More than food: Why restoring the cycle of organic matter in sustainable plant production is essential for the One Health nexus

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CABI Reviews

REVIEW

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Abstract

One Health professes that the health of organisms is interconnected through the exploitation of planetary resources, trade, and transportation, in particular. The impetus for the emergence of this concept in the early 2000s was knowledge of the epidemiology of zoonotic diseases that put humans at risk to diseases carried by animals. In spite of the intended comprehensiveness of One Health, the place of plant health in this concept is vague, and few issues about plant health are debated in the scientific literature related to One Health. Here, we explore the history of concepts related to One Health in an attempt to understand why there is this schism between the plant sciences and the medical and veterinary sciences beyond the prism of zoonotic diseases. We illustrate the rich history of concepts in the plant sciences concerning the oneness of plants, animals and humans, and the debates about the definition and scope of sustainability that are precursors to One Health. These concepts continue to be foundations for research and development, particularly for food security and food safety. The emergence of these concepts from plant sciences was based on fundamental understanding of the food web – where plants are food for humans and animals whose digestive processes create important resources for plant growth and health. Yet, this latter part of the food web – recycling of manures in particular – was ruptured during modernization of agriculture. We explain how attaining sustainable One Health depends on restoring this part of the food web via soil stewardship, whose principal guarantors are the ensemble of actors in plant production.

Keywords: plant health, sustainability, soil health, agriculture, food security, global change, agricultural history

Introduction

One Health is a concept that professes that the health of humans, animals, and the environment are interconnected as part of one world (Gruetzmacher *et al.*, 2021). Although One Health might be construed as a philosophical outlook on nature, it is saliently pragmatic. In practical terms for science, this concept provides a framework to understand the epidemiology of diseases and, in particular, the systemic causes of disease emergence beyond simple etiology and identification of pre-disposing factors. It is applicable not only to diseases caused by microorganisms but also to ailments caused by chemical agents, allergens, microplastics, etc. Insight from One Health can be deployed to establish surveillance and management practices to avoid disease and to establish governance for these practices to be implemented at large geographic scales in the case of major pandemics (Li *et al.*, 2023). The particularity of One Health is its goal to be very comprehensive by identifying the processes and phenomena in systems whose interconnections have impacts on the health of the system components. It defends the need for collaboration of multiple disciplines and a wide range of stakeholders working locally, nationally, and globally to attain optimal health for people, animals, and the environment and thus to be conducive to sustainable societies.

The foundation for today's predominant One Health perspective initially arose from the concern that there could be links between human health and animal health. While numerous historical texts suggest that this link was understood for the first time in the late 1700s or mid-1800s (Bresalier *et al.*, 2020), the earliest traces of this perception date back to the beginning of animal domestication at the time of the transition toward agriculture about 8000–10,000 years ago, thereby highlighting the relative intuitive and conspicuous nature of this link. The increased opportunities

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for the observation of animals that resulted from domestication likely led to intuitive perceptions of this connection (Currier and Steele, 2011). As early as the 18th century BC, this perception was formalized in the Babylonian Laws of Eshnunna (Hubálek and Rudolf, 2010) that required owners of rabid dogs to pay fines for sickness caused to victims of bites (Wu, 2001). Nevertheless, Pasteur's germ theory of disease, announced in 1861, was essential for understanding the mechanistic link between diseases of humans and animals. This new paradigm of microbiology and many of the other important discoveries of the mid-19th century (theories of evolution and natural selection, the cell theory, laws of inheritance of traits, etc.) occurred as the system of knowledge about the natural world was being compartmentalized into distinct scientific disciplines reigned by specialists in search of novelty (Stichweh, 2001). However, by the mid-20th century, unusual health crises including HIV, Legionnaire's disease, SARS, cryptococcal meningoencephalitis, and others up to the COVID-19 pandemic sparked calls for interdisciplinary solutions. These crises made it more and more apparent that the consequences of the stresses being put on our planet – including globalized trade, increasing human travel, and deforestation due to the need for agricultural and urban spaces – were exacerbating the processes of spill-over of zoonotic diseases from animals and from environmental reservoirs to humans (Morris *et al*., 2022). This led to specific calls for comprehensive, interdisciplinary approaches that account for the various and interwoven processes of zoonotic spill-over, culminating in fledgling One Health initiatives. From the first official One Health conference held in 2004, a set of principles arose that were updated in 2019 as the ten Berlin principles intended to orient policies and other actions of economic, social, research, and academic organizations to reconnect the health of humans, animals, and ecosystems in a sustainable economic and socio-political context (Gruetzmacher *et al*., 2021). The intense interest in One Health since these initiatives is illustrated by the increase in the numbers of scientific publications that specifically mention One Health in the title or the abstract (according to the Web of Science) from 22 in 2005 to 265 in 2015, and to 1195 in 2022, for example.

