BBASR PUBLISHERS

Biological and Agricultural Sciences Research Journal
eISSN: 2959-653X; pISSN: 2959-6521
www.basrj.com
DOI: https://doi.org/10.54112/basrj.v2023i1.13
*Biol. Agri. Sci. Res. J., Volume, **2**: 13*

BASRJ

OPEN ACCESS

Check for updates

Review Article

SOIL SECURITY IN THE SCENARIO OF ABERRANT CLIMATIC CONDITIONS: CHALLENGES, OPPORTUNITIES AND CONSTRAINTS

ABID B[1], *KHALID MN[2]

[1]*Department of Botany, Government College and University Faisalabad, Pakistan*
[2]*Department of Plant Breeding and Genetics, University of Agriculture Faisalabad, Pakistan*

**Correspondence author email address:* noumankhalidpbg@gmail.com

(Received, 18th January 2023, Revised 1st July 2023, Published 5th July 2023)

Abstract: *Climate change has significant implications for soil security, a critical issue given soil's pivotal role in supporting food production, biodiversity, and ecosystem services. The rising global temperatures, changes in precipitation patterns, and the increase in extreme weather events threaten soil health and functions, making it crucial to understand the impacts of climate change on soil security. To comprehensively examine these interactions, this review embarked on a mission to identify the challenges and opportunities and provide directions for future research and policy-making. The extensive review of the relevant scientific literature sheds light on various impacts and potential strategies to enhance soil security amidst the changing climate. Interestingly, while climate change presents substantial challenges to soil security, it also opens the door to promising opportunities. Advances in soil science, climate-smart agricultural practices, and policy opportunities offer hope for improving soil health and resilience. The review highlighted the potential of soil carbon sequestration, robust soil policies, climate-resilient farming practices, and various stakeholders' critical role in shaping future directions. By underscoring the need for further research into soil-climate interactions, the paper serves as a guidepost for future research, policy, and practice to enhance soil security and its contributions to climate change mitigation and adaptation. Thus, it contributes to the collective understanding that safeguarding soil health is a scientific endeavor and a social and economic imperative in our fight against climate change.*

[*Citation: Abid, B., Khalid, M, N. (2023).* Soil security in the scenario of aberrant climatic conditions: challenges, opportunities and constraints. *Biol. Agri. Sci. Res. J.,* ***2023*****:** ***13***. *doi: https://doi.org/10.54112/basrj.v2023i1.13*]
Keywords: soil risk; soil security; climate change; policy-making; resilience

Introduction

Soil security, as a concept, refers to the maintenance and improvement of the world's soil resources to produce food, fiber, and freshwater, contribute to energy and climate sustainability, and maintain biodiversity and the overall protection of ecosystem goods and services (McBratney, Field, & Koch, 2014). Its importance lies in its foundational role in all terrestrial life, supporting agricultural production and vital ecosystem functions such as nutrient cycling, water filtration, and carbon sequestration (Bouma & Montanarella, 2016). Soil security is typically discussed in five dimensions: capability, condition, capital, connectivity, and codification, providing a comprehensive perspective on the multifaceted roles and value of soil (McBratney et al., 2014). Indeed, soil security forms the cornerstone of our survival and well-being. It influences everything from the food to the air we breathe, the water we drink, and the climate we live in. The soil's capability, referring to its functional potential or ability to perform certain functions (McBratney et al., 2014), is often directly linked to its ability to support plant growth and food production. Yet, soil is more than just a medium for plant growth. It is also a vast reservoir of biodiversity, hosting a multitude of organisms that drive essential ecological processes such as nutrient cycling and organic matter decomposition (Nielsen et al., 2015). In the second dimension, the soil condition concerns its current state or quality, including its physical, chemical, and biological properties, which, when optimized, allow the soil to fully realize its capability (McBratney et al., 2014). Therefore, the soil's condition is a key determinant of its productivity and ecosystem services. However, soil condition is influenced by natural factors such as climate and human-induced factors like land use and management practices, highlighting the dynamic nature of soil security (Amundson et al., 2015).
Soil capital, the third dimension of soil security, brings in the economic perspective, referring to the

