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The role of soil carbon sequestration in enhancing human resilience in tackling global crises including pandemics

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ABSTRACT

Soils have recently received attention in the policy area due to their various connections to climate change, human health and their key role in sustaining human societies in general. In this context, agricultural production and healthy nutritious food are linked to soil health and the diversity of their (micro-)biome, which depend on organic carbon materials as an energy and nutrient source. In this paper, we review the evidence showing that carbon-rich soils improve the resilience of human societies to pandemics and other crises. We indicate pathways for how the loss of soil carbon due to farming could be reversed by transformations within our food systems. Moreover, we argue that soil carbon has a strong role to play in enhancing environmental and human health in addition to mitigating and adapting to climate change. This multifaceted role requires a transdisciplinary dialogue and multi-stakeholder collaboration.

1. Introduction

The era of globalization, which began after World War II has been jeopardized by the COVID-19 pandemic and the recent military conflict in Ukraine. The global crises following these two events have demonstrated the fragility of our neoliberal food system, which is globally interconnected and strongly dependent on international trade and reliance between different parts of society and the economy (Clapp and Moseley, 2020; Lioutas and Charatsari, 2021). In particular, disruptions of the energy and agricultural input and output supply chains created major problems (Laborde et al., 2020; Moyer 2020; Benton et al., 2022). While, during the pandemic, there was a short-term environmental benefit in terms of global emission reductions of greenhouse gases of 1.1 Gt CO_2 eq (Pomponi et al., 2021), we also observed significant global economic and human losses. The COVID-19 pandemic followed by the Ukraine war can be seen as an inflection point, further emphasizing the

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urgent calls for fundamental transformations in our way of life, economies and food systems to be resilient, healthy, efficient, sustainable and inclusive (IFPRI, 2021). The transition must include a radical system change leading to sustainable societies with circular economies, as outlined by the UN when defining the 17 sustainable development goals (SDGs) and more recently by the European commission when defining their priorities (von der Leynen, 2019). It requires to remain within the planetary boundaries, reduce waste and costs, and improve environmental quality and human diets (SAPEA, 2020). Due to the disruption of global transport systems during the COVID-19 pandemic and the ongoing Ukraine war, people became aware of the importance of local provision not only for vaccines, medical supplies and energy, but also for basic goods such as healthy and nutritious food.

To achieve provision of healthy and nutritious food in the event of global disruption of supply chains, Poch et al. (2020) highlighted the importance of local food production on healthy soil. The promotion of soil health is in line with the Convention on Biological Diversity (CBD 2006) and the one health concept, defined by the World Health Organization (WHO, 2016). This integrated concept extends beyond disease and infirmity and recognizes human connections to other species, ecosystems and the ecological foundation of varied drivers and protectors of human health (WHO, 2016). In this context, soil health was defined as the continued capacity of soils to provide ecological functions for all forms of life, in line with the Sustainable Development Goals …" (Veerman et al., 2021). It must be viewed in an ecosystem perspective and should be used as an overarching principle related to living soil leading to the provision of ecosystem services (Powlson, 2021; Lehmann et al., 2020; Janzen et al., 2021). The most important parameter influencing a multitude of the soil's physical, (micro-)biological and chemical parameters is its organic matter content (Lal, 2004; Janzen et al., 2021). However, due to unsustainable management, about half of all soils have been degraded and depleted in soil organic matter through the loss of their soil organic carbon (SOC) stocks (FAO, 2015). We suggest that one concrete way to respond to global crises in line with the 17 SDGs is to focus on improving soils by replenishing their organic matter content and simultaneously to increase their carbon concentrations. This focus is also strongly aligned to addressing the urgency of the climate crisis due to the contribution that SOC sequestration can make to climate change mitigation and adaptation (IPCC, 2018, 2022). However, although mentioned in some parts of the recent IPCC reports, surprisingly little attention is paid to soils and the role that they may play in climate change adaptation and mitigation. This paper has three objectives: First, to review recent evidence on how SOC sequestration can contribute to enhancing positive linkages between soil and human health to improve the resilience and resistance of societies to pandemics and other global crises. Second, to examine the literature identifying what is needed to induce the transformation of the agricultural sector toward resilient agrifood and agrienergy systems that build soil organic matter and enhance ecosystem services, and third to suggest a way forward toward implementation of the agroecological transition.

2. Establishing meaningful connections between soil organic matter and human health in a one health concept

2.1. Soil-human health nexus

To increase society's resistance and resilience to global crises including pandemics, it is imperative to consider the close link between the health of plants, animals, people, and the environment (Lal, 2020). Preserving soil as a functional living system through sustainable management aiming at maintaining and increasing SOC is key (Lal, 2020; Fig. 1). At the most fundamental, biological activity in soils is crucial for transforming plant residues into persistent soil organic matter (Cotrufo et al., 2013; Dynarski et al., 2020), which in turn improves soil quality (Janzen, 2006) and habitat for soil biota (Thiele-Bruhn et al., 2012). It is also the basis for sustainable and innovative solutions to improve soil fertility and plant growth (Calabi Floody et al., 2018) and generating resistance to crop disease (Jamiolkowska, 2020).