A few decades before the calls for One Health actions, international development organizations and agencies were founding concepts and frameworks that were precursors of One Health in the effort to confront concerns about the future of planetary ecosystems and resources. There was considerable debate around the definition and scope of one important concept – "sustainability" (Becker, 1997). The debate opposed proponents of a biocentric view, who called for a holistic accounting of the impacts of development on all ecosystem components, to those who defended a more focused anthropocentric view. The anthropocentric perspective dominated the 1992 declaration by the United Nations Conference on Environment and Development where "human beings are at the center of concern for sustainable development." With a slightly different nuance, the Consultative Group on International Agricultural Research used "sustainability" in their 1989 mission statement to mean "successful management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources" (Becker, 1997). When the anthropocentric One Health movement took form in 2004, it is possible that the idea was not perceived as particularly novel in some circles depending on their understanding of sustainable development principles. This is likely to be the case for scientists involved in managing plant health where sustainability has been an important issue for decades (He *et al*., 2021). In addition to sustainability, plant production sciences have been inspired by questions analogous to those addressed by One Health such as the ecological relationships within agro-food systems and their link to socio-economic contexts. This interest is manifested by research in diverse approaches to agroecology including organic agriculture, biodynamic production, Integrated Pest Management, permaculture, and eco-agriculture (Merrill, 1983; Baker *et al*., 2020; Knorr, 2023). In face of this rich context for holistic approaches for plant sciences, One Health might have seemed pale. Whatever the real cause, the status of plant health in One Health is perceived as vague (Vittecoq, 2022), and the scientific literature shows little debate on plant health as an issue for One Health. Specifically, for publications that mention One Health in the title or abstract, we found only 10 in 2022 and 6 in 2023, indexed in the Web of Science, that specifically address plant disease epidemiology and/or management of plant health, thereby constituting less than 1% of the publications on One Health in this period (Table 1). This rate is similar to that reported for the time period before 2022 (Andrivon *et al*., 2022).

This article is based on our opinion that plant health management should be an integral part of One Health concepts, policies, actions, and governance. One of our objectives is to convey historical details and perspectives from scientific culture to understand why there is a schism between the plant sciences and the medical and veterinary sciences concerning One Health. As described above, the parallel evolution of the concepts of sustainable development and of One Health – and the respective alignment of the plant sciences vs the medical and veterinary sciences – might offer some explanation about this schism. However, here, we will focus on another factor that underlies this schism, *viz*. the lack of appreciation of the multiple facets of the relationship between plants, animals, and humans that are inherent to their ecology in Earth's biosphere. One obvious facet of this relationship is that plants provide direct services for humans and animals as food and feed. From a One Health perspective, this food and feed should be nutritious and produced with minimal contamination of the environment from chemicals that are detrimental to human and animal health (Hoffmann *et al*., 2022). In light of concern about food security as the world population grows and as the ravages of climate change put considerable stress on plant production (Savary *et al*., 2019), it is easy to understand that this is the dominant perspective on how plant, animal, and human health are related. The second facet of the plant-animal-human relationship, which is rarely evoked explicitly, is that as primary and secondary consumers in the food web, humans and animals digest organic matter, thereby transforming it into essential resources for plants. Whereas this relationship had been fundamental for plant production for millennia, its importance was ultimately forsaken during industrialization and urbanization. Our objective is to describe how this basic principle of ecology was abandoned and why its comeback is critical for achieving *bona fide* One Health.

Review methodology

To assess trends in the frequency of publications concerning One Health, we searched the Web of Science using the query "One Health" for titles and abstracts of papers published in 2005, 2015, 2022, and 2023. To determine the frequency of publications that specifically concerned plant health, we manually screened the results of this query for the years 2022 and 2023. Papers were noted as pertinent to plant health if they specifically addressed plant health concerns in the body of the paper. Literature to support the other parts of the text of this article was found via queries of the Web of Science and Google Scholar for subjects related to soil health, agroecology, sewage management, the history of science, sustainable agriculture, etc. via discussions with colleagues and thanks to recommendations of the reviewers.

Breaking the food web

For about 4000–6000 years, crop production was generally self-sufficient, in terms of the cycle of nutrients, and consequently sustainable (Knorr, 2023). Various compilations of historical crop production practices point out that the sustainability was founded on efficient use of resources and their recycling back into the production system as exemplified by agricultural practices in ancient China or by various indigenous peoples elsewhere (King and Percy, 1911; FAO, 2021). The input of manure, particularly from livestock, has been a key component of plant cultivation

Table 1. Publications in 2022 and 2023 that specifically address plant health from a One Health perspective from the total 2298 publications about One Health indexed in the Web of Science in these 2 years (published before December 4, 2023).