valuation of the soil and its services. This includes its value for agricultural production and the wider ecosystem services it provides, such as carbon sequestration and water filtration. Here, it is essential to recognize that soil, as a form of natural capital, should be managed sustainably to maintain its value for future generations (Robinson et al., 2020). Soil connectivity, the fourth dimension, relates to the spatial arrangement of soil bodies and their interconnections with other components of the landscape and ecosystems. It emphasizes the role of soil as a connecting medium in the landscape, linking the atmosphere, biosphere, and hydrosphere, and influencing the flows of water, energy, and biogeochemical substances (Van der Putten et al., 2020). Finally, soil codification, the fifth dimension of soil security, pertains to the policies, regulations, and societal norms that govern soil use and management. It recognizes the critical role of institutions, governance structures, and legal frameworks in promoting sustainable soil management and protecting soil resources (Bouma & Montanarella, 2016).

On the other hand, climate change is profoundly reshaping the Earth's systems. The consequences of a warming planet are already evident, with a rising number of extreme weather events, melting glaciers, and shifts in species distributions (IPCC, 2018). The impacts on soil systems are similarly far-reaching, affecting soil processes and functions and soil security (FAO & ITPS, 2015; Rillig et al., 2019). The urgency of the situation is heightened by soil's pivotal role in regulating climate change. As a significant reservoir of carbon, soil has the potential to either mitigate or exacerbate global warming, depending on how it is managed. With appropriate management, soil can sequester more carbon from the atmosphere, helping to mitigate climate change. However, poor soil management can lead to carbon loss from the soil, contributing to greenhouse gas emissions (Minasny et al., 2017). This review explores the intricate relationship between climate change and soil security. It seeks to unravel the challenges posed by a changing climate to soil security and explore the opportunities for enhancing soil security in this era of global change. Given the breadth and complexity of the topic, the review will adopt a multidimensional approach, spanning the biophysical, socio-economic, and policy dimensions of soil security and climate change.

Climate Change and Soil Security: Interactions and Implications

How Climate Change Affects Soil Security

Temperature Increases and Implications

Global warming, a salient feature of climate change, affects the temperature regime of soils worldwide. Rising temperatures stimulate the metabolic rates of soil microorganisms, leading to enhanced soil respiration and the decomposition of soil organic matter (SOM), thus altering soil carbon stocks (Crowther et al., 2016). A meta-analysis by Conant et al. (2011) found that soil carbon loss increases with warming, reducing soil capability and its role in carbon sequestration, a significant ecosystem service provided by soil. Moreover, increased soil temperatures could exacerbate evaporation rates, leading to drier conditions that may impair plant growth and agricultural productivity (Lesk, Rowhani & Ramankutty, 2016). The temperature rise can also affect soil fauna and microorganisms, crucial in nutrient cycling and maintaining soil health and biodiversity (Wagg et al., 2019).

Precipitation Changes and Implications

Changes in precipitation patterns, another manifestation of climate change, profoundly impact soil security. Droughts can reduce soil moisture, impair soil structure, and lead to loss of soil biota, thus affecting soil capability and condition (Trenberth et al., 2014). In contrast, increased rainfall and flooding can lead to soil erosion, nutrient leaching, and waterlogging, impairing soil health and fertility and further exacerbating soil degradation (Dai, 2013).

Increased Frequency and Intensity of Extreme Weather Events

Climate change is also predicted to increase the frequency and intensity of extreme weather events such as storms, floods, droughts, and heat waves. These events can cause severe soil erosion, top soil loss, and soil structure degradation, negatively impacting soil condition and capability (Kendon et al., 2014). For instance, heatwaves can cause soil to dry out and become more susceptible to wind erosion, while heavy rainfall events can result in water erosion, leading to a loss of soil productivity (FAO, 2017).

Impacts on Different Aspects of Soil Security

Effect on Soil Capability

Climate change affects soil capability, encompassing its ability to provide ecosystem services such as supporting plant growth, maintaining biodiversity, regulating water flow, and cycling nutrients. Warmer temperatures and changes in precipitation can alter the capacity of soil to retain water and nutrients, affecting plant growth and agricultural productivity (Lesk, Rowhani & Ramankutty, 2016). Climate changes also affect soil biodiversity, potentially impacting ecosystem services such as nutrient cycling and disease regulation (Wagg et al., 2019).

