions.

By linking ecological research with virological surveillance and social sciences, these initiatives contribute to the emergence of a new integrated approach to prevention, one that places biodiversity at the heart of health policies. The challenge is no longer simply to understand how biodiversity loss favors the emergence of diseases, but to identify how protecting biodiversity can become a public health strategy in its own right.

LINKING THE GLOBAL AND LOCAL SCALES: TOWARDS INTEGRATED PREVENTION GOVERNANCE

Challenges surrounding the emergence of zoonotic diseases go far beyond the boundaries of specific disciplines or geographical areas. While major international initiatives such as PREZODE and ZODIAC are laying the foundations for global governance linking biodiversity and health, their effectiveness depends on their capacity to take root in the field.

The key to lasting prevention lies in this interaction between global coordination and local actions.



With this goal in mind, the creation of transnational consortiums makes it possible to link field action and research, ensuring the circulation of knowledge and good practices. These platforms for cooperation favor a genuinely integrated approach to health and biodiversity, where global policies are enriched by learnings from the field, and where local innovations can be disseminated as widely as possible.

One of the most significant examples of this approach is the creation of a regional network of NGOs and local actors from across seven Latin American and Caribbean countries, an initiative that is part of the *Fonds Équipe France – Une Seule Santé* [Team France Funds – One Health] project run by the French embassy in Mexico City and implemented by the IRD. The network fosters the sharing of educational, scientific and operational know-how surrounding the prevention of zoonotic diseases, environmental health and protection of ecosystems. By supporting an approach rooted in the co-construction of field actions and the active participation of local communities, it contributes to boosting territorial resilience in the face of emerging health risks while also embedding the principles of the One Health approach into local practices. Jointly constructed actions include awareness-raising workshops on zoonotic disease risks that incorporate local farming practices and traditional wisdom developed by several NGOs in the network together with local communities. In Mexico, participative educational training modules have been designed in collaboration with local schools and community committees to improve waste management, reduce mosquito larval habitats, and bolster local people's wildlife observations. These initiatives illustrate how co-construction makes it possible to adapt actions to specific local social and environmental realities.

These consortiums embody a new way of thinking about environmental health governance, one that is cooperative, decentralized, and inclusive. By linking the local and global scales, they provide a concrete expression of the fact that biodiversity is no longer merely an ecological concern, but a common good that needs protecting for the sake of everyone's health.

CONCLUSION

The rising number of health crises underlines the need to move beyond purely reactive approaches to a position where the prevention of zoonotic diseases becomes part of public policy centering on protection of the living world. Examples presented in this paper show how scientific advances, provided they are combined with solid international governance and local co-construction dynamics, make it possible to guide territorial management approaches toward measures offering concrete risk-reduction. However, the appropriation of these frameworks remains inconsistent from country to country, highlighting persistent disparities in technical, financial and intersectoral management capacities. Bolstering these mechanisms requires support for national institutions and community-based actors, encouraging productive practices that are compatible with ecosystem health, and consolidating regional cooperation networks. By placing biodiversity at the heart of prevention strategies, it becomes possible to build health systems that are more resilient and capable of anticipating emergent diseases rather than responding to them when it is too late.

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Indicators and Data:

Tools to Link Biodiversity and Health

Dr. David Nogués Bravo

Professor at the Globe Institute of the University of Copenhagen

Integrated biodiversity-health indicators are crucial to understand how changes in biodiversity affect human health, and for public and private actors to make decisions which can affect both biodiversity and health. Despite a push for such indicators at the international level, they remain rare and hard to develop. Without such indicators, governments and companies cannot see the cross impacts of their decisions-missing both health benefits (e.g., immune boosting exposure to nature) and risks (e.g., vector-borne diseases). Integrated metrics would also reveal compound risks, where environmental degradation amplifies health vulnerabilities. Developing them would require cross disciplinary expertise, better data integration, and stronger institutional commitment to systems thinking.

THE NEED FOR INTEGRATED BIODIVERSITY AND HEALTH INDICATORS

WHAT DO WE MEAN BY INTEGRATED INDICATORS AND METRICS, AND WHY DO SUCH INDICATORS REMAIN SO SCARCE TODAY?

Integrated indicators are metrics that help us understand in a combined manner the positive and negative impacts of biodiversity on human health, and answer questions such as: how does biodiversity change, and especially biodiversity loss, negatively or positively impact our health?

Today, biodiversity research and public health research rely on vastly different traditions: biodiversity scientists work with indicators such as species diversity, ecosystem diversity or functional diversity, while public health uses metrics like mortality, morbidity or the burden of disease. These disciplines have been working in separate silos, each studying different objects and generating metrics that cannot be directly connected. This separation remains the main bottleneck to creating integrated metrics. Although our understanding of biodiversity-health links is growing, the lack of indicators which explicitly capture this link makes it difficult to translate knowledge into decision making.

WHY ARE INTEGRATED BIODIVERSITY-HEALTH INDICATORS CRITICAL FOR INFORMING DECISION-MAKING BEYOND ACADEMIA, PARTICULARLY IN PUBLIC POLICY?

To my knowledge, there are no official integrated indicators on which decision makers can rely. There are existing studies linking species diversity to health outputs, such as on how the decline of pollinator populations can cause deficiencies in certain vitamins and worsen global malnutrition, causing an estimated 700,000 additional

annual deaths.¹ Some economic indicators can also assess health risks, for instance by evaluating the monetary cost of the non-use of plant resources as a therapeutic source.² However, these are not integrated indicators, and without such indicators, public and private decision makers are blind to the cross-consequences and implications of their decisions on biodiversity and health.

Denmark provides a good example of this: the Danish government is heavily investing in afforestation by supporting landowners in converting agricultural land into natural land, with an objective to cover approximately 10% of Denmark's total land area into nature and forest by 2045.³ These initiatives can have positive health impacts. Research has shown that natural habitats harbour significantly greater microbial diversity than agricultural or urban land – a pattern now documented in detail for Denmark itself⁴ – and that exposure to this richer environmental microbiome can modulate the human immune system, reducing the risk of inflammatory and allergic conditions.⁵ But afforestation also carries potential negative consequences, including a rise in Lyme disease risk as warming climates expand tick populations. Without integrated indicators, ministries planning land use or forest expansion are missing these opportunities and risks.

1 Smith M, Singh G, Mozaffarian D et al. Effects of decreases of animal pollinators on human nutrition and global health: a modelling analysis *The Lancet*, 2015; 386, 1964-1972. [https://www.thelancet.com/journals/lancet/article/PIIS0140-6736\(15\)61085-6/fulltext](https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(15)61085-6/fulltext).

2 Theodoridis S, Drakou EG, Hickler T, Thines M, Nogués-Bravo D. Evaluating natural medicinal resources and their exposure to global change. *Lancet Planet Health*. 2023 Feb;7(2):e155-e163. [https://doi.org/10.1016/s2542-5196\(22\)00317-5](https://doi.org/10.1016/s2542-5196(22)00317-5).

3 European Commission, 2025 approves €626 million Danish State aid scheme to support planting forests. https://ec.europa.eu/commission/presscorner/detail/en/ip_25_1971.

4 Singleton, C.M., Jensen, T.B.N., Delogu, F. et al. The Microflora Danica atlas of Danish environmental microbiomes. *Nature* 649, 971–981 (2026). <https://doi.org/10.1038/s41586-025-09794-2>.

5 Roslund, M.I. et al. (2020). Biodiversity intervention enhances immune regulation and health-associated commensal microbiota among daycare children. *Science Advances*, 6(42), eaba2578. <https://doi.org/10.1126/sciadv.aba2578>.



At the global level, countries engaged in the Convention on Biological Diversity agreed in November 2024 to consider the health dimensions of biodiversity and to implement a Global Action Plan on Biodiversity and Health, and notably to work on the development of “*integrated science-based indicators, metrics and progress measurement tools on biodiversity and health level*”.⁶ Although not legally binding, this marks an important shift toward recognizing the planet as a “system of systems” and the need for system thinking in both biodiversity and health decisions. However, despite this momentum, no concrete measures have yet been formalized.

IN THE PRIVATE SECTOR, RISKS RELATED TO BIODIVERSITY AND HEALTH ARE OFTEN ASSESSED SEPARATELY. WHAT ARE THE CONSEQUENCES OF THIS SEPARATION?

In the economic and financial sectors, indicators determine how decisions are made and how companies evaluate impacts on their own activities and on their clients. Accountability and traceability can only be seen and understood through indicators. If companies assess biodiversity risks on one side and health risks on another, they overlook how these dimensions interact – and they thereby miss critical information.

This issue was highlighted in June 2025, when the United Nations Environment Programme and several major insurance companies, including AXA and Crédit Agricole Assurances, published a report showing that insurers may be underestimating the risks posed by biodiversity change to human health simply because they can’t connect the dots yet:⁷ nature-related risks are so far not fully integrated in their risk assessment frameworks. For example, there has been little evaluation of the rising risks of diseases and illnesses that might result from the possible future decline in natural products available for pharmaceutical research and development. Indeed, pharmaceutical companies heavily depend on plant and fungal diversity: approximately half of developed pharmaceutical drugs are rooted in or inspired by natural compounds. For instance, Paclitaxel, a compound derived from the Pacific yew tree, is used to manufacture medications that treat breast, ovarian, and lung cancers.⁸ Losing plant species may therefore mean losing current and potential future treatments.²

In the economic and financial sectors, indicators determine how decisions are made and how companies evaluate impacts on their own activities and on their clients

This is also true outside of the health industry. In textiles, producing a single pair of jeans requires thousands of liters of clean water – and biodiversity is one of the main natural filters producing clean water. Construction companies rely heavily on natural resources extracted from ecosystems. And the extraction of these resources often happens off-site, in other parts of the world and disproportionately affects the health of local and indigenous communities whose livelihood may depend on the extracted resources. A concrete example is soy production in the Brazilian Amazon. Much of the animal feed consumed in Europe is derived from soybeans grown thousands of kilometers away, in one of the world’s most biodiverse regions. The expansion of soy farming there has driven large-scale deforestation and intensive pesticide use – at rates more than twice those seen in the United States. Studies show that this pesticide intensification, spreading through local water supplies, was associated with increased childhood cancer mortality in surrounding communities⁹ – communities that had no say in, and no economic benefit from, European consumption patterns. Indigenous peoples are particularly exposed, facing both displacement and the degradation of the ecosystems their livelihoods depend on. This is precisely the kind of compound, cross-border, biodiversity-health risk that current indicators are entirely blind to.

HOW COULD INTEGRATED INDICATORS IMPROVE RISK ASSESSMENT AND HELP AVOID SYSTEMIC UNDERESTIMATION OF RISKS?

When risks are assessed separately, we fail to capture compound risks, a combination of risks which can be of different nature and whose collective impact may be more severe than when they occur alone. Compound risks are not merely added, but they amplify each other. Such risks must be assessed as a system, and not as isolated elements.

For instance, the risks associated with extreme weather events on coastal areas – such as injuries, displacement and mental health impacts – increase when mangroves, an essential ecosystem protecting coastlines from hurricanes and floods, are degraded. If their decline is not accounted for in risk models, the vulnerability to extreme weather events may be severely underestimated. Pandemics show similar patterns: when forests are cleared for infrastructure or urban expansion, species that were previously isolated come into closer contact with humans, increasing the chances of zoonotic transmission.

⁶ Decision adopted by the Conference of the Parties to the Convention on Biological Diversity on 1 November 2024. <https://www.cbd.int/doc/decisions/cop-16/cop-16-dec-19-fr.pdf>.

⁷ United Nations Environment Programme (2025). Rooted in Risk: Framing Nature-Related Assessments for Insurers. <https://www.unepfi.org/wordpress/wp-content/uploads/2025/06/Rooted-in-Risk-1.pdf>.

⁸ Liu, J.C.T., De La Peña, R., Tocol, C. et al. Reconstitution of early paclitaxel biosynthetic network. *Nat Commun* 15, 1419 (2024). <https://doi.org/10.1038/s41467-024-45574-8>.

⁹ Skidmore, M.E., Sims, K.M., & Gibbs, H.K. (2023). Agricultural intensification and childhood cancer in Brazil. *Proceedings of the National Academy of Sciences*, 120(45), e2306003120. <https://doi.org/10.1073/pnas.2306003120>.