Human health is connected to soil in many ways (Table 1; Fig. 1), and the soil-human health nexus has long been known (Oliver and Gregory, 2015; Reeve et al., 2016; Pepper, 2013). Soil can have positive and negative impacts on human health, as recently summarized by Brevik et al. (2020). Positive effects are mostly related to the multitude of ecosystem services that soils provide. Those provisions depend largely on the soils' organic matter content (Table 1). Research around the world has shown that most agricultural soils have lost half of their carbon content since they have been used for cultivation (e.g., Luo et al., 2010), corresponding to 116 Gt of carbon (Sanderman et al., 2017).

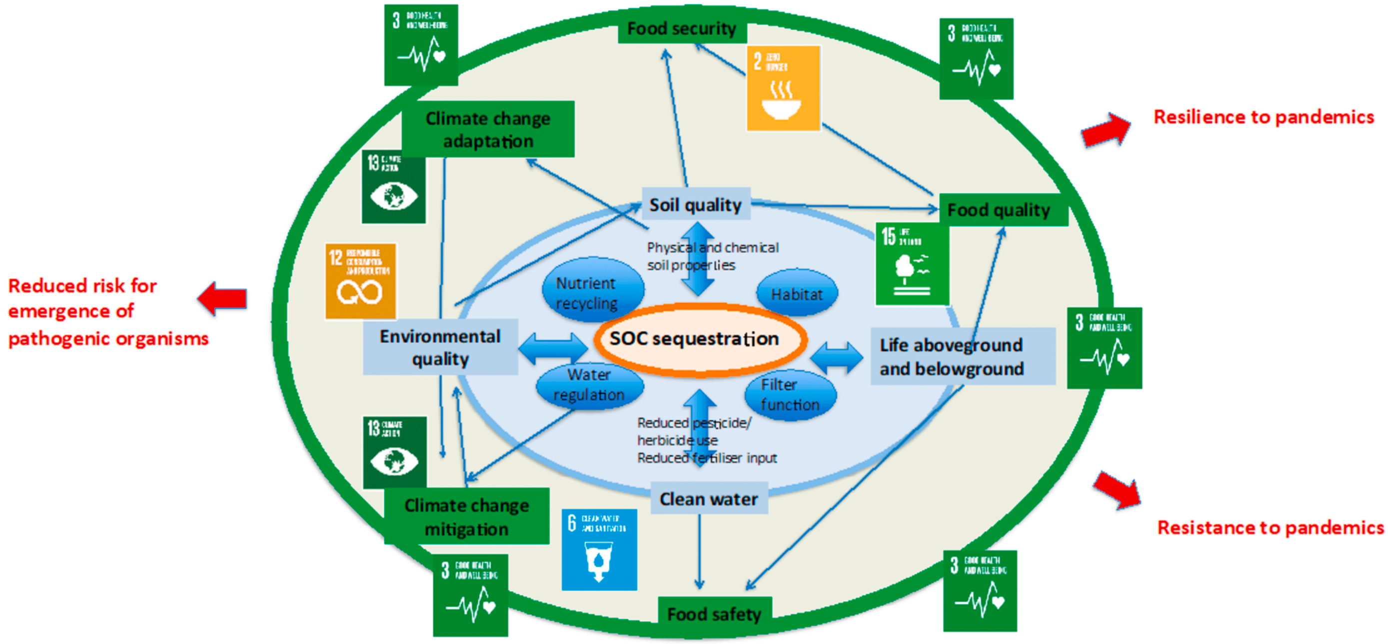
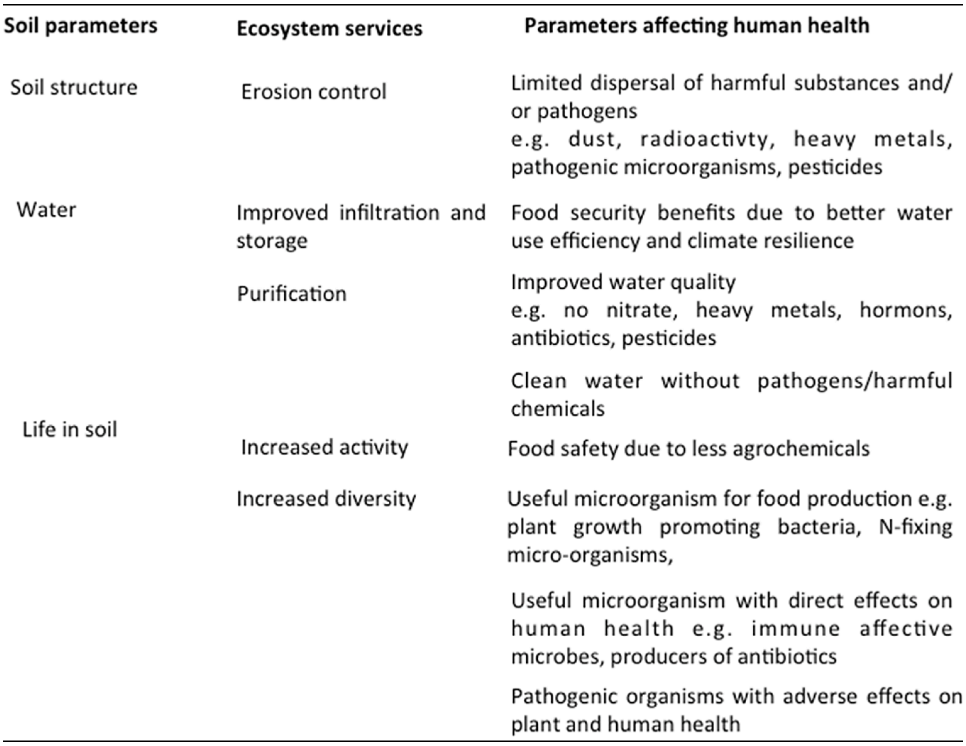