Year	Journal	Title	Reference
2022	Plant Pathology	Plant Health in a One Health world: missing links and hidden treasures	(Andrivon *et al*., 2022)
2022	Nature Reviews Microbiology	Soil microbiomes and one health	(Banerjee and van der Heijden, 2023)
2022	Frontiers in Public Health	Operationalizing One Health as One Digital Health through a global framework that emphasizes fair and equitable sharing of benefits from the use of artificial intelligence and related digital technologies	(Ho, 2022)
2022	CABI Agriculture and Bioscience	A one health approach to plant health	(Hoffmann *et al*., 2022)
2022	JMIR Public Health and Surveillance	The landscape of participatory surveillance systems across the One Health spectrum: Systematic review	(McNeil *et al*., 2022)
2022	Environmental Health	Risk and asset-based strategies in health: priorities in biomedical, life and environmental science literature since the early twentieth century. A rapid review	(Migeot *et al*., 2022)
2022	Agriculture	Antimicrobial use and resistance in plant agriculture: A One Health perspective	(Miller *et al*., 2022)
2022	Frontiers in Sustainable Food Systems	Integrated Soil Health Management for Plant Health and One Health: Lessons From Histories of Soil-borne Disease Management in California Strawberries and Arthropod Pest Management	(Muramoto *et al*., 2022)
2022	Environnement Risques et Santé	Mettre en pratique l'approche « Une seule santé »	(Vittecoq, 2022)
2022	Plant Pathology	One Health concepts and challenges for surveillance, forecasting, and mitigation of plant disease beyond the traditional scope of crop production	(Morris *et al*., 2022)
2023	Symbiosis	Missing symbionts – emerging pathogens? Microbiome management for sustainable agriculture	(Berg *et al*., 2023)
2023	Kafkas Universitesi Veteriner Fakultesi Dergisi	Thiamethoxam Toxicity: A Review in One-Health Perspective	(Qamar *et al*., 2023)
2023	Nature Microbiology	Soil microbiomes must be explicitly included in One Health policy	(Singh *et al*., 2023)
2023	Environmental Research	Glyphosate and environmental toxicity with One Health approach, a review	(Ferrante *et al*., 2023)
2023	Cahiers Agriculture	Crop protection practices and risks associated with human fungal infectious diseases: a One Health perspective	(Ratnadass and Sester, 2023)
2023	Food and Chemical Toxicology	Aflatoxins posing threat to food safety and security in Pakistan: Call for a one health approach	(Ashraf *et al*., 2023)

as early as the Neolithic period and onward (Jones, 2012; Bogaard *et al*., 2013), thereby contributing to the reciprocity of the food web between plants, animals, and humans. With the transition of societies toward industrialization and urbanization that distanced populations from farms, the recycling of resources back to agricultural fields decreased markedly. This led to a major environmental crisis for agriculture in the early 19th century – the severe decline of soil fertility in North America and Europe between about 1830 and 1870 (Foster and Magdoff, 1998) – that set off an international scramble to secure fertilizers for crop production.

Two major quests to secure fertilizers for crop production were launched at the onset of the soil exhaustion crisis. One quest focused on the synthetic production of mineral fertilizers starting with superphosphate of lime from bones, of sulfur from diverse types of rocks, of potassium from wood ashes and culminating in the energy-intensive Haber-Bosch process that succeeded in producing ammonia from atmospheric nitrogen at industrial scales by 1913 (Russel and Williams, 1977). The other quest was the rush to harvest organic materials in the form of bird guano, especially from South American atolls. This guano rush started in 1840, leading to the creation of an elite business class dubbed the "guanopreneurs" (Snyders, 2019) and the Guano Island Act of 1856, whereby the USA annexed, occupied, and exploited over 100 islands for this precious resource (Burnett, 2005). The companies and labor contracts established by the guanopreneurs assured the transportation of millions of metric tons of nitrogen fertilizer and more than 100,000 workers across the globe, producing significant changes in environmental habitats[1] and in labor conditions throughout the world. This was a major paradigm shift for agriculture in that farming was no longer a closed system in which nitrogen was cycled among soil, plants, animals, and people at the local scale. Farming became an open, energy-intensive system for which nitrogen and other mineral resources could come from distant places (Melillo, 2012). This scurry for new resources and the change of paradigm were set in the backdrop of accumulating sewage in urban centers – the cause of numerous outbreaks of cholera epidemics in London from 1817–1854 and

[1] An example of extreme destruction of an entire island and a way of life of its indigenous people occurred on the Micronesian island Nauru that was mined for its rich deposits of phosphate that had accumulated from millions of years of bird migrations. See Gowdy and McDaniel (1999).

the Great Stink of 1858 (De Feo *et al*., 2014), for example. As a so-called solution to the urban sewage problem, sewage was dumped into major rivers such as the Thames and Seine and put on a path out to sea.

The paradox of massive amounts of nitrogen-rich feces being dumped into rivers and oceans in the face of a major fertility crisis for crop production did not escape the attention of intellectuals of the early 19th century. For example, in volume 5 of *Les Misérables*, the influential writer and French parliamentarian Victor Hugo decried the wastefulness displayed in Paris by the dumping of sewage – a resource more valuable than guano in his opinion – into the Seine river (Hugo, 1862). Various intellectuals in Victorian England engaged in a decades' long debate on sewage as a valuable commodity (Goddard, 1996). In *Das Kapital*, the German philosopher, historian, and economist Karl Marx noted the contradiction to sustainable societies of dumping sewage into the Thames River. He exclaimed that the "conscious and rational treatment of the land as permanent communal property is the inalienable condition for the existence and reproduction of the chain of human generations" (Foster, 1999). Likewise, German chemist Justus von Liebig argued in his *Letters on Modern Agriculture* and on *Utilization of Municipal Sewage* that soil nutrients were carried away by modern agricultural practices as a form of robbery of environmental wealth. He noted that the pollution of cities with human and animal excrement and the depletion of the natural fertility of the soil were connected and that organic recycling of nutrients back to the soil was an indispensable part of a rational society with urban and agricultural components (Foster, 1999).

The early efforts to valorize human waste from urban centers were mostly unsuccessful, plagued by the high volume of sewage due to the use of water as the carrier for wastes by the sewage systems that were adopted in Europe and the USA (Goddard, 1996; Hamlin, 1980). Furthermore, the promise of economic gains from the value of the wastes as fertilizers could not overcome the costs and fear of health hazards linked to sanitation issues (i.e. fears of dissemination of diseases such as cholera) and the stigma of these wastes as dirty (Hamlin, 1980; Goddard, 1996). Whatever the advantages of the practices that emerged in the 19th century for capturing and dumping human wastes, they reinforced the societal processes that deprived crop production of an abundant source of organic matter that evidently is beneficial to crop health and productivity (Feller *et al*., 2012; Goldan *et al*., 2023). The rupture of the plant-animal-human food web also contributed to the conception of linear – rather than circular – economies (Rodríguez-Espinosa *et al*., 2023) where resources for sustaining an agricultural system could come from far away.