Effect on Soil Condition

The condition of the soil, including its physical, chemical, and biological properties, is also influenced by climate change. Increased temperatures and changing precipitation patterns can alter soil moisture content, structural stability, pH, nutrient availability, and soil organic matter levels, among other soil properties (FAO, 2015). Climate-induced changes in plant community composition can alter plant-soil feedbacks, further affecting soil conditions (Suding et al., 2008).

Effect on Soil Capital

Climate change can also affect soil capital, which concerns the economic value of soil. Changes in soil productivity due to shifts in climate can influence agricultural yields and hence the economic value derived from soil (Schlenker & Roberts, 2009). Furthermore, altering soil's capability to sequester carbon due to climate change could impact its value in the global carbon market (Smith, 2016).

Effect on Soil Connectivity

Climate change can affect soil connectivity by altering the spatial distribution of soils and their interactions with the wider landscape. Shifts in temperature and precipitation patterns can influence the distribution of soil types, impacting the flows of energy, water, and biogeochemical substances across landscapes (Van der Putten et al., 2020). Furthermore, climate-induced changes in land cover can affect soil-landscape interactions, with potential implications for ecosystem functioning (Foley et al., 2005).

Effect on Soil Codification

Climate change necessitates a reevaluation of soil codification, including policies, regulations, and societal norms governing soil use and management. As climate change impacts become increasingly evident, there may be a need for revised or new legislation, policies, and guidelines to promote adaptive soil management strategies that can mitigate these impacts and enhance the resilience of soil systems (Bouma & Montanarella, 2016).

Challenges for Soil Security in a Changing Climate

Physical Challenges

Erosion, Desertification, Soil Degradation

Climate change exacerbates soil degradation processes such as erosion, desertification, and the loss of soil fertility. Changes in rainfall patterns, increasing temperatures, and the intensification of extreme weather events all contribute to accelerated soil erosion and desertification (IPCC, 2019). Moreover, degradation processes often lead to a loss of soil organic matter and nutrients, affecting soil productivity and contributing to further desertification (Lal, 2004). The severity of these impacts will largely depend on how well soils are managed in light of these changing conditions.

Water Scarcity and Flooding

Changes in precipitation patterns due to climate change also pose significant challenges soil security. Increasing instances of drought can cause water scarcity, leading to soil moisture deficits and impairing soil functions such as nutrient cycling and plant growth (Dai, 2013). Conversely, increased rainfall or flooding can lead to waterlogging and soil erosion, which disrupts soil structure and leads to nutrient losses (Trenberth et al., 2014).

Biological Challenges

Shifts in Soil Biota

Climate change can trigger shifts in soil biota communities, crucial in maintaining soil health and providing ecosystem services such as nutrient cycling and disease regulation. Changes in temperature and moisture regimes can impact the diversity and activity of soil biota, leading to potential knock-on effects on soil functions (Wagg et al., 2019).

Changes in Crop Productivity and Pests/Diseases

Climate changes can directly and indirectly affect crop productivity. Direct effects include changes in temperature and precipitation patterns, while indirect effects involve changes in soil health, water availability, and the prevalence of pests and diseases (Lesk, Rowhani & Ramankutty, 2016). Moreover, climate change may increase the susceptibility of crops to pests and diseases, posing additional challenges to maintaining soil security (Rosenzweig et al., 2001).

Socio-economic Challenges

Impacts on Farming and Food Security

The challenges posed by climate change for soil security directly affect farming and food security. Reduced soil productivity due to soil degradation can negatively impact crop yields, affecting farmers' livelihoods and food insecurity (Schlenker & Roberts, 2009). Moreover, farmers may need to adapt their management practices to cope with changing soil conditions, which can pose significant economic and logistical challenges (FAO, 2017).

Impacts on Rural Economies and Livelihoods

Soil degradation and reduced agricultural productivity due to climate change can also impact rural economies and livelihoods. Agricultural communities may face reduced incomes and job losses, leading to rural-urban migration and social dislocation (FAO, 2017). Moreover, the loss of soil as an economic asset due to degradation could have profound implications for rural economies and land valuation (Bouma & Montanarella, 2016).