Finally, integrated indicators would help correct a fundamental mismatch: the timing of company boards is very different from the timing of natural processes. Ecosystem change unfolds over decades, while corporate decision cycles are short. Indicators make long-term ecological dynamics visible within shorter decision horizons. This logic resembles the planetary boundaries framework, whose philosophical root is systems thinking – linking climate, biodiversity, contaminants, aerosols and other processes into a single interconnected whole. A concrete illustration comes from my work in the Lesotho Highlands,¹⁰ where more frequent storms accelerated soil erosion and reduced key plant species. As vegetation declined, cattle had poorer grazing conditions, became weaker and produced less food for families. This cascade – from ecosystem degradation to livestock health and human nutrition – was entirely missed by existing metrics, showing how deeply interdependent biodiversity and health are, and how invisible these links remain without integrated indicators.

THE CHALLENGES TO THE DEVELOPMENT OF INTEGRATED BIODIVERSITY-HEALTH INDICATORS

WHAT ARE THE MAIN BARRIERS THAT HAVE SO FAR LIMITED THE DEVELOPMENT OF INTEGRATED BIODIVERSITY-HEALTH INDICATORS?

Several obstacles explain why integrated indicators have not yet emerged, despite the growing urgency. The first barrier is the lack of integrated expertise. These indicators sit between disciplines living in silos, and very few institutions or career paths reward boundary crossing work.

A second barrier concerns funding structures. When applying for grants, researchers are often forced to classify their project into strict categories that may not be relevant. Panels and reviewers struggle to determine how to classify work which overlaps over several categories. Even though cross disciplinary grants are slowly increasing, for instance Synergy Grants awarded by the European Research Council, this lack of fit within traditional funding schemes significantly slows down progress.

A third challenge is institutional and data related. Both ecology and public health generate massive amounts of data – from field monitoring to remote sensing, genomic analyses,

and lifelong medical records. But these datasets are not easily comparable, since they differ in spatial and temporal scales, and often belong to separate ministries or institutions. Linking them requires breaking institutional barriers and creating shared data infrastructures, which do not yet exist.

On the international stage, the need for integrated indicators was raised for the first time in plenary at the latest meeting in Panama preparing the next COP on biodiversity in October 2025, an important milestone, but one that also shows how recent and underdeveloped this field still is.¹¹

THE INTERACTIONS BETWEEN BIODIVERSITY AND HEALTH ARE INHERENTLY COMPLEX. HOW CAN INDICATORS CAPTURE THIS COMPLEXITY WHILE REMAINING OPERATIONAL?

Biodiversity is intrinsically complex, covering three levels: genetic diversity, species diversity and ecosystem diversity. Each of these levels interacts with health through multiple positive or negative pathways. Indicators cannot fully capture the complexity of these interactions but must instead simplify them. They help translate complex ecological processes into a form that can be operational for policymakers, such as in the planetary boundaries framework, where scientists managed to identify one key indicator to assess when each boundary is breached. For instance, the climate change boundary was set at a CO₂ concentration in the atmosphere exceeding 350 ppm (parts per million)¹².

There is ongoing discussion in the scientific community about whether we should develop one overarching biodiversity indicator or rely on several complementary indicators. A flagship indicator, such as CO₂ equivalent metrics in climate policy, can help mobilize action, but I do not advocate for a single metric as the solution. In my view, we should pursue both: create metrics that make the issue visible while developing a diverse set of indicators tailored to specific problems, sectors and regions.

The essential question is whether the indicator makes sense for what we need: it must capture the link we want to measure, remain operational, and function across various settings. It must be tested, validated and improved over time, as no single metric can capture all dimensions of biodiversity or all the pathways that connect ecological change to human well-being.¹³

Biodiversity is intrinsically complex, covering three levels: genetic diversity, species diversity and ecosystem diversity. Each of these levels interacts with health through multiple positive or negative pathways

¹⁰ EU MAPOSDA project (Management and Policy Options for the Sustainable Development of Communal Rangelands and their Communities in Southern Africa, INCO-DEV, Contract No. ICA4/CP/2000/50006).

¹¹ Convention on Biological Diversity, 27th Meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA-27), Panama City, 22 October 2025.

¹² Katherine Richardson *et al.*, Earth beyond six of nine planetary boundaries. *Sci. Adv.* 9, eadh2458 (2023). DOI:10.1126/sciadv.adh2458.

¹³ Nogués-Bravo D, Whitmee S, Willetts L. Metrics for biodiversity and health policy integration. *PLOS Glob Public Health*. 2025 Jul;5(7):e0004624. <https://doi.org/10.1371/journal.pgph.0004624>.



MOVING FORWARD ON INTEGRATED INDICATORS

INTERNATIONAL GOVERNANCE FRAMEWORKS ALREADY AIM TO PROMOTE INTEGRATED INDICATORS.

HOW CAN THESE EFFORTS BE STRENGTHENED?

International frameworks such as the Convention on Biological Diversity, established in 1992, and the Kunming-Montreal Global Biodiversity Framework, adopted in 2022, play an important role because they make the need for integrated indicators visible and encourage countries to move in this direction. However, these frameworks describe what indicators should achieve, but the scientific work to produce them is still to be done, and no operational set exists yet. The Global Biodiversity Framework includes health-related indicators, such as the proportion of water bodies with good water quality, pesticide concentrations in ecosystems, availability of pollinator species and disaster mortality. These are useful, but they are not truly integrated. They sit on the biodiversity side and gesture toward health rather than measuring the link between the two.

For indicators to be effective, they must meet several key traits. They should be applicable and comparable across different contexts (geographical, cultural or economic) so that they can guide international policy decisions consistently. They must be scalable, from national planning to local implementation, and flexible enough to adapt to diverse situations. Transparency is also essential: users must understand how indicators are built and be able to replicate them. Finally, indicators should be iterative, able to evolve as new data becomes available and as they are tested with companies and public bodies.

Integrated indicators can be understood as part of a broader preventive approach, since nature itself functions as preventive medicine. Without such indicators, it is impossible to link biodiversity actions to their health implications or anticipate the risks and benefits they create.

WHAT CAN BE DONE TO ACCELERATE THE DEVELOPMENT AND UPTAKE OF INTEGRATED INDICATORS?

Several conditions are needed to move forward. First, we need strong investment, and we need it quickly. Political commitment and regulatory support are crucial to ensure these indicators are developed and adopted.

Second, we must strengthen cross sector collaboration, involving public institutions, private companies and academia. Training experts able to work across these domains is essential. To help fill this gap, we are launching a one-year master's program at the University of Copenhagen on systems thinking, planetary health and biodiversity-health interactions, aimed at building the critical mass of expertise needed and connecting students with interested companies. These indicators are essential not only for understanding current dynamics but also for anticipating what health systems should prepare for in the coming decades.

Third, indicators should benefit everyone, not only a few actors. Many impacts of biodiversity loss fall disproportionately on countries with limited health systems. Indigenous and local communities depend directly on healthy ecosystems for food, water and traditional medicinal plants. Indicators should therefore be developed with these communities, not simply for them.

Finally, scientists must translate indicators into a language relevant for decisionmakers. Many organizations do not yet see the value of integrated indicators, not because of resistance, but because the benefits remain abstract. Concepts such as compound risk help reveal what is currently invisible. Ultimately, indicators allow us to make problems visible, and once visible, they can be addressed.



About the author

Dr. David Nogués Bravo is Professor at the Globe Institute of the University of Copenhagen, specializing in the interactions between biodiversity and human health. With over two decades of experience, he contributes to advancing integrated approaches that link ecological change with vulnerability, exposure, and health outcomes. His work spans quantitative models, conceptual development, and the design of indicators capable of capturing biodiversity-health dynamics in ways that support public policy and private sector decision making.



RNA Technology:

Transforming the Future of Sustainable Agriculture

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Agriculture is entering a critical transition driven by climate change, increasing global food demand, and the urgent need to reduce environmental impact. Conventional agrochemical-based systems, while historically successful in boosting productivity, have generated severe ecological and health concerns, including resistance development, biodiversity loss, and contamination of soil and water systems. In this sense, RNA-based technologies have emerged as a promising alternative, enabling precise and sequence-specific regulation of gene expression through RNA interference (RNAi). This natural mechanism allows the silencing of essential genes in pests and pathogens while minimizing off-target effects and environmental persistence. During the last few years, exogenous RNA technologies, such as spray-induced gene silencing (SIGS), have emerged as a non-transgenic, flexible, and rapidly adaptable approach for crop protection. Beyond pathogen control, RNA molecules can also act as regulators of plant physiology, opening opportunities for crop enhancement and stress tolerance. The convergence of RNA biology, nanotechnology, and scalable production systems positions RNA as a central tool for the next generation of agricultural innovation. This article examines the limitations of conventional agriculture, the emergence of biological alternatives, and the transformative role of RNA technologies in sustainable crop production.

INTRODUCTION

Agriculture is facing unprecedented challenges as climate change intensifies and global food demand continues to rise. At the same time, the environmental and health costs of conventional agrochemical-based systems are becoming increasingly evident, calling for innovative and sustainable alternatives. In this context, RNA-based technologies are emerging as a powerful new approach, offering precise, adaptable, and environmentally friendly solutions for crop protection and improvement. By leveraging natural mechanisms of gene regulation, RNA can act as a programmable tool to manage pests, enhance plant resilience, and reduce reliance on chemical inputs. This article explores how RNA is reshaping the future of agriculture and enabling a transition toward smarter, more sustainable farming systems.

THE HIDDEN COSTS OF MODERN AGRICULTURE

Modern agricultural systems have been shaped by the intensive use of synthetic agrochemicals to sustain high crop yields. Globally, more than 4 million tonnes of pesticides are applied each year, alongside massive inputs of nitrogen-based fertilizers and herbicides such as glyphosate, one of the most widely used compounds worldwide. While these inputs have played a major role in increasing productivity, they have also generated high environmental and societal costs. The widespread application of pesticides, herbicides, and fertilizers has led to contamination of ecosystems, disruption of soil microbiomes, and negative impacts on non-target organisms. These effects include biodiversity

loss and the decline of beneficial species such as pollinators.¹ A well-documented example is the impact of neonicotinoid insecticides, which have been linked to declines in bee populations and impaired pollination services.² Additionally, the repeated use of agrochemicals has driven the emergence of resistant pest and pathogen populations, progressively reducing the long-term effectiveness of these compounds and forcing the continuous development of new chemical solutions. This dynamic not only increases production costs but also amplifies environmental burden.³

From a public health perspective, the consequences are equally concerning. Each year, millions of individuals are exposed, with a significant proportion affecting agricultural workers in low- and middle-income countries.⁴ For instance, in regions of Argentina and Brazil, frequent contact with agrochemicals such as glyphosate and organophosphates has been associated with increased risks of neurological disorders, endocrine disruption, reproductive issues, and certain cancers.⁵ In some cases,

1 Carvalho FP. 2017. Pesticides, environment, and food safety. Food and Energy Security 6: 48–60. <https://doi.org/10.1002/fes3.101>.

2 Goulson D, Nicholls E, Botias C, Rotheray EL. 2015. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science 347: 1255957. <https://doi.org/10.1126/science.1255957>.

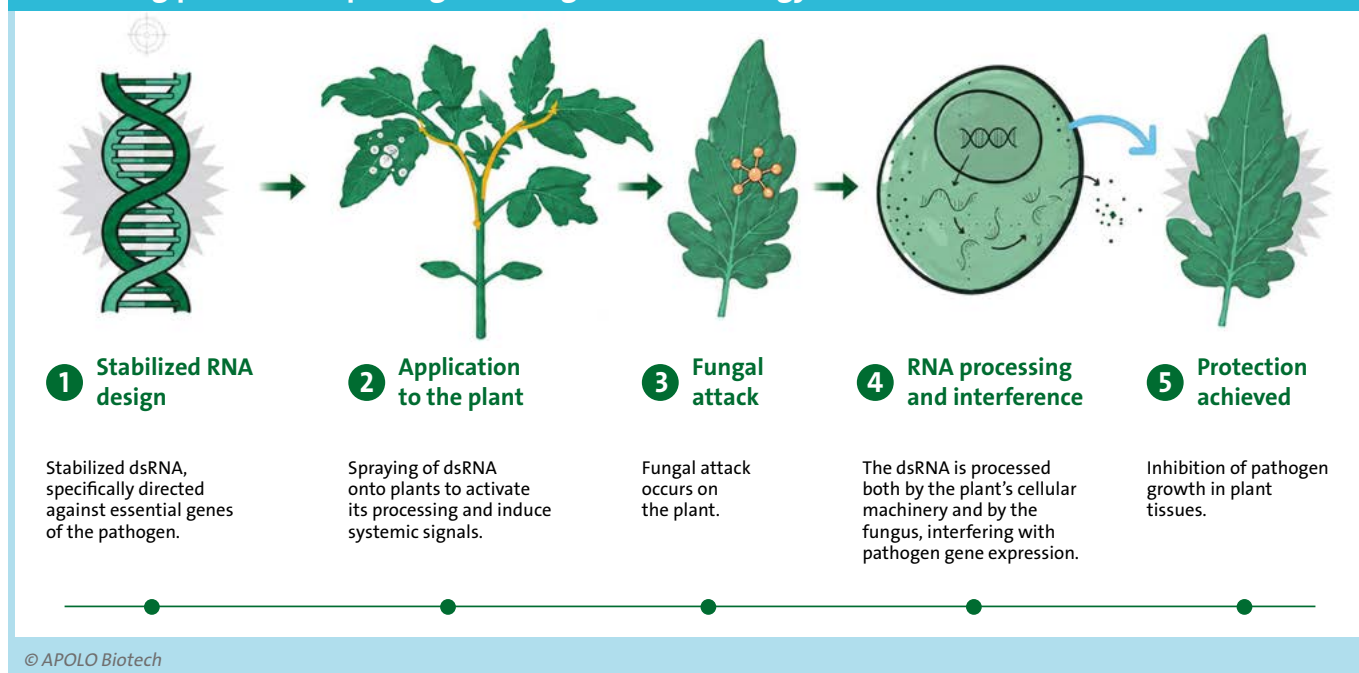
3 Fisher MC, Henk DA, Briggs CJ, Brownstein JS, Madoff LC, McCraw SL, Gurr SJ. 2018. Emerging fungal threats to animal, plant and ecosystem health. Nature 484: 186–194. <https://doi.org/10.1038/nature10947>.