The farm as an organism and the living bridge of soil: the first One Health concepts

The push to recycle nutrients back to the soil continued in the 20th century with publications by Rudolf Steiner in 1924 defending the idea that the soil had properties of an organism (Paull, 2010) and the 1926 publication of Franklin H. King who defended principles of recycling organic materials back to the soil. King's ideas had a remarkable influence. As a soil physicist at the University of Wisconsin, he published "*Farmers of Forty Centuries, or Permanent Agriculture in China, Korea, and Japan*" in 1926 (Paull, 2011; Heckman, 2013). This book was a reaction to his dissatisfaction with the agricultural practices promoted by the US Department of Agriculture at the time where he pointed out the importance of returning composted wastes, especially composted fecal wastes, to agricultural soils. Inspired by King's work and by his own decades of farming experience, the British agricultural scientist Albert Howard formulated the notion of The Law of Return in "*An Agricultural Testament*" published in 1943 (Heckman, 2006). He advocated for the recycling of all organic waste materials including sewage sludge back to agricultural soils, and he described precise conditions for composting as a means to foster "humus farming." The objective of the Law of Return was to build humus and the "living bridge" of soil life that supported the health of plants, livestock, and humans (Heckman, 2006). Paradoxically, and in spite of his proclamation that modern agriculture was robbing soil of its nutrients, Liebig contested the notion that plants could obtain nutrients from the organic constituents of soil. He perceived the Law of Return as an opposition – rather than a complement – to his theory on the Law of the Minimum that focused on soil chemistry and inorganic nutrition, especially for the elements N, P, and K (Heckman, 2013). This "mineralist" doctrine has continued to the present times to dominate agricultural practices, with the role of organic matter and soil structure receiving renewed acceptance only since the early 2000s (Feller *et al*., 2012). Mineral nutrients can indeed be limiting factors for plant productivity. However and paradoxically, their natural abundance in soils can far surpass the amounts provided by synthetic fertilizers and even the total synthetic production capacity as in the case of phosphorus (Gerke, 2022). Organic matter is essential for the chemical and biological reactions that mobilize the soil-bound and recalcitrant forms into bio-available forms that can be assimilated by plants (Gerke, 2022).

This debate on soil quality led to a movement to promote "organic farming," a name coined by polymath and Oxford University lecturer Walter J. Northbourne in his 1940 manifesto "*Look to the Land*" (Paull, 2014). Northbourne intended for the term "organic" to reflect a philosophical perspective where the farm was an organism "having a complex and necessary interrelationship of parts, similar to that in living things" (Heckman, 2006; Paull, 2014). Reflecting Howard's living bridge of soil, Northbourne stressed that "the soil and the micro-organisms in it together with the plants growing on it form an organic whole" (Paull, 2014). The organic farming movement was further propelled in the UK by the foundation of the Soil Association in 1946 (Conford and Holden, 2007), and in the USA by farming practices popularized in the *Organic Farming and Gardening* magazine published by Jerome Rodale starting in 1942 (Heckman, 2006). Notably, one of the objectives of the Soil Association was "to bring together all those working for a fuller understanding of the vital relationships between soil, plant, animal and man" (Conford and Holden, 2007). Overall, this fervor to restore soil and promote a holistic vision of agriculture was not just a farming priority. In the backdrop of the great Dust Bowl catastrophe in North America in the 1930s and 1940s (McLeman *et al*., 2014), it was a cry in the defense of civilization (Reed, 2001).

This surge of defense for organic farming spurred the rise of advocacy groups in the USA, in Australia, and across Europe in particular to promote organic farming practices. In 1974, a meeting of several advocacy groups convened in Versailles, France, under the leadership of the French advocacy group *Nature et Progrès*, thereby fostering the creation of the International Federation of Organic Agriculture Movements (IFOAM) (now called Organics International[2]). Since the beginning of the organic farming movement, its history has been marked by recurrent conflict with what has become conventional agriculture. Its major critics insist that organic farming cannot produce sufficient food for the growing world population (Heckman, 2006). The advocacy groups were created to disseminate knowledge about organic farming practices and to bolster its credibility as a means of sustainable food production. But notably, the origins of organic farming were founded on explicit notions of One Health. This was epitomized by the famous quotation from Eve Balfour, the chair of the inaugural meeting of the Soil Association, that "the health of soil, plant, animal and man is one and indivisible" (Vieweger and Döring, 2015). It has evolved more fully as expressed in the FAO's

[2] Extensive details on the history of organic agriculture are available on the IFOAM website https://www.ifoam.bio/ (accessed 29 November 2023).