Policy and Governance Challenges

Inadequate Policies and Weak Implementation

Ensuring soil security in the face of climate change requires effective policy responses. However, current policies often fail to address the complexities of soil systems or to integrate soil issues into broader environmental and agricultural policy frameworks (Baveye, Baveye, & Gowdy, 2016). Additionally, even where appropriate policies exist, weak implementation and enforcement often hinder their effectiveness in protecting soil resources (FAO, 2015).

Need for Cross-boundary Cooperation and Integrated Approaches

Soil security is a cross-boundary issue that requires cooperation and integrated approaches at multiple scales, from local to global. Climate change impacts on soils do not respect political boundaries, and actions in one area can have significant effects elsewhere (Montanarella, Pennock, McKenzie, Badraoui, Chude, Baptista, Mamo, Yemefack, Singh Aulakh, Yagi, Hong, Vijarnsorn, Zhang, Arrouays, Black, Krasilnikov, Sobocká, Alegre, Henriquez, Mendonça-Santos, Taboada, Espinosa-Victoria, AlShankiti, Kazem AlaviPanah, El Mustafa Elsheikh, Hempel, Camps Arbestain, Nachtergaele, Vargas, 2016). Therefore, there is a need for enhanced international cooperation and integrated approaches to soil management to ensure soil security under climate change.

Opportunities for Soil Security Amidst Climate Change

Advances in Soil Science

Technological Innovations

While climate change poses significant challenges to soil security, technological advances offer an array of tools to mitigate these impacts and ensure long-term soil health. For instance, precision agriculture technologies, like GPS systems, satellites, and drones, are revolutionizing soil management practices. With these tools, farmers can measure and monitor soil parameters, such as moisture content, nutrient levels, and pH, in real-time (Zhang et al., 2002). These accurate, up-to-date insights enable more efficient use of fertilizers and water, reducing input costs and reducing soil degradation risk.

Furthermore, the growing field of soil biotechnology contributes valuable solutions for improving soil fertility and carbon sequestration. One such innovation is biochar, a type of charcoal used as a soil amendment, which has been found to improve water retention and nutrient availability while increasing soil carbon storage (Lehmann & Joseph, 2015). Microbial inoculants, another promising biotechnology, introduce beneficial bacteria or fungi into the soil, boosting plant growth and enhancing soil health.

Improvement in Soil Monitoring and Modeling Techniques

Alongside technological advancements, progress in soil monitoring and modeling techniques is enhancing our ability to predict, monitor, and mitigate the impacts of climate change on soil security. Recent advances have seen an increase in remote sensing technologies, such as satellite imagery and ground-based sensors, to provide real-time data on soil conditions (McBratney, Field, & Koch, 2014).

These data can generate highly accurate forecasts of soil behavior under various climate scenarios. The models can simulate the potential effects of climate variables like temperature and precipitation changes on soil parameters. Hence, they serve as valuable decision-support tools, guiding soil management strategies that are flexible and adaptable to changing climatic conditions (Poulter et al., 2014).

Climate-smart Agricultural Practices

Conservation Agriculture

Various climate-smart agricultural practices are gaining traction in response to the growing recognition of the threat climate change poses to soil security. Conservation agriculture is one such practice, encompassing no-till farming, cover cropping, and crop rotation techniques.

These methods improve soil structure, boost organic matter content, and enhance soil microbial activity, resulting in healthier soils more resilient to climate stresses (Hobbs, Sayre, & Gupta, 2008). For instance, no-till farming reduces soil erosion and compaction, thereby maintaining soil's physical integrity and capacity to store water and nutrients. Similarly, cover cropping and crop rotation contribute to soil biodiversity, aid in pest and disease management, and enhance soil nutrient cycling.