Fig. 1. Links between SOC sequestration and human health leading to face the risks of pandemics.

Table 1

Effects of increasing soil organic matter contents on soil functions, ecosystem services and their relation with human health



Soil parameters	Ecosystem services	Parameters affecting human health
Soil structure	Erosion control	Limited dispersal of harmful substances and/or pathogens e.g. dust, radioactivty, heavy metals, pathogenic microorganisms, pesticides
Water	Improved infiltration and storage	Food security benefits due to better water use efficiency and climate resilience
	Purification	Improved water quality e.g. no nitrate, heavy metals, hormons, antibiotics, pesticides
		Clean water without pathogens/harmful chemicals
Life in soil	Increased activity	Food safety due to less agrochemicals
	Increased diversity	Useful microorganism for food production e.g. plant growth promoting bacteria, N-fixing micro-organisms,
		Useful microorganism with direct effects on human health e.g. immune affective microbes, producers of antibiotics
		Pathogenic organisms with adverse effects on plant and human health

While there may be exceptions, SOC loss may occur within a few years after the beginning of cultivation, and the legacy of agriculture may be long (Mclauchlan, 2006), making the restoration of SOC concentrations and stocks a difficult endeavor. However, replenishing soil carbon may be crucial to support food energy and fibre production and other ecosystem services (Lal, 2004; Soussana et al., 2019; Rumpel et al., 2020).

Soil degradation following soil organic matter loss is in many cases related to agricultural activities that result from a food system that disregards environmental quality and the health of those who consume the food (Moyer, 2020). Soil degradation following land-use change and cultivation of native land may have direct effects on human health through exposure to the numerous pathogenic microorganisms inhabiting soil (Steffan et al., 2020). The degradation of agricultural soils may also adversely affect human nutrition and health through its impact on food quantity and quality, particularly due to (1) continuous and excessive use of agrochemicals (Lal, 2009; Moyer, 2020), and (2) negative impacts on clean water supplies in which healthy, organic matter-rich soils play a fundamental role (Kopittke et al., 2022).

Although very little understood, soils may also be important for our immune system due to the connections between the soil and human microbiomes (Lal et al., 2021). Severe cases of Covid-19 infection are related to the development of inflammatory immune response, which does not allow for the development of protective immunity (Manjili et al., 2020). The development of a functioning human immune system is strongly influenced by the microbiome, which colonizes the gastrointestinal tract (Belkaid and Hand, 2014) and depends upon exposure to pathogens, especially those living in soil (Ottman et al., 2019; Lal et al., 2021). It has increasingly been recognized that soil biodiversity is important for human health (Wall et al., 2015) and needs to be promoted by sustainable management practices . Soils contain vast populations of microorganisms. These highly diverse interacting microbial communities control processes such as mineral weathering and aggregate formation, organic matter decomposition, nutrient cycling, disease suppression, and soil-plant interactions. (Micro-)organisms rely on organic matter-rich soils providing them with energy and nutrients (Hoffland et al., 2020). Consequently, soil biodiversity may be severely compromised by soil organic matter loss, both quality and quantity (Tibett et al., 2020), and prolonged, intensive and indiscriminate application of agrochemicals (Meena et al., 2020; Carvalho, 2006).

We have only started to link soil microorganisms to their functions governed by soil types (Fierer, 2017; Jiao et al., 2021). To safeguard important soil functions and to preserve the basis of plant, animal and human health, it is imperative to develop agroecological practices that maintain soil organic matter, essential for soil biodiversity and its (micro-)biological activity (Lemanceau et al., 2015). It has been suggested that soil care should be integrated into a human health care system with actions for monitoring and restoration of degraded soils (Timmis and Ramos, 2021). We suggest that such a system could be based on monitoring SOC changes.