4 Nicolopoulou-Stamati P, Maipas S, Kotampasi C, Stamatis P, Hens L. 2016. Chemical pesticides and human health. Frontiers in Public Health 4: 148. <https://doi.org/10.3389/fpubh.2016.00148>.

5 Kim KH, Kabir E, Jahan SA. 2017. Exposure to pesticides and the associated human health effects. Science of the Total Environment 575: 525–535. <https://doi.org/10.1016/j.scitotenv.2016.09.009>.



Protecting plants from pathogens using RNA technology



pesticide residues have also been detected in water sources and food products, raising concerns about chronic exposure in the general population. At the same time, global crop losses caused by pests and pathogens remain considerable, typically ranging between 20% and 40% annually, underscoring the limitations of current protection strategies.⁶ Together, these challenges highlight the need for innovative, sustainable, and highly specific alternatives that can reduce environmental impact while maintaining agricultural productivity.

Globally, more than 4 million tonnes of pesticides are applied each year, alongside massive inputs of nitrogen-based fertilizers and herbicides such as glyphosate

FROM CHEMICALS TO SMARTER SOLUTIONS

The transition toward sustainable agriculture has led to increased interest in biological and ecological approaches that reduce reliance on synthetic inputs. Strategies such as the use of beneficial microorganisms, soil microbiome management, and regenerative agricultural practices aim to enhance plant resilience and restore the ecosystem balance.⁷ Plant growth-promoting microorganisms (PGPMs) and mycorrhizal fungi can improve nutrient uptake, stimulate plant immunity, and suppress pathogens through mechanisms such as induced or acquired systemic resistance.⁸

Similarly, soil-focused practices, including reduced tillage, organic amendments, and crop rotation, contribute to improved soil health, microbial diversity, and long-term sustainability.⁹ However, while these approaches are environmentally beneficial, they often lack the precision, predictability, and scalability required to fully replace synthetic agrochemicals. For instance, the performance of PGPMs can vary significantly depending on soil composition, temperature, moisture, and the existing microbial community, leading to inconsistent outcomes across different fields and seasons. Similarly,

practices such as crop rotation or the use of organic amendments generally act through indirect mechanisms, such as improving soil structure or stimulating plant immunity, which can take time to translate into measurable protection against specific pests or pathogens. In addition, these strategies are typically not designed to target a particular organism at the molecular level. As a result, their effects are often broad and context-dependent rather than specific and predictable.

RNA-based technologies bridge this gap by combining biological compatibility with molecular precision. Ribonucleic acid (RNA) is a natural molecule present in all living organisms that plays a central role in translating genetic information into biological functions. In simple terms, RNA acts as a messenger and regulator, carrying instructions from DNA and

6 Rodríguez Melo J, Mammarella MF, Ariel F. 2023. Exogenous RNAs: promising tools for the second green revolution. *Journal of Experimental Botany* 74: 2323–2337. <https://doi.org/10.1093/jxb/erad023>.

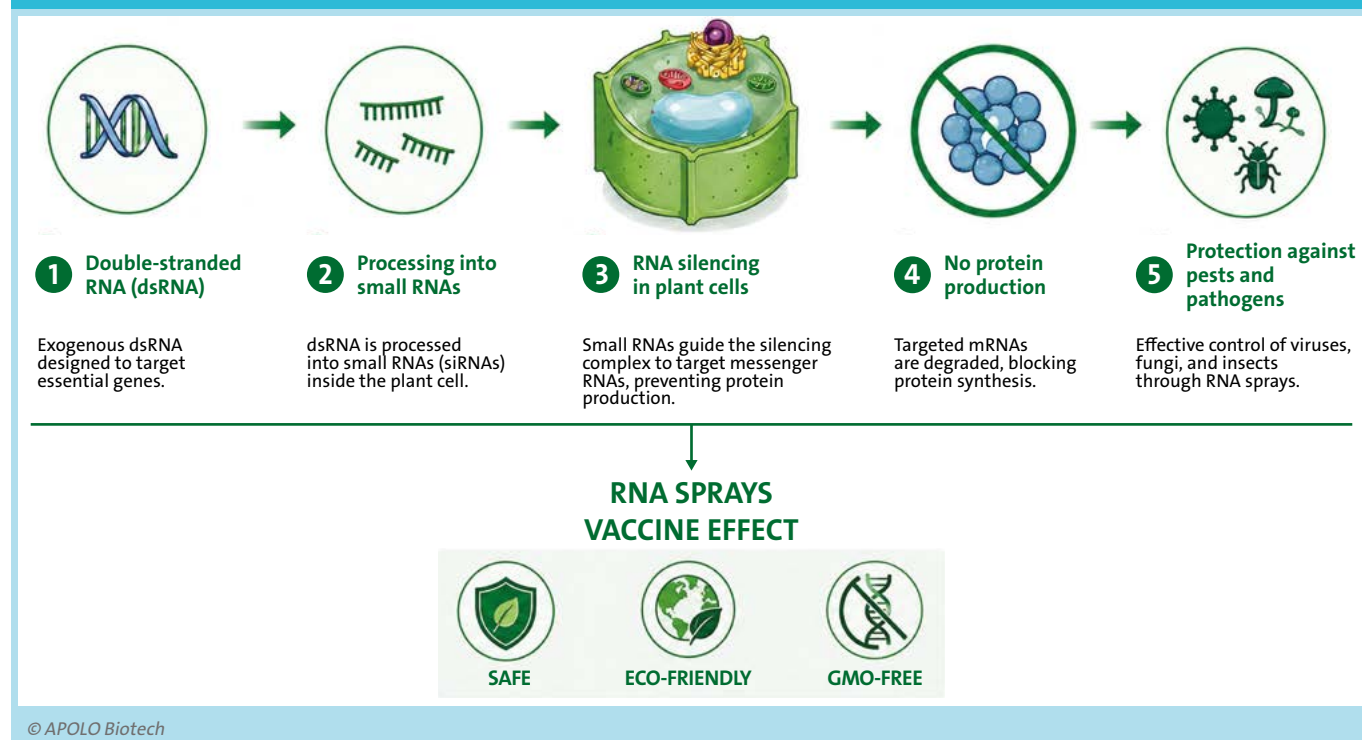
7 Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S. 2002. Agricultural sustainability. *Nature* 418: 671–677. <https://doi.org/10.1038/nature01014>.

8 Backer R, Rokem JS, Ilangumaran G, Lamont J, Praslickova D, Ricci E, Subramanian S, Smith DL. 2018. Plant growth-promoting rhizobacteria: context, mechanisms of action, and road map to commercialization of biostimulants for sustainable agriculture. *Frontiers in Plant Science* 9: 1473. <https://doi.org/10.3389/fpls.2018.01473>.

9 Lal R. 2020. Regenerative agriculture for food and climate. *Journal of Soil and Water Conservation* 75: 123A–124A. <https://doi.org/10.2489/jswc.75.5.123A>.



RNA-based tech in plants



controlling how genes are expressed. RNA molecules can be designed to specifically target essential genes in pests and pathogens, providing a highly selective mode of action¹. By matching a precise genetic sequence, these molecules can silence the expression of a target gene, effectively disrupting vital processes in the organism without affecting others.¹⁰ Unlike many conventional pesticides, RNA-based solutions are biodegradable and generally exhibit limited persistence in the environment. RNA molecules are naturally occurring and are rapidly broken down by environmental factors such as UV radiation, temperature, and naturally present enzymes. In contrast, several synthetic agrochemicals can remain active in soils and water systems for extended periods, depending on their chemical properties and environmental conditions.¹¹ This reduced persistence, combined with the sequence-specific mode of action of RNA, contributes to a more targeted impact on agricultural ecosystems. The effects of RNA molecules are expected to be more selective, reducing unintended impacts on beneficial organisms such as pollinators, soil microbes, and other non-target species. Although only one RNA-based pesticide has so far received regulatory approval for agricultural use — GreenLight Biosciences' Calantha™ for the control of the Colorado potato beetle in the United States — the regulatory

landscape is rapidly evolving in major agricultural producers such as Brazil and Argentina. Consequently, RNA-based technologies are now widely viewed as a cornerstone of the transition toward a more sustainable and resilient agriculture.

Regarding human health, current evidence indicates that RNA-based products present a low risk under typical conditions of use. RNA is a natural molecule that is rapidly degraded in biological systems, and its activity depends on specific cellular uptake and sequence recognition. This reduced persistence, combined with the sequence-specific mode of action of RNA, contributes to a more targeted impact on agricultural ecosystems. In these applications, the active molecules are often double-stranded RNA (dsRNA), which consists of two RNA strands paired together and carrying a specific genetic message to trigger silencing and block an infection.

Importantly, RNA technologies can be rapidly adapted to emerging threats. The ability to redesign dsRNA sequences in response to evolving pathogens provides a dynamic and responsive approach to crop protection,¹² analogous to RNA vaccines under continuous development during the COVID pandemic due to the emergence of novel variants of the virus. The integration of RNA-based tools with biological inputs and precision agriculture technologies represents a paradigm shift toward smarter, data-driven agricultural systems. This convergence enables the development of sustainable solutions that are both effective and environmentally responsible.

¹⁰ Dalakouras A, Wassenegger M, McMillan JN, Cardoza V, Maegele I, Dadami E, Runne M, Krczal G. 2020. Induction of silencing in plants by high-pressure spraying of in vitro-synthesized small RNAs. *Frontiers in Plant Science* 11: 1067. <https://doi.org/10.3389/fpls.2020.01067>.

¹¹ Petrick JS, Brower-Toland B, Jackson AL, Kier LD. 2016. Safety of RNA-based crops. *Regulatory Toxicology and Pharmacology* 66: 167–176. <https://doi.org/10.1016/j.yrtph.2014.12.003>.

¹² Mitter N, Worrall EA, Robinson KE, Li P, Jain RG, Taochy C, et al. 2017. Clay nanosheets for RNAi delivery. *Nature Plants* 3: 16207. <https://doi.org/10.1038/nplants.2016.207>.



RNA: A NEW BIOLOGICAL LANGUAGE FOR AGRICULTURE

RNA molecules play a wide range of fundamental roles in regulating gene expression across all domains of life. Among their diverse functions, small RNAs, including microRNAs (miRNAs) and small interfering RNAs (siRNAs), are key players in RNA interference (RNAi), a conserved mechanism that enables sequence-specific gene silencing. These molecules are short RNA fragments that act as regulators, guiding the cellular machinery to specific genes and reducing their expression. While miRNAs are naturally produced by the organism to fine-tune its own gene activity, siRNAs are often generated in response to external signals, such as viruses or experimentally introduced RNA, helping cells to defend against or silence unwanted genetic information. This process is triggered by dsRNA, which is processed into small RNA molecules that guide the cell to recognize and silence matching genetic messages.¹³

In plants, RNAi is not only a regulatory mechanism but also a fundamental defense system against pathogens, particularly viruses. The RNAi machinery detects and processes pathogen-derived dsRNA, triggering a sequence-specific immune response that limits the infection.¹⁴ This natural defense mechanism has provided the foundation for the development of RNA-based crop protection technologies. The application of RNA technologies in agriculture can be broadly divided into two approaches: transgenic and non-transgenic. The host-induced gene silencing (HIGS) involves the expression of dsRNA within genetically modified plants, enabling continuous production of silencing molecules targeting pests or pathogens.¹⁵ While highly effective, this approach faces regulatory and public acceptance challenges. For example, crops engineered to express insect-targeting dsRNA, such as maize developed for resistance against the Western corn rootworm, have demonstrated strong protection in field conditions, but their deployment is subject to strict GMO regulatory frameworks, particularly in regions such as Europe, where approval processes are lengthy, and public perception remains cautious.