Agroforestry, Cover Cropping, and Diversified Farming Systems

Agroforestry, the practice of integrating trees into crop and livestock systems, offers multiple benefits for soil security and climate resilience. Trees in agroforestry systems can stabilize soils, improve water infiltration, and enrich soil fertility through leaf litter and root symbioses (Jose, 2009). These benefits contribute to higher crop yields, enhanced biodiversity, and better resilience to climate-induced stresses, such as droughts or heat waves. Similarly, diversified farming systems, including polycultures and mixed crop-livestock systems, can enhance soil health and agroecosystem resilience. These systems promote a more balanced and efficient nutrient cycling, improve soil structure and organic matter content, and increase biodiversity at various trophic levels, thus creating a robust defense against pest outbreaks and disease spread (Kremen & Miles, 2012).

Socio-economic Opportunities

Soil Carbon Sequestration and Potential for Carbon Markets

Soils play a crucial role in the global carbon cycle, acting as a major reservoir of organic carbon. Hence, they hold immense potential for mitigating climate change through carbon sequestration –capturing and storing atmospheric carbon dioxide in the soil. Conservation agriculture, agroforestry, and organic farming can increase soil carbon stocks and help offset anthropogenic greenhouse gas emissions (Paustian et al., 2016). Moreover, the concept of carbon markets, where sequestered carbon is traded as a commodity, could incentivize farmers and land managers to adopt soil conservation practices. By putting a price on carbon, these markets could transform carbon sequestration from a cost into a source of income, boosting the profitability of sustainable farming and contributing to rural development (Smith, 2004).

Job Creation and Rural Development

Transitioning towards more sustainable and climate-resilient agricultural systems could stimulate economic growth in rural areas by creating new jobs. Opportunities might arise in sectors like organic farming, agroforestry, and ecosystem restoration. Moreover, the drive for sustainable agriculture could fuel other rural industries, like agritourism and local food markets, fostering a diverse and resilient rural economy (FAO, 2018).

Policy and Governance Opportunities

Developing Robust Soil Policies and Climate-Resilient Land Use Planning

Climate change underlines the necessity for robust soil policies and climate-resilient land use planning. Policymakers acknowledge the need to include soil health parameters in environmental and agricultural regulations. Such policies might encourage sustainable soil management, protect soils in sensitive and high-value areas, and incorporate soil considerations into broader climate mitigation and adaptation strategies (Baveye, Baveye, & Gowdy, 2016).

International Collaborations and Agreements

Soil security is a global issue; addressing it effectively requires international collaboration and agreement. Initiatives like the Global Soil Partnership and the 4 per 1000 Initiative offer platforms for knowledge sharing, joint action, and international advocacy for soil issues (FAO & ITPS, 2015; Minasny et al., 2017). Through these partnerships, countries can align their efforts, share successful strategies, and leverage international funding, significantly improving the effectiveness of measures to secure soils amidst climate change.

Future Research Directions and Recommendations

A. Gaps in Current Knowledge and Research Needs

The multifaceted interactions between climate change and soil security continue to demand a rigorous scientific investigation. While substantial research has been conducted on the impacts of climate change on soil health, there is still much that remains unknown. For instance, understanding how variations in temperature and precipitation influence the distribution and activities of soil microbes at different spatial and temporal scales is still rudimentary (Fierer, 2017). Similarly, the impacts of extreme weather events on soil properties, particularly in terms of their effects on soil structure and related hydrological properties, are poorly understood. Understanding the role of soil in the global carbon cycle is another significant area requiring further research. Although the potential of soil as a carbon sink has been recognized, the precise mechanisms and the extent to which soil can sequester carbon, especially in a warming climate, need further elucidation (Paustian et al., 2016). Moreover, the valuation of soil resources and capital remains complex and challenging. There is a need for research on integrating soil capital into existing economic frameworks, enabling soil security considerations to inform policy and decision-making processes effectively. (Baveye et al., 2016).

B. Recommendations for Policy and Practice

Several measures can be suggested to enhance soil security in a changing climate. First, policies that promote sustainable farming practices like conservation agriculture, agroforestry, and diversified farming systems should be advanced. These farming practices not only boost soil health but also increase the resilience of agricultural systems to climate-induced shocks (FAO, 2018). Second, recognizing the economic value of soil and incorporating it into policy frameworks can contribute significantly to soil security. Policies that incentivize farmers to adopt soil-friendly practices and establish mechanisms for soil carbon trading could prove particularly beneficial (Minasny et al., 2017).