Due to the links between the human immune system, the soil microbiome, and food quality and human health, sustainable soil management can make a valuable contribution to SDG 3 'Good health and Wellbeing' (Lal et al., 2021). Moreover, due to its positive effect on climate change adaptation and mitigation, it may help to control pathogenic organisms and increase the resilience of agricultural production. Briefly, increasing soil health through sustainable management aiming at increasing SOC stocks may improve the resistance and resilience of the human population to global crises.

2.2. What is needed to induce the transformation of the agricultural sector involving resilient agrifood systems that build soil organic matter?

Current food systems result from a growing reliance on ever-expanding large corporate agricultural systems that aim to increase the quantity of food available to feed a wealthier and rapidly growing global population (Giller et al., 2021). The resultant trend towards more homogenous commodities, less labor-intensive production in large, often monoculture, farming systems has decreased diversity at all levels. The recent COVID-19 pandemic and the climate crisis emphasize the limits of these highly specialized agricultural systems, their vulnerability to pathogens, market forces and climate variability, and their inability to provide sufficiently diverse food to maintain or increase health in animal and human populations (Dury et al., 2019). A shift away from traditional diverse and nutrient-rich diets has been linked to obesity and diet-related chronic diseases (Hawkes, 2006), which in turn increase vulnerability to more serious symptoms if infected with the SARS-CoV-2 virus that causes COVID-19. In response, a transition towards ecologically resilient diverse food production systems has been proposed as a pathway to positive environmental, social and human health benefits (Altieri and Nicholls, 2020, Nyström et al., 2019) to meet the needs of urban and rural dwellers in rich and poor countries.

Well established agroecological principles provide a pathway to more resilient and sustainable agricultural systems by focusing on diverse production and maintaining ecosystem services centered on soil health through high organic matter inputs and protecting and increasing SOC stocks in agricultural soils. Agroecology generally supports agricultural systems producing food, fibre or bioenergy while restoring ecological processes across landscapes (HLPE, 2019). It is a concept applicable at all scales rather than a single farming method. Systems consistent with agroecological principles include: (1) local farming, referring to agricultural products that are grown or produced, processed and sold within a certain restricted area; (2) diversified farming systems that promote practices and landscapes that intentionally include functional biodiversity at multiple spatial and/or temporal scales; and (3) circular economy, a systemic approach to economic development designed to benefit businesses, society, and the environment (HLPE, 2019).

One vehicle to encourage that these practices are installed at scale, is to provide trusted standards certifying environmentally friendly, sustainable production systems that can form the basis of consumer choice, corporate marketing, and public investment. While still representing a small fraction of food sales worldwide, organic certifications are well established and markets for organic produce, dairy products, seafood and others are projected to continue to show strong growth (GVR, 2022), especially as COVID-19 has emphasized the importance of healthy diets. Guidelines exist for the development of accreditation systems that may be more widely applicable than organic certification and which can certify that commodities from large corporate systems as well as small-scale farms meet standards for environmental sustainability and social justice (FAO and INRAE, 2020). Corporate agricultural and food companies are already seeking ways to gain market advantage through differentiation as environmentally, socially and culturally sustainable. They have the capacity to invest in improving their production systems to protect their reputation and market share.

One challenge to effectively promoting action is that accreditation schemes must have metrics able to detect genuine biophysical and social impacts. Interdisciplinary methods and appropriate metrics in line with new paradigms (Hoffland et al., 2020) have to be agreed to measure soil health and ecosystem services, and to define region-specific threshold values. This could help accreditation systems and government organizations like the European Union to allocate budgets to payment for ecosystem services rather than making bland payments per hectare farmed. In this context, a challenge is to provide incentives for soil health that lead to production within agroecological principles, supported by incentivization frameworks with tools, technical advice and rigorous monitoring reporting and verification (MRV) schemes. We suggest that such systems should focus on measures of organic carbon stocks as a practical universal soil health indicator impacting the resilience of societies against crises (Fig. 1).

The principles of distributed production and circular economy are important for increasing innovation for an agroecological transition. Increasing sustainability in agriculture involves minimizing the energy consumed, waste generated, and toxic or greenhouse gases emitted by the production system. Digital agriculture can help to increase the transparency of the food production system, by improving traceability in terms of provenance and resource use. As far as possible, nutrient and carbon cycles in agriculture need to be closed based on circular economy principles with little external inputs. Thus, one important agroecological strategy could be taking advantage of the possibilities of transforming residual organic matter, i.e., organic wastes, into organic soil amendments and fertilizers (Gomez-Sagasti et al., 2018). An important caution, however, is that organic wastes may contain contaminants and pathogens, so their origin, and their transformation processes must be carefully evaluated and legally framed. For example, treated mixed urban waste applied to soil could be contaminated with microplastics (Cattle et al., 2020). Nevertheless, many studies indicated that several organic amendments efficiently induce soilborne pathogen suppression and increase plant health (Bonanomi et al., 2010; Vida et al., 2019). As organic residues can also be used as raw materials for other applications in non-circular approaches (e.g., creating construction materials), different complementary strategies need to be addressed by researchers and policymakers (Ward et al., 2016; Gomez-Sagasti et al., 2018).