In contrast, exogenous RNA application methods, such as spray-induced gene silencing (SIGS), offer a non-transgenic alternative. This approach involves the external application of dsRNA onto plant surfaces, where it can be absorbed by plant tissues or directly taken up by pathogens and pests. Once internalized, the dsRNA triggers RNAi-mediated silencing of essential genes, leading to reduced virulence or disease symptoms.¹⁶

Several studies have demonstrated the effectiveness of exogenous dsRNA against a wide range of pathogens and diseases. For example, *Botrytis cinerea*, a parasitic fungus responsible for grey mold disease in many crops, can be controlled by targeting genes involved in its RNA processing machinery which are essential for its growth and ability to infect plants. Similarly, dsRNA applications have been shown to reduce infections caused by other major fungal pathogens, including *Fusarium* and *Sclerotinia*, both of which are responsible for significant agricultural losses worldwide.¹⁷ RNA-based strategies have also been successfully applied against insect pests, where they can interfere with genes essential for survival or reproduction, leading to increased mortality and reduced population growth.

While other technologies can act against a broad-spectrum of pathogens, a key advantage of RNA-based technologies is their specificity. dsRNA sequences can be designed to target unique regions of a specific pathogen genome that are not shared with other organisms. This level of precision allows the silencing of essential genes in the target organism while minimizing the likelihood of affecting non-target species, whose genetic sequences differ. As a result, RNA-based approaches can reduce unintended impacts on beneficial organisms and contribute to a more selective form of crop protection. This precision represents a major improvement over broad-spectrum chemical pesticides.¹⁸

Despite these advantages, the practical implementation of RNA technologies faces challenges related to stability, delivery, and cost. Naked dsRNA molecules are susceptible to degradation by environmental factors such as UV radiation, limiting their persistence and effectiveness. To overcome these limitations, significant efforts have been directed toward the development of advanced delivery systems. For example, some approaches use clay-based nanoparticles, such as layered double hydroxides (LDH), which can bind and shield RNA molecules from degradation on plant surfaces, allowing them to remain active for longer periods. Other strategies rely on natural polymers, such as chitosan, a biodegradable material derived from crustacean shells, which can encapsulate RNA and facilitate its uptake by plant cells. These delivery systems act as protective carriers, helping RNA molecules reach their target and extending their duration of action under field conditions.¹⁹ In parallel, advances in RNA production technologies are improving scalability and reducing costs. Both in vitro transcription systems and microbial production platforms are being optimized to enable large-scale manufacturing of dsRNA for agricultural applications.

13 Baulcombe D. 2004. RNA silencing in plants. *Nature* 431: 356–363. <https://doi.org/10.1038/nature02874>.

14 Pumplin N, Voinnet O. 2013. RNA silencing suppression. *Current Opinion in Plant Biology* 16: 541–550. <https://doi.org/10.1016/j.pbi.2013.06.003>.

15 Baum JA, Bogaert T, Clinton W, Heck GR, et al. 2007. Control of coleopteran insect pests through RNA interference. *Nature Biotechnology* 25: 1322–1326. <https://doi.org/10.1038/nbt1359>.

16 Dalakouras A, Wassenegger M, McMillan JN, Cardoza V, Maegele I, Dadami E, Runne M, Krczal G. 2020. Induction of silencing in plants by high-pressure spraying of in vitro-synthesized small RNAs. *Frontiers in Plant Science* 11: 1067. <https://doi.org/10.3389/fpls.2020.01067>.

17 McLoughlin AG, Wytinck N, Walker PL, Girard IJ, Rashid KY, de Kievit T, Fernando WGD. 2018. dsRNA targeting fungal pathogens. *Plant Biotechnology Journal* 16: 1651–1660. <https://doi.org/10.1111/pbi.12872>.

18 Petrick JS, Brower-Toland B, Jackson AL, Kier LD. 2016. Safety of RNA-based crops. *Regulatory Toxicology and Pharmacology* 66: 167–176. <https://doi.org/10.1016/j.yrtph.2014.12.003>.

19 Schwartz SH, Hendrix B, Hoffer P, Sanders RA, Zheng W. 2020. Carbon dots for efficient small interfering RNA delivery and gene silencing in plants. *Plant Physiology* 184: 647–657. <https://doi.org/10.1104/pp.20.00733>.



Taken together, these advances position RNA as a new biological language for agriculture, one that enables precise, programmable, and environmentally sustainable interactions with living systems. By leveraging the inherent regulatory capacity of RNA, it is possible to design solutions that are both highly specific and adaptable to changing agricultural challenges.

RNA-BASED TECHNOLOGIES BEYOND CROP PROTECTION: SPEAKING THE LANGUAGE OF PLANTS IN A CONTEXT OF CLIMATE CHANGE

Beyond their well-established role in crop protection, RNA-based technologies are opening new avenues for directly modulating plant physiology in response to environmental challenges. Central to this emerging paradigm is the noncoding transcriptome, which refers to the collection of RNA molecules that do not encode proteins but instead act as regulators of gene activity. These noncoding RNAs, including small RNAs (such as miRNAs and siRNAs, mentioned above) and long noncoding RNAs (lncRNAs), help control when and how genes are turned on or off. Once considered the “dark matter” of the genome, these molecules are now recognized as key regulators of gene expression, coordinating complex developmental programs and adaptive responses to stress.²⁰ In plants, noncoding RNAs play pivotal roles in sensing and responding to environmental cues, including drought, extreme temperatures, salinity, and pathogen attack. Specific ncRNAs are differentially expressed under stress conditions, where they regulate gene networks involved in hormone signaling, osmotic balance,²¹ reactive oxygen species detoxification, and immune responses. This dynamic and highly specific regulatory layer effectively constitutes a molecular language through which plants interpret and respond to their environment.²² Recent advances suggest that this language can be externally harnessed and reprogrammed, opening new avenues for climate-resilient agriculture. Exogenous RNA applications, traditionally focused on gene silencing in pests and pathogens, can be extended to deliver regulatory RNA molecules that mimic endogenous stress signals.²³ By designing RNA sprays that encode specific ncRNAs, it becomes possible to “inform” plants of imminent or ongoing environmental stress,

RNA-based approaches can reduce unintended impacts on beneficial organisms and contribute to a more selective form of crop protection

priming their defense and adaptation mechanisms before severe damage occurs. Studies have demonstrated that externally applied RNA molecules can modulate gene expression associated with stress responses, supporting the feasibility of this approach. These findings suggest that RNA applications could act beyond crop protection and directly influence plant responses to environmental cues. For instance, RNA molecules associated with drought-responsive pathways could be applied to activate water conservation strategies, while others could enhance tolerance to heat waves or cold stress by modulating protective gene networks.²⁴ Importantly, this capacity for rapid, targeted, and reversible intervention aligns with the urgent need for flexible and scalable solutions to sustain crop productivity under climate instability.

WHO LEADS THE RNA REVOLUTION? REGULATION AS THE DECISIVE FACTOR

In parallel with scientific and technological advances, the regulatory landscape will play a decisive role in shaping the deployment of RNA-based solutions in agriculture. In the United States, RNAi-based products have been largely classified as biopesticides under the regulatory framework of the Environmental Protection Agency, providing a relatively clear and innovation-friendly pathway for their evaluation and commercialization. This classification acknowledges the biological nature, specificity, and favorable environmental profile of dsRNA molecules, facilitating a faster translation from laboratory to field. At the same time, major agricultural producers such as Brazil have rapidly embraced

biological solutions, driven by the need to maintain productivity while reducing chemical inputs and meeting global sustainability demands, highlighting a growing recognition of RNA-based technologies as a key pillar of next-generation agriculture. In contrast, Europe is currently at a pivotal crossroads, where traditionally precautionary regulatory approaches could evolve to support innovation in alignment with strategic frameworks such as the Farm to Fork Strategy and the European Green Deal, both of which call for a reduction in chemical pesticide use and the promotion of safer, sustainable alternatives. By leveraging its long-standing leadership in RNA biology and biochemistry and establishing science-based, proportionate regulatory pathways tailored to the unique characteristics of RNA molecules, Europe has a clear opportunity to accelerate adoption, enhance agricultural sustainability, and strengthen its global competitiveness in agri-biotech innovation.

20 Zhang YC, He RQ, Cheng Y, Wang D, Ariel F, Chen YQ. Long noncoding RNAs as molecular architects: Shaping plant functions and physiological plasticity. *Mol Plant*. 2025 Oct 6;18(10):1643-1671. <https://doi.org/10.1016/j.molp.2025.09.008>.

21 Osmotic balance means a stable concentration of water and salts inside plant cells.

22 Chorostecki U, Bologna NG, Ariel F. 2023. The plant noncoding transcriptome: a versatile environmental sensor. *The EMBO Journal* 42: e114400. <https://doi.org/10.15252/embj.2023114400>.

23 Mammarella MF, Lucero L, Hussain N, Muñoz-Lopez A, et al. 2023. Long noncoding RNA-mediated epigenetic regulation of auxin-related genes controls shade avoidance syndrome in Arabidopsis. *The EMBO Journal* 42: e113941. <https://doi.org/10.15252/embj.2023113941>.

24 Attallah C, Conti G, Zuljan F, Zavallo D, Ariel F. 2025. Noncoding RNAs as tools for advancing translational biology in plants. *The Plant Cell* 37: koaf054. <https://doi.org/10.1093/plcell/koaf054>.



Tomato plants were treated with exogenous formulated dsRNA targeting *Botrytis cinerea*. Twenty-four hours after dsRNA application, plants were sprayed with a spore suspension of *B. cinerea*. Photos were taken 5 days post inoculation (dpi).



Non-treated plant



RNA-treated plant

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CONCLUSION

The increasing demand for sustainable agricultural practices requires innovative technologies that balance productivity with environmental and human health. RNA-based technologies offer a powerful alternative to conventional agrochemicals, providing precise, adaptable, and environmentally friendly solutions for crop protection and improvement. Ultimately, RNA technologies represent a paradigm shift in agriculture, enabling a transition toward more intelligent, precise, and sustainable farming systems. As part of an integrated strategy that includes biological inputs and improved agronomic practices, RNA-based solutions have the potential to contribute to global food security by helping maintain stable crop yields under increasing environmental pressure. Beyond productivity, these technologies may also

play a role in reducing reliance on synthetic agrochemicals, thereby lowering environmental contamination and potential exposure risks for farmers and consumers. In this sense, RNA technologies move beyond acting as external inputs and begin to function as informational tools, capable of interfacing with the plant regulatory network and modulating its behavior in a programmable way. Harnessing the regulatory capacity of the noncoding transcriptome positions RNA as a central component in the development of climate-resilient agriculture, supporting food systems that are not only more productive but also safer, more sustainable, and better aligned with long-term human and environmental health.

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Images, Narratives and Perceptions:

Tools for Preserving Biodiversity

Véronique Andrieux
CEO at WWF France

Biodiversity is collapsing faster than ever, and the knock-on effects are becoming increasingly visible. Despite this, the urgent need to preserve biodiversity is not translating into concrete actions due to inadequate or appropriated institutional messaging. This in turn creates distrust that encourages wait-and-see attitudes. This means that reimagining how we preserve the living world requires a shift in messaging and perceptions surrounding biodiversity. Health is emerging as a powerful narrative as part of this shift, capable of unifying the various aspirations of a fragmented public opinion. Shining a light on local, day-to-day biodiversity also provides the general public with concrete tools for preserving it. Additionally, short formats suited to social media and accessible messages rooted in popular culture offer a route for getting people interested in local ecological issues. Rethinking narratives is now an essential mechanism for raising awareness of biodiversity and health challenges. The ultimate goal is to make tangible the positive impacts citizen action can have for restoring biodiversity.