definition of organic agriculture,[3] adopted in 1999, as a "holistic production management system which promotes and enhances agro-ecosystem health, including biodiversity, biological cycles, and soil biological activity. FAO's definition of organic agriculture emphasizes the use of management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, agronomic, biological, and mechanical methods, as opposed to using synthetic materials, to fulfil any specific function within the system." The principles of organic agriculture promoted by IFOAM go a step farther in their comprehensiveness by proclaiming that "organic agriculture should sustain and enhance the health of soil, plant, animal, human and planet as one and indivisible" (Paull, 2010). This holistic approach has not been confined to organic farming. It is also espoused in tenants of various strategies of agroecology including permaculture, syntropic agriculture, and regenerative agriculture, for example. Permaculture principles were formulated in the late 1970s and advocate for a more comprehensive understanding of yield where self-regulation and feedback of ecosystem services come into play (Ferguson and Lovell, 2014; Krebs and Bach, 2018). Syntropic agriculture, proposed in 1992 (Cossel *et al*., 2020), professed that soil-physical cultivation parameters including humus cover, fertility, water infiltration, and erosion control are enhanced through management of plant diversity and reliance on within-system material input. Regenerative agricultural principles were developed as an offshoot of organic farming practices that targeted productivity but were founded on both biological and socio-economic stability (Giller *et al*., 2021). These ideas are part of the efforts to deploy agroecological principles to achieve sustainability by leveraging the diverse dimensions of food production. These dimensions include soil quality management, water and energy conservation, reduction of pesticides, forecasting technological innovations, fostering cooperation and value-creation in the food chain, and deploying climate-smart farming – all to promote ecological resilience and social responsibility (Marchetti *et al*., 2020). The ensemble of these perspectives are precursors to and are fully coherent with the current principles of One Health (Gruetzmacher *et al*., 2021).

One Health in the face of unsustainability

Whatever the capacity of conventional farming to produce sufficient food and feed for the world population of humans and livestock that has exploded since the end of World War II, it is being achieved at the cost of the quasi-total alienation of the One Health principles promoted by the sustainable agroecological approaches described in the previous sections. This alienation is expressed not only in terms of technical practices but also in terms of the loss of domains of competence among farmers, agronomists, and other practitioners. The resulting imbalances in the ecological processes that could assure plant nutrition and that could mitigate the explosion of populations of pathogens or weeds, for example, have been compensated for with synthetic chemicals (fertilizers, pesticides, herbicides). Synthetic nitrogen fertilizers epitomize this imbalance through the intensive capture of gaseous nitrogen from the atmosphere to create reactive nitrogen for conventional farming, thereby seriously disrupting the nitrogen balance of the planet. Via the Haber-Bosch process, the USA, for example, captures 13,100 kt of atmospheric nitrogen per year that is turned into reactive nitrogen. This is equivalent to the total annual 13,200 kt of reactive nitrogen already available in wastes from livestock, food wastes, and sewage wastewater in the USA (Lavallais and Dunn, 2023). On a worldwide scale, the fabrication of synthetic fertilizer for crop production and the modern practice of intensified legume cultivation convert around 120 million tons of nitrogen from the atmosphere annually into reactive forms of nitrogen. This quantity is greater than the combined forms of reactive nitrogen generated from all of Earth's terrestrial processes leading to an excessive – and unnecessary – overload of reactive nitrogen in the environment with devastating consequences on Earth system processes and resource quality (Liu *et al*., 2020). This led Rockström and colleagues to declare more than a decade ago that this disequilibrium is outside the "safe operating space for humans" on planet Earth (Rockström *et al*., 2009). The safe operating space defined by these authors identifies the thresholds of nine Earth system processes that are likely to have irreversible consequences if they are crossed – i.e. planetary boundaries. These include processes that lead to climate change, biodiversity loss, ocean acidification, global freshwater availability, nitrogen and phosphorus distribution in the environment. Since the initial definition of these planetary boundaries, six of the nine boundaries have been crossed as of 2023 (Richardson *et al*., 2023).

Since the soil exhaustion crisis of the 19th century, changes in soil fertilization practices reinforced by the invention of the Haber-Bosch process have markedly altered soil physics and biology as well as soil chemistry (Toor *et al*., 2021). The physical and biological properties of soil are now recognized as critically important to plant health (Feller *et al*., 2012; Nwokolo *et al*., 2021; Kopittke *et al*., 2022; Allen *et al*., 2023). These soil qualities have degraded during the abandonment of traditional farming practices that had focused on maintaining and cycling soil nutrients (Toor *et al*., 2021). For example, the complexity of microbial communities in soil can keep plant pathogens in check. The addition of manure to soil has been repeatedly shown to contribute to the establishment of these microbial communities and to the concomitant disease-suppressive capacity of soil (Janvier *et al*., 2007; Nwokolo *et al*., 2021). Changes in the functions of soil microbial communities due to the impoverishing organic matter are being exacerbated by the use of antimicrobials (pesticides, antibiotics) and herbicides (Kang *et al*., 2021; Liao *et al*., 2021; van Bruggen *et al*., 2021), leading to dramatic and worrisome proliferation of resistance to antimicrobials among bacterial and fungal pathogens of humans and animals (Hernando-Amado *et al*., 2020). These imbalances in microbial communities are contributing to the crossing of yet another of the Earth system thresholds, *viz*. the functional component of biosphere integrity (Richardson *et al*., 2023). If humans are indeed part of the functional component of biosphere integrity, it is critical to note that pesticide exposure also deteriorates farmer health and thus reduces farm productivity (Athukorala *et al*., 2023; Kitole *et al*., 2023). By diminishing farmer health, pesticides further exacerbate the negative effects of poverty and poor education on the capacity of farmers to implement good agronomic practices that assure crop yields (Guest *et al*., 2023). The deleterious effects of synthetic pesticides on human health permeate beyond farmers to the neighboring residents and into the food chain (Dereumeaux *et al*., 2020; Lombardi *et al*., 2021). The social costs are enormous. In France, for example, the social costs attributable to the use of synthetic pesticides (372 million euros) amount to more than 10% of the 2017 annual budget of the Ministry of Agriculture due primarily to the significant effects on the environment and human health (Alliot *et al*., 2022), thereby diminishing resources that could otherwise contribute to farm productivity.