By introducing more diverse agricultural systems and enhancing local and urban agriculture to improve soils, the (agro-)ecological transition can be achieved while protecting and enhancing soil functions (Lal et al., 2020; Poch et al., 2020). These concepts are entirely in line with the international 4 per 1000 initiative aiming to maintain and increase soil organic carbon for food security, climate change adaptation and climate change mitigation through the development and implementation of sustainable agricultural practices (Rumpel et al., 2018). The 4 per 1000 initiative as a multi-stakeholder platform focuses on SOC sequestration, with the intent to improve soils, enhance biodiversity and food quality, and contribute to climate change adaptation and climate mitigation if sustainable practices are brought to scale. Therefore, the objectives of the 4 per 1000 initiative to maintain and increase soil organic matter address multiple sustainable development goals, including human health and global partnerships (Rumpel et al., 2020).

Building upon the ongoing experience of the COVID-19 pandemic, (Lioutas and Charatsanri, 2021) discuss three potential mechanisms to mitigate the impacts of major crises or disasters in agriculture: resilience-promoting policies, community marketing schemes, and smart farming technology. Conceiving and implementing strategies in relation to these mechanisms would be best addressed with a multi-stakeholder approach allowing the different actors, scientists, and policymakers to come together to address the potential and feasibility of specific actions. Due to the multitude of pedoclimatic and socioeconomic conditions and production systems, the adopted approaches to improve food systems (IFPRI, 2021) and soils (Amelung et al., 2020) need to be region-specific. However, the region-specific approaches need to be discussed in a global context with collaboration between multiple stakeholders from different countries because agriculture, through the production of raw materials such as fiber and energy is intimately linked with other industries (Storm, 1995). Solutions must be globally inclusive because the large-scale processes have repercussions at the local scale and, ultimately local control mechanisms. For local actions to reach impact at scale, international, global inclusive collaboration is necessary. This can lead to the cross-fertilisation of ideas and adoption of cooperative approaches between developed and less developed countries (Lal, 2019). To facilitate these interactions, the 4 per 1000 initiative has created a web-based platform to encourage multi-stakeholder cooperation and knowledge exchange.

2.3. *The way forward: a call for soil research networks*

To respond effectively to global crises, collaboration across the globe, including various stakeholders and scientists, is necessary (OECD, 2020). While global crises such as the COVID-19 pandemic have been disruptive to many research areas, including agricultural and food studies, it also led to the adaptation of the world scientific community with the development of numerous tools allowing for easy interactions among scientists and between scientists and other stakeholders in different parts of the world. It is in the interest of all countries to continue to reduce the inequality in access to these tools, known as the digital divide (UN, 2021), and improve digital communication tools and their use worldwide to enhance global crisis response for the benefit of the entire population.

There has been strong investment in research on the different aspects of COVID crisis management, including medical, societal and environmental issues, as evidenced by the 286,807 scientific articles with COVID as a research topic published in the last two years (Clarivate Scientific, 2022). Obviously, in the short term, the pandemic led to research priorities in the health sector. As accessed on the 10th of June 2022, only 3.8 % (11,000) of the 286,807 articles published in the Web of Science were associated with Environmental Science (Clarivate Scientific, 2022). Transdisciplinary research is necessary to increase understanding of the fundamental dependence of human nutrition and health on soils and on soil organic matter as the cornerstone of soil health to improve societal response to global crises, including probable future pandemics. A dialog between different disciplines should be initiated via transdisciplinary funding opportunities and publications in transdisciplinary journals. Research is also urgently needed on the role of soil quality and functioning in social-ecological connections that build the resilience of the global production ecosystem that will sustain the health of human populations into the future (Nyström et al., 2019). A global coordination effort to identify region-specific solutions should focus on soil carbon sequestration and involve farmers, businesses, policymakers, and scientists. SOC sequestration is a key sustainable development strategy with a likely strong potential to increase the resistance and the resilience of societies towards future crises, in addition to being beneficial for climate change mitigation and adaptation and food security. Monitoring soil carbon changes and greenhouse gas emissions, soil health indicators, and ecosystem services requires the development of practical inexpensive methods that are universally applicable. To show that carbon sequestration by introducing sustainable practices is feasible, results from long-term (regional) field studies are necessary. Stocktaking and communication of the links between sustainable practices, SOC and soil health to a large audience of stakeholders is crucial to initiate transition in the agricultural sector to more resilient production systems that can also improve the resilience of human health to future pandemics and other crises.

Declaration of Competing Interest

We, the authors declare that we do not have a conflict of interest.

References

Altieri, M.A., Nicolls, C.I., 2020. Agroecology and the emergence of a post COVID-19 agriculture. Agric. Hum. Values 37, 525–526.