INTRODUCTION

Our mobilization is rooted in scientific proofs, backed by substantiated data. For example, our *Planète Vivante* report¹ highlights the collapse of biodiversity: wild vertebrate populations have fallen 68% since 1970. We know what causes this decline – deforestation, land conversion, overexploitation, climate disruption, pollution, and invasive species – and we know what the solutions are: reforming the food system, protecting and restoring ecosystems, and repurposing financing.

Despite the wealth of available knowledge, institutional messaging struggles for a foothold in public debate. In 2025, climate change dropped to seventh place on the ranking of French people's priorities, behind health,² despite the fact that the erosion of the living world directly increases health risks. It is clear that the problem lies not in a lack of information but in the lack of a sense of community. What can we learn from this contradiction and how can we give ecological evocations new momentum by 2030?

ANTI-NARRATIVES TRIGGER RESISTANCE AND A FEELING OF POWERLESSNESS

Although French people see ecological concerns as less of a priority, this does not reflect lack of awareness, as illustrated by a WWF Ipsos survey carried out in summer 2025: 96% of

respondents stated that nature is important to them.³ This disconnect could be explained by a feeling that they are deprived of concrete means of taking action. And political parties do not appear to be meeting people's demands for solutions to environmental problems. According to the 2025 *Destin Commun* survey, 58% of French people feel their elected representatives should do more to combat climate change and protect the population.⁴

The truth is that a number of narratives play a large part in people's lack of engagement with ecological issues. First, depictions of biodiversity as doomed fuel a climate of catastrophism. Although warnings about the twin-pronged climate and biodiversity crisis are based on solid scientific research, particularly studies by the IPCC⁵ and IPBES⁶, they do not always generate buy-in among the public. Instead of engagement, they are just as likely to trigger feelings of anxiety, resignation and paralysis that take away people's power to act. Then there is the problem that scientific jargon and a lack of emotion fail to help spread the message, everything from ecosystem services and functional biodiversity, to figures expressed in TWh and ppm. So many notions understood by experts but incomprehensible to the public. This technical language can create a distancing effect, even rejection, as the public does not identify with the people raising the alarm.

1 WWF France (2024) *Planète Vivante 2024 – Un système en péril* [Living Planet 2024 - An endangered system]. <https://www.wwf.fr/sites/default/files/doc-2024-10/Rapport%20Planete%20Vivante%202024%20-%20WWF%20France.pdf>.

2 Ipsos bva (2025) *Ce qui préoccupe les Français* [What Worries People in France] - September 2025 | Ipsos. <https://www.ipsos.com/fr-fr/ce-qui-preoccupe-les-francais>.

3 Ipsos bva. (2025). *La perception par les Français du lien entre écologie et politique* [How people in France see the link between ecology and politics] – October 2025. <https://www.wwf.fr/sites/default/files/doc-2025-11/Ipsos%20bva%20pour%20WWF%20-%20Ecologie%20et%20politique%20-%20Octobre%202025.pdf>.

4 Destin Commun (2025) *Élections municipales 2026 : à quatre mois du scrutin, les Français expriment des attentes claires pour leurs communes* [2026 local elections: four months from the vote, French people express what they expect of municipalities]. <https://www.destincommun.fr/analyses-et-debats/elections-municipales-2026-mobilisation-et-attentes-des-francais-destin-commun/>.

5 Intergovernmental Panel on Climate Change.

6 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.



The fight to protect biodiversity is sometimes linked to what is known as punitive ecology. Too often ecology is portrayed as synonymous with a series of moralizing and guilt-laden constraints, while the cost to the cost to the community of the negative externalities of environmental destruction and damage is hidden. The public is deprived of concrete means for taking action when support and funding for the transition are not guaranteed. The carbon tax increase of 2018 is instructive: it crystalized a feeling of injustice and contributed to the emergence of the yellow-vest movement in France. Most people feel they face a dichotomy between the end of the world and the end of the month, and the issue of purchasing power ranks highest among French people's concerns.² But opposing these two struggles is misleading. Climate change exacerbates inequalities: the poorest inhabitants are hit hardest despite their smaller environmental footprint, and therefore very little responsibility for the situation. In working-class districts, badly insulated housing worsens the effects of heatwaves and cold, demonstrating the interdependence between social justice and ecological transition.

Climate change exacerbates inequalities: the poorest inhabitants are hit hardest despite their smaller environmental footprint, and therefore very little responsibility for the situation

At the same time, the direction taken by public debate serves neither to ease tensions nor to encourage complex thinking. Changes in the media sphere, now structured by social media, necessitate short formats very much guided by algorithmic principles. New narratives therefore need to take account of these new codes, while retaining their scientific rigor and power to explain.

THE POWER OF NARRATIVES AND EVOCATIONS: THE WWF FRANCE EXPERIMENT

New narratives subjected to public consultation

In 2025, WWF France carried out an ambitious experiment. Over a nine-month period, it gathered a multi-disciplinary group of researchers, field actors, artists and experts in an encounter of different perspectives designed to promote the emergence of ecological narratives grounded in contemporary evocations. Narratives were then tested in real life via surveys, scientific discussions, and a wide-reaching public consultation (10,000 participants). The aim was to identify narratives capable of triggering people's emotions, engagement, and support.⁷ Next, the themes pinpointed (health, heritage, geopolitics and the economy) were checked and approved using a poll organized in collaboration with Ipsos Bva.⁸ The results were conclusive.

Health emerged as the most powerful tool for engagement: 79% of participants felt the link between biodiversity and health was "significant" and 19% said that environmental health impacts their mental wellbeing. Narratives anchored in personal journeys are the most effective: the health

narrative had the strongest foothold, with the example of clusters of pediatric cancers in the French department Charente-Maritime linked to pesticides. These narratives confirm that people take action when they feel personally concerned (creating local collectives, mapping exposure, setting up epidemiological surveys, etc.).⁷ According to one participant: "You don't protect the planet out of altruism alone, but because you want to protect what's important to you: your health, your home, the place where you live, your wallet." Conversely, geopolitical issues such as conflicts surrounding water or reliance on uranium remain abstract and are the least inspirational narratives.

When ecology draws on personal, concrete experiences, it becomes impossible to ignore. To avoid crippling anxiety, it is essential to offer concrete ideas such as:

- "Here's how to reduce exposure to pesticides: buy organic goods, support farmers converting to organic agriculture, demand buffer zones around schools."
- "In the Loire-Atlantique region, parents succeeded in having spraying banned near housing. And it works."

The financial argument is pivotal for home-owning middle classes: a drop in the value of their main residence clearly illustrates the link between economy and climate. Knowing that your home insurance premium could double by 2050 makes the threat tangible, even if it is not happening just yet. To make the issue more immediate, it is useful to point to accessible solutions such as insulating homes, greening neighborhoods, and restoring wetlands.

Connecting French people's daily lives and biodiversity

The big five: powerful symbols that serve to drive engagement as well as encourage inaction

The big five (lions, elephants, leopards, buffalos and rhinoceroses) alongside other iconic species (tigers, polar bears and great apes) remain powerful tools for engagement. "The lion symbolizes unspoiled nature, an archetype that speaks to our collective imagination. When the lion disappears, part of our humanity is lost," says Alexandra Palt, President of WWF France.⁹ These star animals embody the beauty of the natural world. Their images always generate peak levels of sharing on social media. WWF has already taken advantage of this, including with the #LastSelfie campaign in 2014. Selfies posted on Snapchat with the message "Don't let this be my #LastSelfie" went viral.¹⁰



7 WWF (2025) *Récits pour une écologie populaire - renouer avec les préoccupations des Français*.pdf [Narratives for a people's ecology: reconnecting with French people's concerns].

8 Ipsos bva (2025). *La perception par les Français du lien entre écologie et politique* [How people in France see the link between ecology and politics] – October 2025. <https://www.wwf.fr/sites/default/files/doc-2025-11/Ipsos%20bva%20pour%20WWF%20-%20Ecologie%20et%20politique%20-%20Octobre%202025.pdf>.

9 WWF (2026) *Faire la Paix avec les lions* [Making Peace with Lions] (p. 5). <https://www.wwf.fr/vous-informer/effet-panda/faire-la-paix-avec-les-lions>.

10 JUPDLC (2014) WWF surfe sur la vague des selfies pour défendre les espèces menacées [WWF surfs the selfie wave to protect endangered species]. <https://jai-un-pote-dans-la-com/wwf-surfe-vague-selfies-defendre-les-especes-menecees/>.

But messaging that centers disproportionately on these species can be counterproductive. Some people wonder why it is relevant to protect ecosystems on the other side of the world when they struggle to meet their immediate needs or afford the basics. For many people, especially in poorer areas and cities, protecting biodiversity comes across as exotic if not elitist. Focusing narratives on ordinary, local biodiversity can make it easier for people to understand the issues and interdependencies that connect us to a healthy natural world.

Local biodiversity: an overlooked but effective driver

Local biodiversity is omnipresent but often invisible, despite the central role it plays in our diet and our health. A 2025 WWF campaign¹¹ centering on earthworms – “without them there’s no fertile soil – and no food on your plate” – was an unexpected hit with farmers as it directly addressed their profession and economic survival.

“Soil with no earthworms is like a body with no intestines: it can’t digest anything” explains a farmer in Brittany. The campaign was shared thousands of times in a few weeks and generated dozens of requests for training in agroecology.



Other WWF campaigns on Instagram are designed to clearly link local biodiversity, ecosystem health and human health. One example was a call to sign the Hands off Nature petition (2026) to combat plans to dismantle EU nature protection laws.¹²

Two key strategies for linking biodiversity more closely to daily life have emerged.

First, it is important to highlight emblematic species that inhabit the places where we live: wolves, foxes, hedgehogs and badgers embody our capacity to coexist with the living world and are sources of wonder and emotion. Second, we need to provide information on the role ordinary species play as guarantors of our wellbeing:

- “A sparrow in your garden is the sign of a healthy neighborhood,” because the species can only survive where there are plants, clean air and quality food.
- “Bats near your home? They eat up to 3,000 mosquitoes a night.” Their presence can regulate the mosquito population and limit transmission of certain diseases.

These narratives make ecology accessible and bring it to life. “Protecting nature is not only about saving the Amazon, it also means looking after the river near where you live” is how a participant in our public consultation summed it up. For instance, ordinary biodiversity can ground actions in daily life through concrete tools like the WWF guide “Opening a hotel for bees”, teaching people how to protect biodiversity on their balconies and in their gardens.¹³

TALKING ABOUT BIODIVERSITY IN THE SOCIAL MEDIA ERA: THREE SECONDS TO GRAB ATTENTION

Communicating narratives in the social media era calls for a strategy that reflects shorter attention spans and algorithms that prioritize instant emotional pull. This strategy needs to be based on three key ingredients: simplicity, emotion, and atypical voices. NGOs, inhabitants, influencers and, sometimes, businesses can all contribute to the conversation about biodiversity, as long as they have the right frameworks.

The short-format challenge

The average attention span has dropped dramatically.¹⁴ The main pitfall is to reduce biodiversity to sensationalist images (isolated polar bear, forest in flames) likely to trigger rejection or lassitude. An effective response is offered by short, emotional, interactive formats that can transmit a narrative in a few seconds. WWF has used this format on Instagram, such as during a 2025 partnership with online media Konbini for a two-episode mini-series: “Enraciné.e.s”, in which we discover local initiatives for preserving biodiversity.¹⁵



¹³ WWF (2019) *Des Balcons et des jardins vivants pleins de fleurs et d'abeilles* [Balconies and gardens alive with flowers and bees].

¹⁴ Stanford University, Fargol Rozati (2025) Analyzing the Effects of TikTok on the Attention Span of Evolving High School Students | *Intersect: The Stanford Journal of Science, Technology, and Society*.

¹⁵ Konbini (2025) *En Tunisie, Férès part à la rencontre de ceux qui luttent contre la crise climatique* [In Tunisia, Férès meets the people fighting the climate crisis].

¹¹ WWF (2025) *Le ver de terre* | WWF France [The Earthworm].

¹² WWF (2026) *Hands off nature*.



Using non-expert voices

To reach new audiences, it is vital to move away from traditional ecological representations and turn to local voices anchored in everyday life. This gives influencers a role as the new storytellers of biodiversity. For example, Mamadou Dembélé (@TheImpactStory with over 600,000 followers) posted a video called “Why earthworms are the superheroes of our plates” which racked up over two million views, 40% of them aged 18 to 25. On Instagram,¹⁶ a series of publications called “*Petites discordes entre voisins*”¹⁷ promotes the CIBEL program on cohabitation between humans and wild animals in Congo with a format voiced by actors Camille Lellouche and Sabrina Ouazani, and rapper Youssoupha.¹⁸

Citizen ambassadors provide authentic voices that boost messages’ legitimacy. They need to use clear jargon-free language, like “nature helps us out” rather than “ecosystem services.” Their ability to simplify complex notions expands engagement with biodiversity beyond activist circles.