Finally, international collaborations and agreements on soil health are crucial. As soil degradation and climate change are global issues, the solutions should also be global. Cross-boundary cooperation can help share knowledge, resources, and technologies to improve soil security (FAO & ITPS, 2015).

C. The Role of Different Stakeholders

Stakeholders at all levels are responsible for promoting soil security in a changing climate. Governments and policy-makers need to develop and implement robust soil policies and frameworks that promote sustainable land use and soil management practices. They should also invest in research and development to improve soil monitoring and management technologies (McBratney et al., 2014). Farmers and land managers, as frontline stakeholders, need to adopt soil-friendly farming practices. Non-profit organizations can contribute by raising awareness about soil health and advocating for soil-friendly policies. Researchers and scientists must continue investigating soil-climate interactions and develop innovative technologies to improve soil security. Finally, the general public can contribute by being more responsible consumers, supporting farmers who practice sustainable farming, and advocating for the importance of soil health (FAO, 2018).

Conclusion

In conclusion, the interplay between soil security and climate change is a complex and crucial subject of growing concern. As underscored by the analysis in this paper, climate change has profound implications for soil security, with impacts ranging from physical and biological alterations to socio-economic and policy challenges. Increased temperature, precipitation changes, and an upsurge in the frequency and intensity of extreme weather events disturb the intricate balance of soil systems, affecting soil capability, condition, capital, connectivity, and codification. Furthermore, we face the challenge of preserving soil health amidst threats such as erosion, desertification, degradation, water scarcity, shifts in soil biota, changes in crop productivity, and socio-economic impacts. Nevertheless, amidst these challenges lie promising opportunities. Technological innovations and improved soil monitoring and modeling techniques offer unprecedented scope for advancing our understanding of soil-climate interactions. Climate-smart agricultural practices, including conservation agriculture, agroforestry, and diversified farming systems, provide viable solutions to enhance soil health and resilience.

Furthermore, the potential of soil as a carbon sink opens up economic opportunities, such as carbon markets, while contributing to climate change mitigation. Policy and governance also play an essential role in soil security. Developing robust soil policies, implementing climate-resilient land use planning, and fostering international collaborations are vital for addressing the challenges of soil security in a changing climate. In light of the gaps in current knowledge, future research should focus on improving our understanding of soil-climate interactions and integrating soil security considerations into policy and economic frameworks. Moreover, the role of various stakeholders - from governments and policy-makers to farmers, researchers, non-profit organizations, and the general public - is crucial in advancing the cause of soil security. Therefore, as we navigate the pressing climate change issues, we must invest time, resources, and concerted efforts toward ensuring soil security. By doing so, we protect this invaluable resource that sustains life on earth and empowers it to be a significant ally in our fight against climate change.

Declarations

Conflict of interest

The authors have no conflict of interest.

Data Availability statement

All data generated or analyzed during the study are included in the manuscript.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Funding

Not applicable

References

Amundson, R., Berhe, A. A., Hopmans, J. W., Olson, C., Sztein, A. E., & Sparks, D. L. (2015). Soil and human security in the 21st century. Science, 348(6235), 1261071. https://doi.org/10.1126/science.1261071

Baveye, P. C., Baveye, J., & Gowdy, J. (2016). Soil "Ecosystem" Services and Natural Capital: Critical Appraisal of Research on Uncertain Ground. Frontiers in Environmental Science, 4, 41. https://doi.org/10.3389/fenvs.2016.00041

Bouma, J., & Montanarella, L. (2016). Facing policy challenges with inter- and transdisciplinary soil research focused on the UN Sustainable Development Goals. SOIL, 2(2), 135–145. https://doi.org/10.5194/soil-2-135-2016

Conant, R. T., Ryan, MG., Ågren, G. I., Birge, H. E., Davidson, E. A., Eliasson, P. E., Evans, S. E., Frey, S. D., Giardina, C. P., Hopkins, F. M., Hyvönen, R., Kirschbaum, M. U. F., Lavallee, J. M., Leifeld, J., Parton, W. J., Steinweg, J. M., Wallenstein, M. D., Wetterstedt, J. Å. M., & Bradford, M. A. (2011). Temperature and soil organic matter decomposition rates – synthesis of current knowledge and a way forward. Global Change Biology, 17(11), 3392–3404. https://doi.org/10.1111/j.1365-2486.2011.02496.x