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., Bol, R., Collins, C., Lal, R., Leifeld, J., Minasny, B., Pan, G., Paustian, K., Rumpel, C., Sanderman, J., van Groenigen, J.W., Mooney, S., van Wesemael, B., Wander, M., Chabbi, A., 2020. Towards a global-scale soil climate mitigation strategy. Nat. Commun. 11, 1–10.

Belkaid, Y., Hand, T.W., 2014. Role of the microbiota in immunity and inflammation. Cell 157, 121–141.

Benton, T.G., Froggatt, A., Wellesley, L., 2022. The Ukraine war and threats to food and energy security: Cascading risks from rising prices and supply disruptions. Res. Pap., Lond.: R. Inst. Int. Aff. https://doi.org/10.55317/9781784135225.

Bonanomi, G., Antignani, V., Capodilupo, M., Scala, F., 2010. Identifying the characteristics of organic soil amendments that suppress soilborne plant diseases. Soil Biol. Biochem. 42, 136–144.

Brevic, E.C., Slaughter, L., Singh, B.R., Steffen, J.J., Collier, D., Barnhart, P., Pereire, P., 2020. Soil and human health: current status and future needs. Air, Soil Water Res. 13, 1–21.

Calabi-Floody, M., Medina, J., Rumpel, C., Condron, L.M., Hernandez, M., Dumont, M., Mora, M.L., 2018. Smart fertilizers as a strategy for sustainable agriculture. Adv. Agronomy 147, 119–157.

Carvalho, F.P., 2006. Agriculture, pesticides, food security and food safety. Environ. Sci. Policy 9, 685–692.

Cattle, S.R., Robinson, C., Whatmuff, M., 2020. The character and distribution of physical contaminants found in soil previously treated with mixed waste organic outputs and garden waste compost. Waste Manage. (Oxford) 101, 94–105.

CBD, 2006. Global Biodiversity Outlook 2 Secretariat of the Convention on Biological Diversity, Montreal, 81 + vii pages.

Clapp, J., Moseley, W.G., 2020. This food crisis is different: COVID-19 and the fragility of the neoliberal food security order. J. Peasant Stud. 47, 1393–1417.

Clarivate Scientific, 2022. Web of Science database. https://www.webofscience.com/wos/woscc/basic-search.

Cotrufo, F., Wallenstein D., M., Boot M., C., Denef, K., Paul A., E., 2013. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? Global Change Biol. 19, 988–995.

Dury, S., Bendjebbar, P., Hainzelin, E., Giordano, T., Bricas, N., 2019. Food systems at risk: new trends and challenges. FAO, Rome.

Dynarski, K., Bossio, D., Scow, K., 2020. Dynamic stability of soil carbon: reassessing the "permanence" of soil carbon sequestration. Front. Environ. Sci. 8, 514701.

FAO, 2015. Healthy soils are the basis for healthy food production. Fact sheet.. FAO.

FAO and INRAE, 2020. Enabling sustainable food systems: Innovators' handbook. Rome. https://doi.org/10.4060/ca9917en.

Fierer, N., 2017. Embracing the unknown: disentangling the complexities of the soil microbiome. Nat. Rev. https://doi.org/10.1038/nrmicro.2017.87.

Giller, K.E., Delaune, T., Silva, J.V., et al., 2021. The future of farming: Who will produce our food? Food Sec. 13, 1073–1099.

Gomez-Sagasti, T., Hernandez, A., Artexte, U., Garbisu, C., Becerril, J.M., 2018. How Valuable Are Organic Amendments as Tools for the Phytomanagement of Degraded Soils? The Knowns, Known Unknowns, and Unknowns. Front. Sustain. Food Syst. 2, 68.

GVR, 2022. Organic Food And Beverages Market Size, Share & Trends Analysis Report By Product (Organic Food, Organic Beverages), By Distribution Channel (Offline, Online), By Region, And Segment Forecasts, 2022 –2030, 80p.

Hawkes, C., 2006. Uneven dietary development: linking the policies and processes of globalization with the nutrition transition, obesity and diet-related chronic diseases. Glob. Health 2, 4.

Hoffland, E., Keyper, T.W., Comans, R.N.J., Creamer, R.E., 2020. Eco-functionality of organic matter in soils. Plant Soil 455, 1–22.

HLPE, 2019. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

IFPRI, 2021. Global Food Policy Report: Transforming Food Systems after COVID-19. International Food Policy Research Institute, Washington, DC. https://doi.org/10.2499/9780896293991.

IPCC, 2018. Summary for Policymakers. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press, Cambridge, UK and New York, NY, USA [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

[IPCC, 2022. Summary for Policymakers. In: Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J. (Eds.), Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA [(eds.)].

Jamiolkowska, A., 2020. Natural compounds as elicitors of plant resistance against diseases and new biocontrol strategies. Agronomy 10, 173.

Janzen, H.H., 2006. The soil carbon dilemma: Shall we hoard it or use it? Soil Biol. Biochem. 38, 419–424.