The need for segmented communications

People’s expectations, value systems and concerns are far from homogenous. The Destin Commun think tank classifies society into six families of opinion with very different expectations and sensibilities: disillusioned militants, identity focused, wait-and-see, optimistic liberals, left behind, and stabilizers.¹⁹ This degree of heterogeneity means narratives need to be adjusted to suit the specific expectations of each group; a one-size-fits-all message will inevitably be ineffectual.

Dominant topics for engaged young people are social justice and health, covered on social media like Tiktok, Instagram and Twitch. WWF uses these platforms to take a fun approach to raising awareness among younger audiences.²⁰ For rural inhabitants and the middle-aged, transition is often associated with protecting their property and shifts in agricultural practices. It is therefore crucial to frame communication campaigns for these groups by linking agricultural practices directly to climate action: “And what if cows were also a climate solution? But on one condition: that they graze in fields!” and “With no hedges, your land loses 20% of fertility”.



CONCLUSION

Treating ecological transition as a technical problem is no longer sufficient. Transition will not only take place in institutions and expert reports but also in the heads and daily lives of everyone, everywhere. It is now essential to invest the same level of expertise and interest in the cognitive sciences, the societal sphere, and popular culture. We need to focus on developing public demand for sustainability and provide concrete illustrations of the direct influence of environmental health on our physical and psychological health. For instance, people can see and understand the health benefits of local pollution reduction policies: less asthma, fewer heart attacks, fewer premature deaths.

To create the sort of collective momentum that is needed, we have to dissociate ecology from notions of constraint and guilt. We need to show that protecting nature is not about taking a step backward, but inventing a fairer and more desirable way of living, imbued with meaning and the promise of a better quality of life. In short, we need to incorporate nature into people’s habits so that it becomes a cultural practice and the concrete foundation for a shared reflex.

¹⁶ WWF (2025) campaign on Instagram.

¹⁷ Quarrels between neighbors.

¹⁸ https://youtu.be/By9cZ_9qrOM.

¹⁹ Destin Commun (2019) *Les six familles de Français* [The Six Families of French People].

²⁰ WWF (2022) Fun awareness campaign for WWF - WWF - WOÖ.

About the author

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What the Water Reveals Through Citizen Science:

Insights from Bolivia and Kenya

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Millions of people rely on water that is never tested. This gap is particularly pronounced in low and middle-income countries, where less than 3% of global water quality data is produced.¹ Monitoring systems are often costly and technically complex, limiting their implementation in rural communities. As a result, socio-environmental risks remain largely invisible, even when they directly affect human health and the biodiversity on which livelihoods depend.

Drawing on experiences in Bolivia and Kenya, this article shows how the lack of accessible water quality information shapes how communities understand and respond to environmental change. In the Katari River Basin, Indigenous communities live with ongoing pollution but lack the data needed to support claims of environmental injustice. In the Yala Swamp, citizen science makes visible how the wetland improves water quality, while also revealing growing pressures on its ability to do so.

These cases show that the challenge is not only about collecting more data, but about making information meaningful and usable. Citizen science can help bridge this gap, but its impact depends on stronger links between local knowledge and decision-making processes at various levels.

INTRODUCTION

Across many parts of the world, water pollution is not only an environmental issue, it is a lived reality. Yet, in many cases, it remains largely invisible. In regions where monitoring systems are weak or absent, communities rely on water they cannot assess, making risks difficult to understand, communicate, or challenge. This is not accidental; it reflects deeper inequalities in how environmental knowledge is produced and accessed.

One way to address this gap is through citizen science, an approach where local people take part in collecting and understanding environmental data. In the case of water quality, this can help communities better understand the risks they face, including exposure to polluted water, waterborne diseases,² and the impacts on local biodiversity upon which their livelihoods depend. It can also strengthen awareness of how water quality connects to health and food systems.³ Around the world, this approach is growing,

and in countries such as Zambia and Sierra Leone, data collected through citizen science are already being used in official reporting on water quality (SDG 6.3.2).

Our work in Bolivia and Kenya builds on a simple but powerful idea: when communities generate their own water quality data, they begin to see, and question, what was previously hidden.

LIVING WITH POLLUTION: THE KATARI RIVER BASIN

In the Katari River Basin, which drains into Lake Titicaca, concerns about water contamination are part of everyday life. Communities downstream have long pointed to pollution originating from upstream activities, including 2 million m³ of mining waste, 20 million m³ of untreated or inadequately treated urban wastewater, and agricultural runoff.⁴ The basin has been shaped by decades of these pressures, from a legacy of mining waste to the rapid growth of El Alto, where limited sewer coverage results in large volumes of untreated wastewater entering local rivers.

¹ United Nations Environment Programme (2024). Progress on Ambient Water Quality: Mid-term status of SDG Indicator 6.3.2 and acceleration needs, with a special focus on Health, Nairobi. <https://unepdhi.org/sdg632-2024-progress-report-en/>

² gramont, A., Martinez, A. B., Gharesifard, M., Philippsborn, L. V., Lizarazo-Rodriguez, L., Warner, S., & van Griensven, A. (2026, March). Indigenous community-based approaches to environmental justice through citizen science. In Sustainability Nexus Forum (Vol. 34, No. 1, p. 5). Berlin/Heidelberg: Springer Berlin Heidelberg. <https://doi.org/10.1007/s00550-026-00588-2>.

³ Gharesifard, M., Ceccaroni, L., Gold, M. et al. Citizen science and the nexus approach: unlocking synergies for sustainable development. SNF 33, 4 (2025). <https://doi.org/10.1007/s00550-025-00562-4>.

⁴ Agramont, A., Van Cauwenbergh, N., Van Griesven, A., & Craps, M. (2022). Integrating spatial and social characteristics in the DPSIR framework for the sustainable management of river basins: case study of the Katari River Basin, Bolivia. Water International, 47(1), 8-29. <https://doi.org/10.1080/02508060.2021.1997021>.



For families living in Chojasivi, an Indigenous Aymara community at the Katari River discharge into Lake Titicaca, this is not an abstract environmental issue, it directly shapes daily life. Local biodiversity has been severely affected, with the disappearance of local fish populations, including Andean native species such as Karachi and Mauri, that once provided the main source of protein and livelihood for the community.⁵ Pollution has also altered soil conditions, rendering areas that were previously used for agriculture unsuitable for cultivation. In addition, there is evidence of trace metals entering the local food web, where they tend to accumulate in living organisms, posing a serious health risk to local community members.⁵

While the contamination experienced daily is evident, it is difficult for communities to clearly demonstrate the extent of the problem with local reliable data to engage with authorities.⁶ To address this issue, a community-based monitoring initiative was carried out in Chojasivi. Over four months, local students and community members collected 46 water samples, with 38 included after quality checks. Using simple, low-cost tools, they measured key indicators such as turbidity (water clarity), dissolved solids, and nutrients.

The results provide a more precise characterization of water quality conditions across the study sites. Several key parameters – including turbidity, total dissolved solids (TDS), and phosphate (PO₄) – consistently exceeded the Bolivian national standards for Class C surface waters.² Turbidity levels were particularly critical: while the legal threshold is 50 NTU,⁷ independent measurements recorded average values of approximately 240 NTU and peaks exceeding 1,000 NTU, indicating severely degraded water conditions. Similarly, TDS concentrations frequently surpassed the regulatory limit of 500 mg/L, reaching up to 1,890 mg/L in the Katari River. Phosphate concentrations also showed persistent exceedances, with values rising to 4.0 mg/L, far above the national guideline of 0.5 mg/L.

While the contamination experienced daily is evident, it is difficult for communities to clearly demonstrate the extent of the problem with local reliable data to engage with authorities



A community leader from the Chojasivi Aymara Indigenous community holding the water quality monitoring tools used as part of local monitoring efforts.
 © Afnan Agramont

Temporal analysis further revealed a clear seasonal pattern. Pollutant concentrations – including conductivity, TDS, and salinity – increased progressively from March to June, corresponding to the transition from the rainy to the dry season, when reduced river flows limit the dilution capacity of the system. Nutrient dynamics showed episodic peaks, such as elevated phosphate concentrations following the rainy season and nitrate increases in May, likely linked to agricultural and urban runoff. Although the monitoring period was limited to four months, these quantitative patterns closely align with long-standing observations reported by community members, reinforcing the consistency between measured data and lived experience.

What made this process particularly meaningful was how the results connected with people's own experiences. Participants described visible signs of pollution – such as darker water, unpleasant smells, and waste – and many linked these conditions to declining fish populations or health concerns. For some, the monitoring helped put numbers to what they had long experienced.

At the same time, the experience revealed important challenges. While participants became more confident in understanding water quality, many were unsure how to use this information to influence decisions or hold institutions accountable. Several expressed frustration at the limited response from authorities, despite the evidence collected.

This highlights an important point: generating data is a crucial first step, but it does not automatically lead to change. What it can do, however, is make environmental problems more visible and open space for discussion – within communities and, potentially, beyond them.

5 Gloria Rodrigo, M., Ortuño, T., Isela, R., Becerra, C., Choque, R., & Ibañez, C. (2018). Contaminación por metales pesados y su efecto sobre organismos vivos en un gradiente de la cuenca Katari. [Heavy metal pollution and its effects on living organisms along a gradient in the Katari Basin]. Universidad Mayor de San Andrés: La Paz, Bolivia.

6 Agramont Akiyama, A., Peres-Cajías, G., Villafuerte Philippsborn, L., Van Cauwenbergh, N., Craps, M., & Griensven, A. V. (2022). Framing Water Policies: A Transdisciplinary Study of Collaborative Governance; the Katari River Basin (Bolivia). Water, 14(22), 3750. <https://doi.org/10.3390/w14223750>.

7 NTU refers to the Nephelometric Turbidity Unit, used to measure the turbidity of a fluid.





Students from the Indigenous community of Chojasivi conducting water quality monitoring in their community.
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A WETLAND THAT CLEANS WATER

In western Kenya, at the northeastern edge of Lake Victoria, the Yala Swamp forms one of the country's largest freshwater wetlands and is recognized as a key biodiversity area. Dominated by extensive stands of papyrus (*Cyperus papyrus*), the system supports species such as the Sitatunga antelope and papyrus-dependent birds including the Papyrus Gonolek and Papyrus Yellow Warbler, while also providing refuge for cichlid fish species that have disappeared from Lake Victoria.⁸

As water from the Yala River flows through this wetland, sediments are trapped and pollutants are retained, improving water quality before discharge into the lake. Although this water filtration function is widely acknowledged, it has rarely been documented through systematic and locally grounded observation.

To better understand this process, a year-long citizen science initiative engaged secondary school students at both the inlet and outlet of the swamp. Each month, they collected water quality data across four seasons, building a continuous record of how water changes as it passes through the wetland.

The results made the swamp's function visible. Across all seasons, water leaving the wetland consistently showed better quality than water entering it. Turbidity – the clearest signal of suspended pollution – remained significantly lower at the outlet throughout the year, highlighting a strong capacity to retain sediments. Other indicators, including electrical conductivity, total dissolved solids, and salinity, also showed reductions downstream, although these patterns shifted with seasonal conditions.

When combined into a Water Quality Index, the pattern became even clearer: outlet waters consistently fell within the “good” range, while inlet waters ranged from “poor” to “marginal.” What enters the swamp does not leave it in the same condition.

For the students involved, this went beyond numbers. Comparing upstream and downstream conditions allowed them to directly observe the swamp's role as a natural filtration system. Many described it as a “water purifier,” referring to its capacity to trap debris, absorb pollutants, and slow water movement. These interpretations closely matched the measured patterns, strengthening the link between observation and lived experience.

At the same time, the monitoring revealed a more complex reality. The swamp's capacity to regulate water quality is not constant. Seasonal rainfall and flow conditions influence how effectively pollutants are retained, especially for dissolved substances. During certain periods, this function becomes less stable and more difficult to predict.

The data also pointed to increasing and interconnected pressures on the wetland. Students identified human waste, invasive water hyacinth, and land conversion as key threats, observations that align with scientific evidence⁹ showing that population growth and demand for land have driven encroachment, wetland reclamation, and agricultural expansion in the Yala Swamp. In many areas, papyrus vegetation is burned to enable cultivation, degrading habitats and disrupting breeding grounds for fish, birds, and species such as the Sitatunga. At the same time, the use of agrochemicals and fertilizers, together with activities such as sand harvesting, brick making, and overexploitation of papyrus, contribute to pollution, eutrophication, and broader ecological degradation, further compounded by climate-related stresses such as droughts and flooding.