The structure of soil is assured in large part by the maintenance of organic content, allowing the soil to confer its major services to plants and the environment (including water holding and filtration, nutrient cycling, decomposition and recycling of organic materials, and production of biomass) (Hu *et al*., 2023). Yet, in 2015, about one-third of the world's soils had been classified as "degraded" (Toor *et al*., 2021). Unfortunately, efforts to rectify soil health are increasingly in conflict with other uses of biomass in the multitude of initiatives to recycle biomass. The use of biomass as an energy source alternative to fossil fuels is a leading competitor (Chojnacka *et al*., 2022). Although fertilizers can be extracted from the combusted biomass, this mode of recycling continues to reinforce the outmoded mineralist doctrine of plant nutrition that hampers the full scope of ecosystem services, thereby limiting the potential

[3] Available at: https://www.fao.org/3/X0075e/X0075e.htm (accessed 29 November 2023).

of those natural services that contribute to the health of plants, animals, and humans.

Following the wake of the catastrophic dust storms of North America, US President F.D. Roosevelt declared in 1937 that the "nation that destroys its soil destroys itself" (Toor *et al*., 2021). Since then, multiple initiatives have been launched to alert to the importance of renewing and protecting soils. This culminated in the declaration by the United Nations that 2015–2024 would be the International Decade of Soils (Singh *et al*., 2017). Soils are considered as the "single most important common variable in sustaining life on our planet" (Kopittke *et al*., 2022). This re-awakening about the centrality of soils to sustainability has also brought attention to their centrality to One Health because of their roles as habitats and havens of passage of microorganisms with direct impacts on the health of plants, humans, and animals. A recent report brilliantly points to examples of microorganisms in soil that (i) are pathogens of plants, humans, or animals, (ii) promote plant growth, (iii) produce antibiotics, (iv) assure basic soil functions such nutrient cycling, (v) mitigate consequences of climate change including adaptation to drought and so on, and that can even (vi) influence levels of anxiety via their role in gut health (Banerjee and van der Heijden, 2023). Many of the microorganisms found in soil are in passage between other habitats making soil a hub for exchange and interconnectedness among habitats (van Bruggen *et al*., 2019; Sessitsch *et al*., 2023). The state of the microbial biodiversity in soils is directly impacted by land use and agricultural practices, with conventional agricultural practices leading to diminished biodiversity in contrast with organic or conservation practices that are linked to enriched biodiversity (Tahat *et al*., 2020; Barros-Rodríguez *et al*., 2021).

Managing soil quality for crop production to facilitate the future of One Health

One of the major contributions of modern One Health initiatives has been to elucidate the new connections among disparate ecosystems and habitats that have arisen via population growth, urbanization, industrialization, transportation, and the concomitant exploitation of Earth's resources that have become root causes of disease emergence. Pointing out and surveying these new connections are important goals of One Health. Nevertheless, importantly, the ensemble of insight gained from One Health-based analyses of the root causes of disease emergence can be deployed to reconstruct a more sustainable world where some of these root causes are diminished. Multiple authors before us have clearly defended the position that attending to soil quality is essential for sustainability and for assuring human health in the context of One Health (Keith *et al*., 2016; Singh *et al*., 2017; van Bruggen *et al*., 2019; Yan *et al*., 2022; Banerjee and van der Heijden, 2023; Kopittke *et al*., 2023; Singh *et al*., 2023). According to a 2022 study by the FAO, the soil microbiome in particular – a key component of soil quality – is a "game changer" for food security, and human and planetary health (Kendzior *et al*., 2022). Among the key findings of this study was the role of manures and compost in nurturing the soil microbiome and in maintaining long-term soil fertility and functions. However, in stark contrast to this perspective, a 260-page report on "*The State of Food Security in the World"* issued by the WHO in the same year mentioned soils only four times, mostly to indicate policies that did not take soils into account (Flaxman, 2023). These examples reveal the striking disparity in perspectives of a major organization focused on human health vs that of its counterpart organization focused on food production. These organizations (UN, FAO, WHO) and the World Organization for Animal Health united their efforts, again in 2022, produce a 70-page plan of action for One Health (FAO *et al*., 2022). In a rather telling outcome, soils were mentioned only six times in this report. These mentions concerned precautions about soil pollution and sources of contaminants but not about fertility or soil health, reflecting an important ambiguity by the main international forces behind One Health policies in their consensus opinion on organic practices to manage soil quality.