Janzen, H.H., Janzen, D.W., Gregorich, E.D., 2021. The 'soil health' metaphor: Illuminating or illusory? Soil Biol. Biochem. 159, 108167.

Jiao, S., Peng, Z., Qi, J., Gao, J., Wei, G., 2021. Linking Bacterial-Fungal Relationships to Microbial Diversity and Soil Nutrient Cycling. mSystems 23, e01052-20.

Kopittke, P.M., Berhe, A.A., Carrillo, Y., Cavagnaro, T.R., Chen, D., Chen, W.-L., Dobarco, M.R., Dijkstra, F.A., Field, D.F., Grundy, M.J., He, J.-Z., Hoyle, F.C., Kögel-Knabner, I., Lam, S.K., Marschner, P., Martinez, C., McBratney, A.B., McDonald-Madden, E., Menzies, N.W., Mosley, L.M., Mueller, C.W., Murphy, D.V., Nielsen, U. N., O'Donnell, A.G, Pendall, E., Pett-Ridge, J., Rumpel, C., Young, I.M., Minasny, B., 2022. Ensuring planetary survival: the centrality of organic carbon in balancing the multifunctional nature of soils. Crit. Rev. Environ. Sci. Technol. https://doi.org/10.1080/10643389.2021.2024484.

Laborde, D., Martin, W., Swinnen, J., Vos, R., 2020. COVID-19 risks to global food security. Science 369, 6503.

Lal, R., 2004. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science 304, 1623–1627.

Lal, R., 2009. Soil degradation as a reason for inadequate human nutrition. Food Security 1, 45–57.

Lal, R., 2019. Promoting "4 Per Thousand" and "Adapting African Agriculture" by south-south cooperation: Conservation agriculture and sustainable intensification. Soil Tillage Res. 188, 27–34.

Lal, R., 2020. Soil science beyond COVID. J. Soil Water Conserv. 75, 79A–81A.

Lal, R., Brevic, E.C., Dawson, L., et al., 2020. Managing Soils for Recovering from the COVID-19 Pandemic. Soil Syst. 4, 46.

Lal, R., Bouma, J., Brevik, E., et al., 2021. Soils and Sustainable Development Goals of the United Nations (New York, USA): An IUSS Perspective. Geoderma Regional 25, e00398.

Lehmann, J., Bossio, D.A., Kogel-Knabner, I., Rillig, M.C., 2020. The concept and future prospects of soil health. Nat. Rev. Earth Environ. 1, 544–553.

Lemanceau, P., Maron, P.-M., Mazurier, S., Mougel, C., Pivato, B., Plassart, P., Ranjard, L., Revellin, C., Tardy, V., Wipf, D., 2015. Understanding and managing soil biodiversity: a major challenge in agroecology. Agron. Sustain. Dev. 35, 67–81.

Lioutas G., E., Charatsanri, C., 2021. Enhancing the ability of agriculture to cope with major crises or disasters: What the experience of COVID-19 teaches us. Agric. Syst. 187, 103023.

Lioutas, E.D., Charatsari, C., 2021. Enhancing the ability of agriculture to cope with major crises or disasters: What the experience of COVID-19 teaches us. Agric. Syst. 187, 103023.

Luo, Z., Wang, E., Sun J., O., 2010. Soil carbon change and its responses to agricultural practices in Australian agro-ecosystems: A review and synthesis. Geoderma 139, 211–223.

Manjili, R.H., Zarai, M., Habibi, M., Manjili, M., 2020. COVID-19 as an acute inflammatory disease. J. Immunol. 205, 12–19.

Mclauchlan, K.K., 2006. The Nature and Longevity of Agricultural Impacts on Soil Carbon and Nutrients: a Review. Ecosystems 9, 1364–1382.

Meena, R.S., Kumar, S., Datta, R., et al., 2020. Impact of Agrochemicals on Soil Microbiota and Management: A Review. Land 9, 34.

Moyer, J., 2020. A time of reflection: a time for change. Agric Human Values 12, 1–2.

Nyström, M., Jouffray, J.B., Norström, A.V., Crona, B., Jørgensen, P.S., Carpenter, S.R., Bodin, Ö., Galaz, V., Folke, C., 2019. Anatomy and resilience of the global production ecosystem. Nature 575 (7781), 98–108.

Oliver, M.A., Gregory, P.J., 2015. Soil, food security and human health: a review. Eur. J. Soil Sci. 66 (2), 257–276.

Ottman, N., Ruokolainen, L., Suomalainen, A., Hanski, I., Alenius, H., Fyhrquist, N., 2019. Soil exposure modifies the gut microbiota and supports immune tolerance in a mouse model. Environ. Occup. Des. 143, 1198–1206.

Pepper, I.L., 2013. The Soil Health-Human Health Nexus. Crit. Rev. Environ. Sci. Technol. 43 (24), 2617–2652. https://doi.org/10.1080/10643389.2012.694330.