These pressures are not abstract, they directly undermine the swamp's ecological functioning. As wetland areas are drained, cultivated, or degraded, their capacity to retain sediments, filter pollutants, regulate floods, and sustain biodiversity becomes increasingly fragile.

In this case, monitoring did more than reveal a problem. It made visible the value of a system that often remains overlooked, and what stands to be lost if current trends continue.

⁸ Aloo, P. Biological diversity of the Yala Swamp lakes, with special emphasis on fish species composition, in relation to changes in the Lake Victoria Basin (Kenya): threats and conservation measures. *Biodiversity and Conservation* 12, 905–920 (2003). <https://doi.org/10.1023/A:1022869624524>.

⁹ Maua, J. O., Mbuvi, M. T. E., Matiku, P., Munguti, S., Mateche, E., & Owili, M. (2022). The difficult choice-to conserve the living filters or utilizing the full potential of wetlands: Insights from the Yala swamp, Kenya. *Environmental Challenges*, 6, 100427. <https://doi.org/10.1016/j.envc.2021.100427>.



CONCLUSION

Across both Bolivia and Kenya, a similar shift becomes visible.

In these two cases, citizen science contributed to moving monitoring from a distant, technical exercise to a more locally grounded practice. Communities did not remain passive recipients of information; they observed, measured, and interpreted environmental change in relation to their own experiences.

This process generated several important outcomes. Environmental risks that had previously been difficult to document became more visible. Local understanding deepened as observations connected with lived realities linked to local ecosystems. New spaces for dialogue also emerged, both within communities and across different groups sharing the same water systems.

Importantly, these processes may contribute to decision-making processes at the local level. As communities engage with data, they can strengthen water literacy, understood here as the ability to interpret and discuss water-related information in ways that are meaningful in everyday contexts. This, in turn, can support reflection on local practices, strengthen collective discussion, and encourage forms of environmental stewardship and protection of local ecosystems.

At the same time, the two cases highlight the scale-dependent nature of these outcomes. While locally generated knowledge can support understanding and action within communities, its influence becomes more limited as it moves towards broader governance levels.

In Bolivia, communities gained clearer evidence of contamination, yet substantial barriers remained when attempting to translate this knowledge into institutional response. In Kenya, recognition of the wetland's ecological role increased, yet pressures such as land conversion and pollution continued to threaten its capacity to function.

Taken together, these cases suggest that generating data at the local level can strengthen understanding and support local forms of action, but is often not sufficient, on its own, to influence decisions at higher institutional scales. Citizen science can make environmental change visible and socially meaningful, yet its broader impact depends on how this knowledge connects with decision-making processes, institutions, and governance frameworks. Without such connections, even robust local evidence may remain marginal in formal decision-making arenas.

Moving from observation to action therefore requires more than data alone. It requires processes that recognise, integrate, and respond to locally generated knowledge across governance levels, so that what communities observe and measure can more effectively inform the decisions that shape their environments and their lives.



Participants conducting water quality monitoring at the wetland's outlet, alongside a local community member collecting water for household use.
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About the author

Afnan Agramont is a researcher in water and environmental governance at the Vrije Universiteit Brussel (VUB) Department of Water and Climate. His work focuses on the inclusion of local communities in decision-making processes across scales, with particular attention to rural and Indigenous groups in the Global South. His research centres on citizen science, participatory climate adaptation, and socio-environmental justice. He contributes to inter/transdisciplinary research that integrates environmental monitoring, stakeholder engagement, and policy-relevant approaches to address complex socio-environmental challenges.



Insurance: A Strategic Lever for Financing Nature Restoration

Aurélie Fallon Saint-Lô

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The world's health and its economies depend closely on the health of its ecosystems. But investment in nature restoration remains at levels well below what is needed to ensure long-term protection for the natural world. The answer cannot come solely from conventional financing mechanisms, predominantly public, as they remain insufficient. There is a need to mobilize new private capital by creating innovative solutions that limit uncertainty and risk profiles. This is why AXA teamed up with SCOR to launch an insurance product that covers the cost of restoring natural ecosystems following an incident, as part of nature restoration projects. Rigorous processes based on exhaustive due diligence and a network of international experts have secured reliable restoration pathways to encourage investors to finance nature restoration.

The World Economic Forum reminded us that around 50% of the global economy depends directly or indirectly on healthy ecosystems¹. This means that as well as protecting natural ecosystems from anthropic pressures, restoring them is equally important. The upsurge in interest in nature restoration can be gauged by the growing body of laws and regulations in recent years, such as the Kunming-Montreal Global Biodiversity Framework adopted in 2022, Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on nature restoration,² legislation on biodiversity net gain in England,³ the Basic Act on Biodiversity in Japan,⁴ and Law 2173 from 2021 in Colombia on the Promotion of Ecological Restoration.⁵

The United Nations Conferences of the Parties on biological diversity in Cali (COP16) and climate in Belém (COP30) both highlighted ongoing challenges surrounding how to finance nature restoration and conservation. The objective set out in 2022 at COP15 of raising USD200 billion a year for biodiversity protection by 2030 has not yet been met, and there seems little likelihood that it will be in the future. According to the United Nations Environment Programme (UNEP),⁶ a fourfold increase in financing is needed, rising from 64 billion dollars in 2022 to around 296 billion in 2030, if global biodiversity and climate targets are to be met.

There are persistent disagreements between countries regarding how restoration and conservation should be financed, and it may be the case that national governments are not in a position to make the financial commitments needed for tackling these challenges. Stable ecosystems and healthy biodiversity are essential to supporting mitigation of climate disruption, and to adaption and resilience in the face of the physical impacts of a changing climate as well as being a determining factor in human health. Protecting and rebuilding nature and biodiversity has never been more important. It is a strategic necessity for ensuring economic resilience, food sovereignty, public health, and national security.

FINANCING NATURE RESTORATION

A range of nature restoration projects have been rolled out to protect the biodiversity that is so vital to our health. These projects involve bringing life back to degraded ecosystems, such as wetlands, forests and grasslands, with the aim of improving soils and water quality and providing a home for biodiversity. This restores natural ecosystems' original ecological role and ability to provide ecosystem services. It requires concrete actions such as rewilding, desealing soils, (re)planting, and changes in practices to boost local communities' resilience in the face of extreme weather events.

As an example, restoring a wetland, farm pond, large peat bog, or alluvial marsh consists of re-establishing its hydrological, ecological and biological operation, based on prior diagnosis of the water regime, soil, biodiversity, human uses, and the reasons for its deteriorated condition.

¹ World Economic Forum (2020) Nature Risk Rising: Why the Crisis Engulfing Nature Matters for Business and the Economy.

² Regulation - EU - 2024/1991 - EN - EUR-Lex.

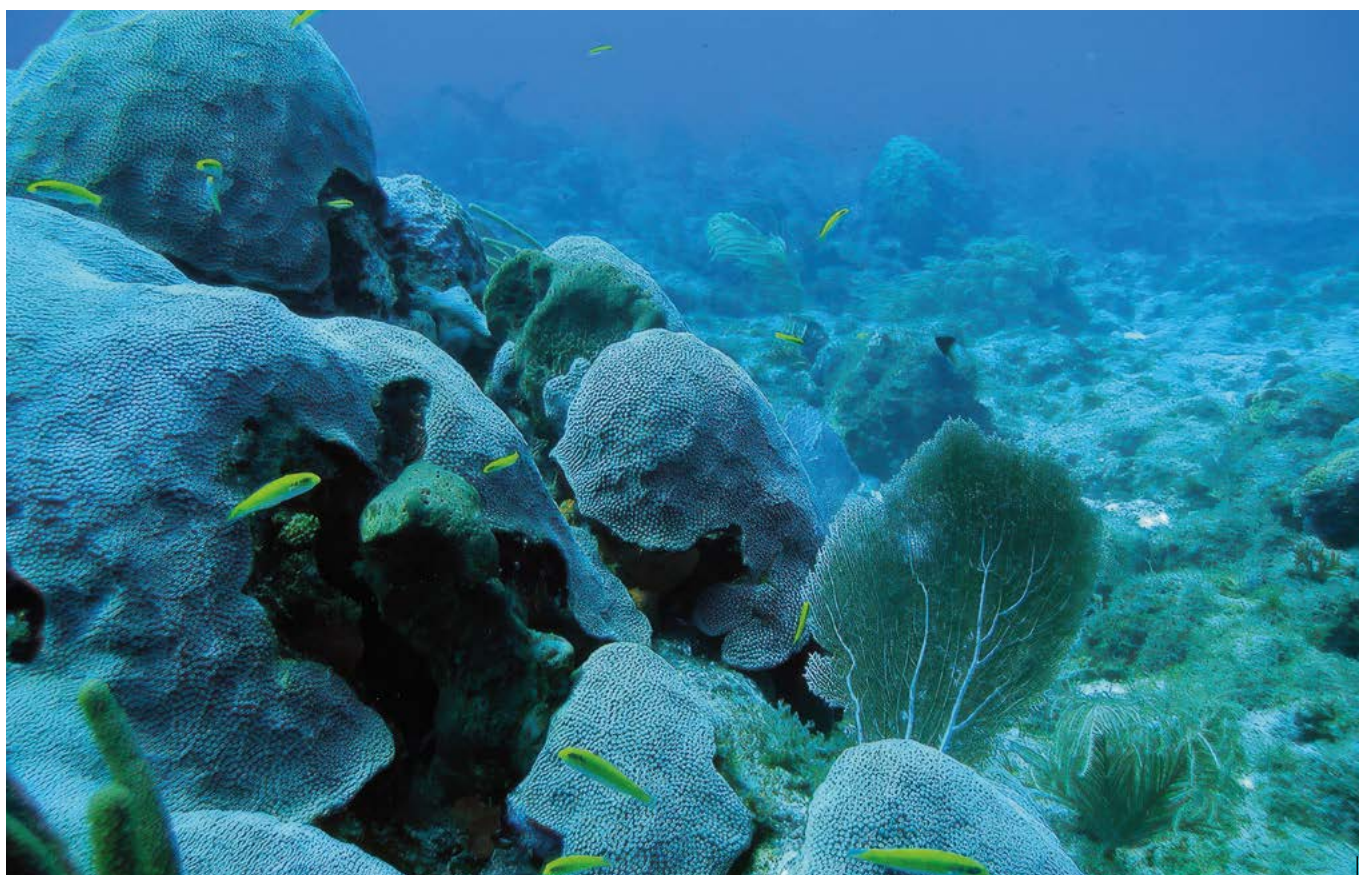
³ Biodiversity net gain - GOV.UK.

⁴ <https://www.cbd.int/doc/nbsap/nbsapcbw-seasi-02/NBSAP-Xian-Japan-implementation.pdf>.

⁵ Ley 2173 de 2021 – Restauración Ecológica a través de la siembra de árboles y creación de bosques en el territorio nacional [Law 2173 from 2021 - Ecological Restoration based on planting trees and creating forests nationally].

⁶ UNEP (2026) State of Finance for Nature 2026 report.





Coral reefs⁷

There can be multiple causes, including drainage, infilling, water course diversion, pollution, invasive species, soil sealing, or climate events amplified by climate breakdown, which is both cause and consequence. Restoring wetlands is crucial, particularly in terms of re-establishing their role as sponges in order to reduce flood risks.

Projects of this type require significant financing, provided by a diverse range of actors. Traditional financing mechanisms rely primarily on public financing.^{8,9} Yet despite this central role, levels of public investment remain inadequate in the face of growing needs. Private financing for environmental restoration remains relatively limited, around 27% of total amounts. Other channels, such as financing from conservation NGOs, philanthropy, and impact investment, remain marginal.

Over two thirds of private financing come via environmental offset mechanisms intended to compensate for the impact of a particular project, such as a mining project, by restoring

or protecting ecosystems in another location.⁶ They mostly take the form of voluntary carbon markets, where carbon credits are traded, and biodiversity credits that attract private financing.

Any promoter of a project aiming to reduce or capture CO₂ emissions, with reforestation for example, can issue carbon credits for each ton of CO₂e avoided or stored. These credits are then acquired by third parties to offset their own emissions, in a process that provides financing for the project. Past controversies, however, mean the voluntary carbon market has to prove it is climate-positive and generate environmental and social co-benefits by relying on rigorous standards and frameworks. Only a very small percentage of credits correspond to genuine reductions in additional emissions,¹⁰ with some analyses showing unintended side-effects of carbon credit trading and intensification of anthropic pressures in the regions concerned.¹¹

Stable ecosystems and healthy biodiversity are essential to supporting mitigation of climate disruption

⁷ "Coral Reef" by NOAA's National Ocean Service is marked with Public Domain Mark 1.0.