Independently from motivations inspired by One Health, actions to close the gap on the life cycle of fecal wastes – from the farm to the consumer and back to the farm – are increasing. In the European Union (EU), for example, actions are emerging from the EU's commitment to the United Nations' Sustainable Development Goals, for which seven concern soil either directly or indirectly. From 2014 to 2022, the EU's Common Agricultural Policy encouraged improvements in soil and manure management through various incentives. Legislative initiatives are currently being prepared for monitoring and to assure their high standards, with the recommendation by auditors to avoid derogations and conflicts with other policies that could hinder the goal of restoring soil quality (ECA, 2023). Soil quality can be improved by amending with various sources of fecal matter including manures and bio-solids derived from sewage sludge. There are various advantages (fertility, circular economy, etc.) and disadvantages (chemical pollutants, pathogenic microorganisms, etc.) of applying waste-based amendments to soil (Houot *et al*., 2016) that need to be addressed. The EU has a growing body of legislation for the use of bio-solids from sewage in agricultural fields as dumping into landfills is becoming widely prohibited (Collivignarelli *et al*., 2019). However, the management of fecal wastes from centralized waste management systems such as sewers concerns less than half of the world's population. Currently, 3.6 billion people live outside of centralized waste management systems (Allen *et al*., 2023). Although most of these people are in the developing world, rural and mountainous settings in Europe and elsewhere also require decentralized waste management systems (Risch *et al*., 2021). There is need for innovation in waste treatment to respond to these different socio-economic contexts, and, fortunately, there are more and more technological solutions (Shukla *et al*., 2023). Furthermore, the EU has established and is continuously updating its regulations about effluent quality from decentralized wastewater management systems because of the abundance of European rural habitations that are not connected to centralized systems (Falipou *et al*., 2022). In light of the fact that human excreta could meet between 9% and 22% of agricultural demand for the three essential plant macronutrients – nitrogen, phosphorus, and potassium – it is becoming untenable to ignore the value of the almost 1 billion tons of feces generated each year (Allen *et al*., 2023). An extensive review of the literature concerning tests of the effect of fecal amendments on crops found that amendments derived from on-site sanitation systems had a positive impact on crop yields when compared to unamended control treatments and also produced yields equivalent to those for treatments with synthetic nitrogen-based fertilizers (Allen *et al*., 2023). These experimental results weaken the argument that organic farming cannot be as productive as conventional farming. However, they need to add considerations about the necessary caveats for adoption in different ecosystems (e.g., dry vs tropical contexts) and landscapes (e.g., polyculture vs monoculture) to bolster their applicability. Cost-benefit analyses could be performed in these different situations at the level of individual farms and from a more holistic perspective encompassing indirect or non-intentional positive and negative effects to assess cost-benefits for society. Furthermore, these analyses should be conducted in the context of prospection on future agricultural landscapes and agronomic practices that facilitate circular economies.

If soils are indeed central to One Health, then the stewards of soil quality should be central actors of One Health initiatives. Who are these actors? Farmers who produce crops and those involved in the scientific disciplines that support them are the central players for managing soil quality. Based on the rich history of practices and scientific literature concerning organic agricultural and of agro-ecological methods for crop production, this corps of actors can foster practices that are founded on century-old concepts of the oneness of the health of humans, animals, and plants. This insight needs to be leveraged to address questions of how to restore the food web in plant production and on how to reinforce methods of assuring plant health without synthetic pesticides (Fig. 1). This will need to be accomplished all while fostering the ecosystem services of soil that, for example, mitigate the impacts of drought, detoxify pollutants in soils, liberate soil-bound mineral reserves for plant nutrition, limit the proliferation of antibiotic resistance (Banerjee and van der Heijden, 2023), foster the storage of carbon (Gerke, 2022), etc. Part of the transformation of soil management will indeed need to promote an "underground revolution" via ecological engineering to assure specific soil activities and functions (Bender *et al*., 2016).

Overall, our relationship with soil and our understanding of its role in the health of humans, animals, plants, and the biosphere in general, can be markedly modernized. Such a dramatic change in understanding has a well-known precedent, embodied in the functions of the human gut. The human gut has been transmogrified from something dirty to foundational for good health. For the upcoming transition in our relationship with soil, we call on scientists and practitioners to find indicators of soil health, to conceive advice for feeding and caring for soil, to reveal soil's protective role for plant and animal health, and to elucidate the range of environmental functions soil assures directly or indirectly – in the same manner as we have come to understand these for the human gut. For soil, the scope of the actions and innovations needed for this transformation will also need to encompass the full extent of the food web, calling into play engineers and economists, in particular, to establish production and value chains for organic matter (Fig. 1). Therefore, farmers who cultivate crops, alongside professionals in scientific disciplines supporting agriculture, possess essential knowledge to contribute to building a world aligned with modern One Health principles. Recognizing and encouraging their pivotal role in One Health initiatives, practices, and policies is crucial.

Conclusion

The adaptation of agriculture to industrialization and urbanization ruptured a fundamental part of the food web related to the production of plants. This robbed plant production of an important resource and led to serious disruption of planetary mineral cycles, overexploitation and waste of resources, habitat destruction, and other major global changes. This major alteration of planetary