Crowther, T. W., Todd-Brown, K. E. O., Rowe, C. W., Wieder, W. R., Carey, J. C., Machmuller, M. B., Snoek, B. L., Fang, S., Zhou, G., Allison, S. D., Blair, J. M., Bridgham, S. D., Burton, A. J., Carrillo, Y., Reich, P. B., Clark, J. S., Classen, A. T., Dijkstra, F. A., Elberling, B., Emmett, B. A., Estiarte, M., Frey, S. D., Guo, J., Harte, J., Jiang, L., Johnson, B. R., Kröel-Dulay, G., Larsen, K. S., Laudon, H., Lavallee, J. M., Luo, Y., Lupascu, M., Ma, L. N., Marhan, S., Michelsen, A., Mohan, J., Niu, S., Pendall, E., Peñuelas, J., Pfeifer-Meister, L., Poll, C., Reinsch, S., Reynolds, L. L., Schmidt, I. K., Sistla, S., Sokol, N. W., Templer, P. H., Treseder, K. K., Welker, J. M., & Bradford, M. A. (2016). Quantifying global soil carbon losses in response to warming. Nature, 540(7631), 104–108. https://doi.org/10.1038/nature20150

Dai, A. (2013). Increasing drought under global warming in observations and models. Nature Climate Change, 3(1), 52–58. https://doi.org/10.1038/nclimate1633

FAO & ITPS. (2015). Status of the World's Soil Resources (SWSR) – Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy.

FAO. (2017). The future of food and agriculture – Trends and challenges. Rome.

FAO. (2018). The State of Agricultural Commodity Markets 2018. FAO. http://www.fao.org/3/I9542EN/i9542en.pdf

Fierer, N. (2017). Embracing the unknown: disentangling the complexities of the soil microbiome. Nature Reviews Microbiology, 15(10), 579–590. https://doi.org/10.1038/nrmicro.2017.87

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N., & Snyder, P. K. (2005). Global Consequences of Land Use. Science, 309(5734), 570–574. https://doi.org/10.1126/science.1111772

Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1491), 543-555. https://doi.org/10.1098/rstb.2007.2169

IPCC. (2018). 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.

IPCC. (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/srccl/

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: an overview. Agroforestry Systems, 76(1), 1-10. https://doi.org/10.1007/s10457-009-9229-7

Kendon, E. J., Rowell, D. P., Jones, R. G., & Buonomo, E. (2008). Robustness of future changes in local precipitation extremes. Journal of Climate, 21(17), 4280–4297. https://doi.org/10.1175/2008jcli2082.1

Kremen, C., & Miles, A. (2012). Ecosystem Services in Biologically Diversified versus Conventional Farming Systems: Benefits, Externalities, and Trade-Offs. Ecology and Society, 17(4), 40. https://doi.org/10.5751/ES-05035-170440

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. Geoderma, 123(1-2), 1-22. https://doi.org/10.1016/j.geoderma.2004.01.032

Lehmann, J., & Joseph, S. (Eds.). (2015). Biochar for Environmental Management: Science, Technology and Implementation (2nd ed.). Routledge.

Lesk, C., Rowhani, P., & Ramankutty, N. (2016). Influence of extreme weather disasters on global crop production. Nature, 529(7584), 84–87. https://doi.org/10.1038/nature16467

McBratney, A., Field, D. J., & Koch, A. (2014). The dimensions of soil security. Geoderma, 213, 203–213. https://doi.org/10.1016/j.geoderma.2013.08.013

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z. S., Cheng, K., Das, B. S., Field, D. J., Gimona, A., Hedley, C. B., Hong, S. Y., Mandal, B., Marchant, B. P., Martin, M., McConkey, B. G., Mulder, V. L., O'Rourke, S., Richer-de-Forges, A. C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C. C., Vågen, T. G., van Wesemael, B., & Winowiecki, L. (2017). Soil carbon 4 per mille. Geoderma, 292, 59-86. https://doi.org/10.1016/j.geoderma.2017.01.002