⁸ UNEP (2024). State of Finance for Nature: Restoration Finance Report. Growing the Green: Why and how restoration finance needs to quadruple by 2030, p. 8. Nairobi. <https://wedocs.unep.org/20.500.11822/46730>.

⁹ UNEP (2024) Nature is staging a comeback: UN recognizes seven World Restoration Flagships.

¹⁰ The Guardian (2023) Revealed: more than 90% of rainforest carbon offsets by biggest certifier are worthless, analysis shows | Carbon offsetting.

¹¹ Zhou Z. & Almond D. (2024) Biodiversity Co-Benefits in Carbon Markets? Evidence from Voluntary Offset Projects, p.15.



The Gouldsboro State Park Wetlands¹³

Biodiversity credits are intended to finance actions with a positive impact on biodiversity, for example, by protecting or restoring ecosystems. Actors purchase credits to support ecological gains that are measured using specialist indices, although they are less standardized and more complex to quantify than carbon credits. The market in biodiversity credits is at an early stage and worth no more than eight million dollars annually. However, structuring it around strict shared standards and supported by a favorable policy environment could increase that figure to two billion dollars a year in 2030.¹²

Mobilizing private capital is essential to raising the amounts needed for restoring nature, but it requires the sort of solid guarantees offered by insurance instruments. Nature restoration projects face numerous risks, including fire, lack of rainfall, and flooding. Because of these risk factors, governments, businesses, financial institutions, NGOs, and private individuals can be reticent when it comes to financing projects relating to natural ecosystem restoration:

They mostly take the form of voluntary carbon markets, where carbon credits are traded, and biodiversity credits that attract private financing

nature is intrinsically unpredictable and the complex dynamics at work in ecosystems and the factors that impact them may give investors pause for thought. Innovative insurance solutions are therefore indispensable when it comes to reassuring investors, guaranteeing the quality and long-term future of projects whilst simultaneously protecting them from negative impacts.

AXA GROUP TAKES ACTION TO SUPPORT NATURE RESTORATION PROJECTS

AXA Group has taken a pioneering role in protecting these ecosystems with its parametric insurance developed by AXA Climate, guaranteeing the resilience of coastal and marine ecosystems threatened by extreme climate events. Coral reefs are essential to protecting shores from coastal erosion, preserving the health of marine ecosystems, and supporting the livelihoods of local communities. Parametric insurance programs set in place for the San Andrés coral reef,¹⁴

¹² WEF (2023) Biodiversity Credits: Demand Analysis and Market Outlook, p. 37.

¹³ "GboroSP Wetland" by Nicholas from Pennsylvania, USA is licensed under CC BY 2.0.

¹⁴ AXA (2025) A Pioneering Parametric Insurance Programme to Protect the Caribbean's Second-Largest Coral Reef.



and for protected marine reserves in the Philippines with Blue Finance, offer protection from the consequences of tropical cyclones that impact communities who depend on natural resources by offering rapid and predictable payouts. However, the escalating intensity of extreme weather events is placing these ecosystems under severe stress.

As well as this mechanism, an insurance instrument called Restore launched in partnership by SCOR and AXA in 2026 marks a shift: it is designed to provide security for the actual financing of nature restoration projects, particularly for land-based ecosystems. The product provides cover during the implementation phase of a project that aligns with the restoration masterplan. This essential phase in the environmental restoration chain is particularly critical since it determines the long-term success of projects that can last for several decades. The initial phase is very often the most risky due to the compromised ecological integrity of the site in question, and must be rigorously executed to ensure the project's long-term future.

Restore is designed to fill the gap between the need and the desire to finance ecological restoration projects by derisking the associated investment opportunities. AXA and SCOR have leveraged their experience and expertise in natural disaster management to create innovative solutions for transferring risks facing investors and financiers. The product works as follows: once a restoration project is under way, if the initial trajectory for restoring the integrity of the ecosystem defined in the restoration plan is negatively impacted by a pre-defined threat (such as an earthquake, fire or flooding), the insurance covers financial costs relating to creating the restoration conditions needed to return the ecosystem to its initial (or revised) restoration trajectory.

Mobilizing private capital is essential to raising the amounts needed for restoring nature, but it requires the sort of solid guarantees offered by insurance instruments

The quality and sustainability of these operations are ensured via collaborations with experts, particularly from the Society for Ecological Restoration,¹⁵ who ensure a rigorous due diligence process. These experts assess each project against a number of criteria, including diversity of species planted, social impact, financial planning, and respect for reference ecosystems. Only projects offering excellent environmental, social, and financial integrity are selected, which helps to minimize risks and ensure the long-term future of the restored ecosystem. The collaboration between AXA and SCOR, including a key partnership with Lloyd's, constitutes a strategic advance for rolling out the approach worldwide. The partners offer the expertise, financial capacity, and global network needed to cover complex, frequently large-scale projects around the world.

This insurance solution is already in place for a very large swamp restoration project in Louisiana and the planting of over two million native trees including swamp cypress. The project will cut risks relating to hurricanes and flooding as well as improving water quality, creating economic value, and boosting the resilience of local communities. It also aims to capture over 900,000 million tons of CO₂e_q over a 40-year period.

CONCLUSION

Given that this is a new asset class with very little historical data, insurance cover plays a key role in mitigating perceived risks for investors, thereby facilitating the expansion of innovative financial solutions for supporting biodiversity and climate resilience. It fully aligns with AXA's biodiversity roadmap by providing insurance cover to projects seeking to restore damaged ecosystems and boost their resilience in the face of climate events such as flooding, fire, and drought. By supporting private investment in nature-related projects, this approach contributes to creating healthier ecosystems capable of attenuating climate risks while also preserving biodiversity.

¹⁵ Society for Ecological Restoration. <https://www.ser.org/>.

About the author

Aurélie Fallon Saint-Lô is Head of Sustainable Underwriting at AXA Group. She studied environmental sciences at Mines ParisTech and has over 20 years' experience in managing environmental risks, designing sustainable insurance solutions, and raising awareness about challenges linked to biodiversity. She created and heads the CSR committee at AXA XL France and was nominated as 2015 Insurance Woman of the Year. She has also served as councilor in charge of environment and sustainability for the municipality of Nogent-sur-Marne and participates in United Nations Environment Programme (UNEP) working groups, with a focus on sustainable insurance.



CONCLUSION

Biodiversity and Health: Bringing Systems Together to Transform How We Take Action

Cédric Baecher - Partner at Wavestone



One thing becomes obvious as our understanding of the links between biodiversity and health increases: it is no longer possible to think of them in isolation. The articles in this edition of FACTS Reports clearly show how biodiversity is more than simply an environmental framework for human health. It is in fact a critical “infrastructure” that directly conditions our food

supplies, biological balances, capacity for medical innovation, and the resilience of our societies in general.

From farmland to human microbiota, zoonotic disease dynamics to therapeutic resources derived from the living world, everything is on the same continuum, reminding us that, sooner or later, every alteration to the living world will impact human health.

The figures are unambiguous. Almost 35% of global food production depends on pollinators,¹ and the origins of a significant proportion of emerging infectious diseases lie in interactions between people, animals, and degraded ecosystems. Equally, our knowledge of existing species covers a fraction of them, around 10%, even as their decline is accelerating. These orders of magnitude underline a simple truth: our health relies on a biodiversity that we do not fully understand, and that we are undermining at a rapid rate.

Given these realities, the key takeaway from this issue of FACTS Reports is that fragmentary approaches have reached their limits. Acting alone on the climate, biodiversity, health, or food inevitably leads to trade-offs that are unsatisfactory at best, when not actively counter-productive. On the other hand, the different bodies of work presented here, whether looking at food systems, microbiota, emerging diseases or biomimetics, all agree on the need for thinking systemically so that natural ecosystems can be linked with economic systems and health dynamics.

This integrated approach lies at the heart of the One Health framework and is now a precondition for effectiveness rather than a conceptual option. It calls for a shift in perspective, from focusing only on limiting impacts to working to restore functional balances between human systems and systems in the living world.

This transformation is now a strategic issue. In January 2026, the British government explicitly labelled biodiversity loss and ecosystem collapse as direct threats to national security owing to their potential impacts on public health, supply chains, access to vital resources, and geopolitical dynamics.² This is a powerful signal heralding a shift in how states view issues that are no longer simply environmental concerns, but constitute challenges to the systemic resilience of our societies.

This being the case, thinking in terms of systems is not enough: action requires alliances. The diversity of contributions in this issue points to another vital necessity: to decompartmentalize actors, share expertise, and organize the effective circulation of knowledge between fundamental research, applied research, businesses, institutions, and civil society.

The most promising advances in agroecology, microbial medicine, eco-epidemiological surveillance, and biomimetics are all based on the capacity to connect disciplines that far too often continue to work in silos. These areas of crossover are where decisive breakthroughs are created, and from them can emerge a form of collective intelligence capable of engaging with the complexity of the living world.

In this context, artificial intelligence may prove decisive, responsible for accelerating both challenges and solutions. On the one hand, it increases environmental pressures, primarily because it needs massive amounts of resources (water, energy, land) and a lot of infrastructure. On the other hand, it offers the promise of unprecedented capacities to understand the extraordinary complexity of interactions between biodiversity and health.

¹ IPBES (2022) Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services, p.9.2, FAO Home | Global Action on Pollination. https://files.ipbes.net/ipbes-web-prod-public-files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf.

² HM Government (2026) National security assessment - global biodiversity loss ecosystem collapse and national security, p.6. https://assets.publishing.service.gov.uk/media/696e0eae719d837d69afc7de/National_security_assessment_-_global_biodiversity_loss__ecosystem_collapse_and_national_security.pdf.



By allowing massive amounts of data to be processed, such as genomics, environmental surveillance and clinical research, AI opens the door to a more granular understanding of ecological and health dynamics as well as to the development of better targeted and more efficient solutions. Provided that there is ethical and responsible oversight, AI could become a key tool in bringing about convergence between scientific knowledge and operational action.

This shift also calls for greater pragmatism. Contrary to received wisdom, many of the solutions already exist: restoring ecosystems, transforming agricultural practices, embedding biodiversity into health policies, innovations inspired by the living world, and prevention mechanisms rooted in greater understanding of ecological interactions.

However, difficulties with scaling mean their impact remains limited. Solving this will require working more effectively to develop the links between research, innovation and economic models in order to transform initiatives that are often local into truly system-wide trajectories. Moving to scale also calls for financial incentives and regulatory frameworks to align with targets for protecting health and the living world. This is vital to overcoming the fixation on short-term objectives.

As well as covering a range of technical and scientific solutions, this edition also focuses on a more deep-seated change: the narrative shift. By positioning health as central to the challenges facing biodiversity, new narratives provide a common language that is capable of mobilizing on a scale that reaches much further than expert circles. Because there is more at stake than just preserving ecosystems; the ability

of our societies to offer living conditions that are sustainable, fair and secure is also in the balance. Biodiversity, whether visible or invisible, spectacular or mundane, is the cornerstone this ambition is built upon. Biodiversity is a guarantee, a resource, and a source of innovation.

Ultimately, the added value offered by this edition of FACTS Reports lies in its ability to create links, provide structure, and look to the future. Creating links between disciplines, actors, and scales of action. Structuring systemic understanding of the links between biodiversity and health. Looking to the future to identify workable actions rooted in cooperation, knowledge, and experimentation.

This approach offers a vital anchor in an age of growing uncertainty: it makes it clear that the challenge does not only involve limiting risks, but reinventing growth models to make the living world a central plank for everybody's health and wellbeing.

This is now a collective responsibility. Researchers must continue to explore interdependencies in the living world. Businesses must embed these challenges into the heart of their strategies. Public authorities must create the conditions needed to scale up. And more generally, every one of us must contribute to this transformation and the behavioral changes required.

Because fundamentally, as so powerfully described in the articles in this edition, protecting biodiversity is not only an environmental question: it is very much a condition for our survival, now and in the future.

Fragmentary approaches have reached their limits. Acting alone on the climate, biodiversity, health, or food inevitably leads to trade-offs that are unsatisfactory at best, when not actively counter-productive



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" We are linked to biodiversity both physically and mentally. It shapes our well-being in many ways, including the abundance, variety, and quality of food, the functioning of our immune system, and the medicines we use. "

Harvey V. Fineberg

Professor of Health Policy and Management, Emeritus, Harvard T.H. Chan School of Public Health,
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