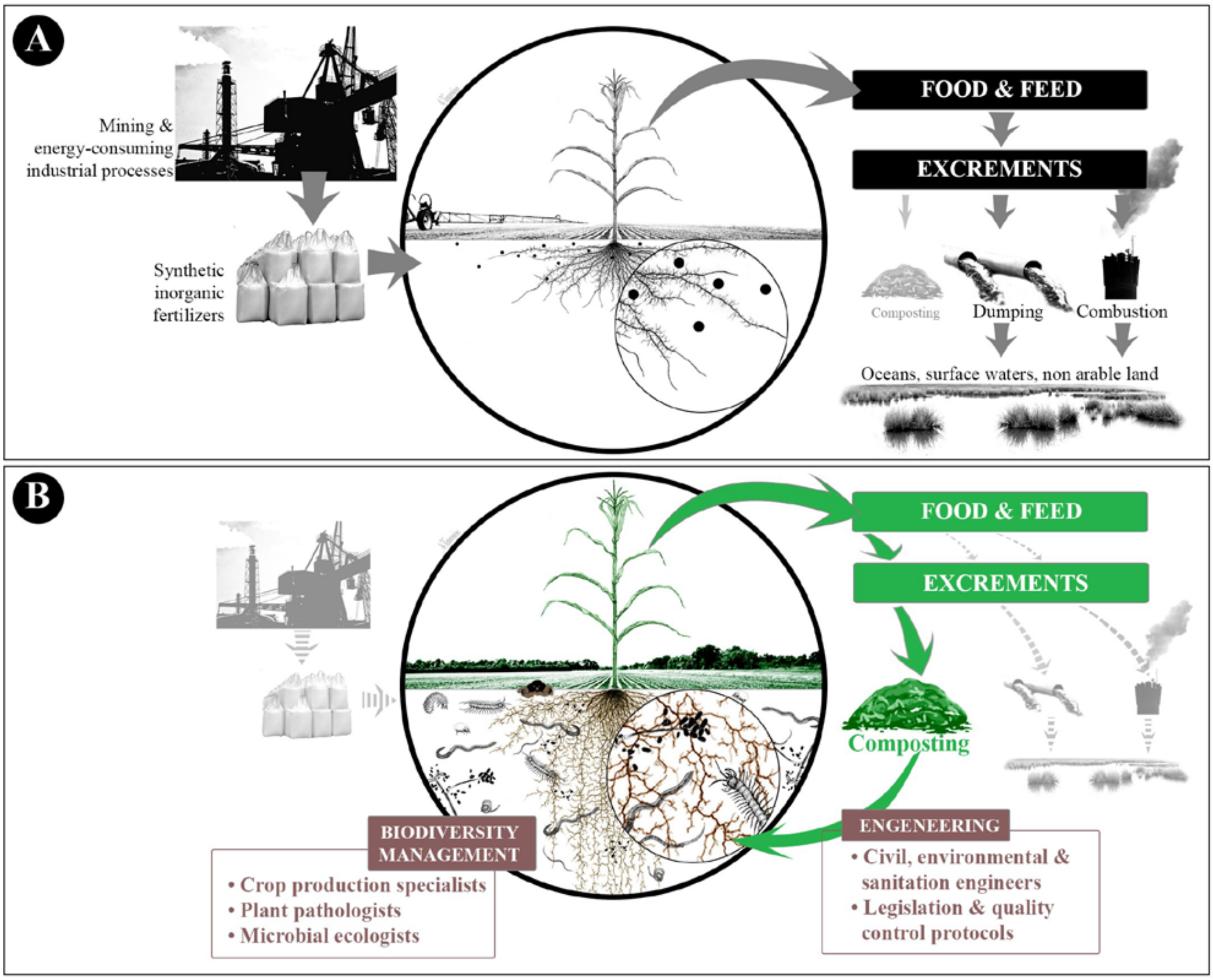

Fig. 1. Component processes and actors for diverting the disuse of organic wastes (A) toward the restoration of the cycle of organic matter (B) for sustainable plant production that strengthens the One Health nexus of plants, animals, humans, and the environment. In general, conventional plant production practices (A) resort to mining and energy-consuming industrial processes to produce synthetic fertilizer all while wasting a large part of excrements from food and feed digestion that hold resources for plant production. The One Health nexus of plants, animals, humans, and the environment can be strengthened by reducing the need for synthetic fertilizers via the valorization of excrements from digestion of food and feed and hence averting their loss or their negative impacts on the environment (B). This will bring into play a range of actors to assure the hygienic qualities of composts and their suitability as fertilizers and to deploy them for optimizing the ecosystem functions of the soil microbiome that contribute to the health of plants, animals, and humans.

ecology occurred despite knowledge about the importance of food web processes and the rational use of resources for sustainability and, importantly, despite the existence of well-formulated concepts of the interconnectedness of the health of organisms that were precursors to the modern One Health concept. These concepts centered on the role of soil – with its physical and chemical properties as well as its microbiology – as a hub that links the health of plants, animals, and humans. As the modern One Health concept emerged in the 2000s, the precursor concepts from agriculture were mostly ignored. Today, the position of plant health in the One Health concept is unclear, and few scientific publications in the field of One Health directly treat issues related to plant production apart from the role of plants as food and feeds. Here, we have addressed the history of how plant health became disconnected from the One Health nexus. We propose a central role for the major stewards of soil quality – farmers who produce crops and those involved in the scientific disciplines that support them – in strengthening and rendering sustainable One Health initiatives, practices, and policies.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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AUTHOR CONTRIBUTIONS

CEM conceived the initial idea for this work; CNM, GG, and SS contributed to defining its scope; CN, AR, and NS contributed to the elaboration of precise technical information and coherence of the manuscript content. CEM wrote the initial version and all authors contributed to revising subsequent versions. CEM and NS conceived the figure and NS made the figure. All authors approve the content of the manuscript.

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