Poch, R.M., dos Anjos, L.H.C., Attia, R., et al., 2020. Soil: the great connector of our lives now and beyond COVID-19. Soil 6, 541–547.

Pomponi, F., Li, M., Sun, Y.Y., Malik, A., Lenzen, M., Fountas, G., D'Amico, B., Akizo-Gardoki, O., Anguita, M.L., 2021. A Novel Method for Estimating Emissions Reductions Caused by the Restriction of Mobility: The Case of the COVID-19 Pandemic. Environ. Sci. Technol. Lett. 8, 46–52. https://doi.org/10.1021/acs.estlett.0c00764.

Powlson, D.W., 2021. Is 'soil health' meaningful as a scientific concept or as terminology? Soil Use Manag. https://doi.org/10.1111/sum.12721.

Reeve, J.R., Hoagland, L.A., Villalba, J.J., Carr, P.M., Atucha, A., Cambardella, C., Davis, D.R., Delate, K., 2016. Organic farming, soil health, and food quality: considering possible links. Adv. Agronomy 137, 319–367.

Rumpel, C., Amiraslani, F., Koutika, L.-S., Smith, P., Whitehead, D., Wollenberg, E., 2018. Put more carbon in soils to meet Paris climate pledges. Nature 564, 32–34.

Rumpel, C., Amiraslani, F., Chenu, C., Garcia Cardenas, M., Kaonga, M., Koutika, L.-S., Ladha, J., Madari, B., Shirato, Y., Smith, P., Soudi, B., Soussana, J.-F., Whitehead, D., Wollenberg, E., 2020. The 4p1000 Initiative: opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. Ambio 49, 350–360.

Sanderman, J., Hengl, T., Fiske, G.J., 2017. Soil carbon debt of 12,000 years of human land use. Proc. Natl Acad. Sci. 114, 9575–9580.

SAPEA, 2020. A sustainable food system for the European Union. Evidence Report, 7. European Union, pp. 1–224.

Soussana, J.F., Lutfalla, S., Ehrhard, F., Rosenstock, T., Lamanna, C., Havlik, P., Richards, M., Wollenberg, E., Chotte, J.L., Torquebiau, E., Ciais, P., Smith, P., Lal, R., 2019. Matching policy and science: Rationale for the '4 per 1000 - soils for food security and climate' initiative. Soil Tillage Res. 188, 3–15.

Steffan J., J., Derby A., J., Brevic, E., 2020. Soil pathogens that may potentially cause pandemics, including severe acute respiratory syndrome (SARS) coronaviruses. Curr. Opin. Environ. Sci. Health 17, 35–40.

Storm, S., 1995. On the role of agriculture in India's longer-term development strategy. Cambridge J. Econ. 19, 761–788.

Thiele-Bruhn, S., Bloem, J., De Vries, F.T., Kalbitz, K., Wagg, C., 2012. Linking soil biodiversity and agricultural soil management. Curr. Opin. Environ. Sustain. 4, 523–528.

Tibbett, M., Fraser, T.D., Duddigan, S, 2020. Identifying potential threats to soil biodiversity. PeerJ 8, e9271.

Timmis, K., Ramos, J.L., 2021. The soil crisis: the need to treat as a global health problem and the pivotal role of microbes in prophylaxis and therapy. Microb. Biotechnol. 14, 769–797.

OECD, 2020. Available at: https://www.oecd.org/coronavirus/policy-responses/the-territorial-impact-of-covid-19-managing-the-crisis-across-levels-of-government-d3e314e1/. Accessed June 14, 2021.

U.N., 2021. https://www.un.org/press/en/2021/dsgsm1579.doc.htm, accessed on 15.06.21.

Veerman, C., Pinto Correia, T., Bastioli, C., Biro, B., Bouma, J., Ciemciala, E., Emmett, B., Frison A., E., Grand, A., Hiristov, L., Kriauciuniene, Z., Pogrzeba, M., Soussana, J.-F., Vela, C., Wittkorwski, R., 2021. Caring for soil is caring for life – Ensure 75% of soils are healthy by 2030 for healthy food, people, nature and climate. Interim report of the Mission Board for Soil health and food.. European Union, pp. 1–56.

Vida, C., de Vincente, A., Carzola, F.M., 2019. The role of organic amendments to soil for crop protection: Induction of suppression of soilborne pathogens. Ann. Appl. Biol. 176, 1–15.

von der Leynen, U., 2019. A Union that strives for more. My agenda for Europe.. European Union, pp. 1–24.

Wall H., D., Nielsen N., U., Six, J., 2015. Soil biodiversity and human health. Nature 528, 69–76.

Ward, S.M., Holden, N.M., White, E.P., Oldfield, T.L., 2016. The 'circular economy' applied to the agriculture (livestock production) sector – discussion paper. Workshop on the Sustainability of the E.U.'s Livestock Production Systems hosted by the EU commission on the 14-15.9.2016.

WHO, 2016. World report on ageing and health 2015. WHO editions, Geneva.