Montanarella, L., Pennock, D. J., McKenzie, N., Badraoui, M., Chude, V., Baptista, I., Mamo, T., Yemefack, M., Singh Aulakh, M., Yagi, K., Hong, S. Y., Vijarnsorn, P., Zhang, G. L., Arrouays, D., Black, H., Krasilnikov, P., Sobocká, J., Alegre, J., Henriquez, C. R., Mendonça-Santos, M. L., Taboada, M., Espinosa-Victoria, D., AlShankiti, A., Kazem AlaviPanah, S., El Mustafa Elsheikh, E. A., Hempel, J., Camps Arbestain, M., Nachtergaele, F., Vargas, R. (2016). World's soils are under threat. SOIL, 2(1), 79–82. https://doi.org/10.5194/soil-2-79-2016

Nielsen, U. N., Ayres, E., Wall, D. H., & Bardgett, R. D. (2015). Soil biodiversity and carbon cycling: a review and synthesis of studies examining diversity–function relationships. European Journal of Soil Science, 66(1), 265–282. https://doi.org/10.1111/ejss.12188

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. Nature, 532(7597), 49-57. https://doi.org/10.1038/nature17174

Poulter, B., MacBean, N., Hartley, A., Khlystova, I., Arino, O., Betts, R., Bontemps, S., Boettcher, M., Brockmann, C., Defourny, P., Hagemann, S., Herold, M., Kirches, G., Lamarche, C., Lederer, D., Ottlé, C., Peters, M., & Peylin, P. (2014). Plant functional type mapping for earth system models. Geoscientific Model Development, 7(7), 3025–3039. https://doi.org/10.5194/gmd-7-3025-2014

Rillig, M. C., Ryo, M., Lehmann, A., Aguilar-Trigueros, C. A., Buchert, S., Wulf, A., Iwasaki, A., Roy, J., & Yang, G. (2019). The role of multiple global change factors in driving soil functions and microbial biodiversity. Science, 366(6467), 886–890. https://doi.org/10.1126/science.aay2832

Robinson, D. A., Fraser, I., Dominati, E. J., Davíðsdóttir, B., Jónsson, J. O. G., Jones, L., Jones, S. B., Tuller, M., Lebron, I., Bristow, K. L., Souza, D. M., Banwart, S., & Clothier, B. E. (2020). On the value of soil resources in the context of natural capital and ecosystem service delivery. Soil Science Society of America Journal, 74(3), 685–700. https://doi.org/10.2136/sssaj2009.0213

Rosenzweig, C., Iglesias, A., Yang, X. B., Epstein, P. R., & Chivian, E. (2001). Climate Change and Extreme Weather Events; Implications for Food Production, Plant Diseases, and Pests. Global Change & Human Health, 2(2), 90–104. https://doi.org/10.1023/A:1015086831467

Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. Proceedings of the National Academy of Sciences, 106(37), 15594–15598. https://doi.org/10.1073/pnas.0906865106

Smith, P. (2004). Carbon sequestration in croplands: the potential in Europe and the global context. European Journal of Agronomy, 20(3), 229-236. https://doi.org/10.1016/j.eja.2003.08.002

Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. Global Change Biology, 22(3), 1315–1324. https://doi.org/10.1111/gcb.13178

Suding, K. N., Lavorel, S., Chapin, F. S., Cornelissen, J. H. C., Díaz, S., Garnier, E., Goldberg, D., Hooper, D. U., Jackson, S. T., & Navas, M.-L. (2008). Scaling environmental change through the community-level: A trait-based response-and-effect framework for plants. Global Change Biology, 14(5), 1125–1140. https://doi.org/10.1111/j.1365-2486.2008.01557.x

Trenberth, K. E., Dai, A., van der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K. R., & Sheffield, J. (2014). Global warming and changes in drought. Nature Climate Change, 4(1), 17–22. https://doi.org/10.1038/nclimate2067

Van der Putten, W. H., Ramirez, K. S., Poesse, L. et al. (2020). Changing climate and the value of the soil ecosystem. Nature Reviews Earth & Environment, 1, 74–84. https://doi.org/10.1038/s43017-020-0026-1

Wagg, C., Bender, S. F., Widmer, F., & van der Heijden, M. G. A. (2014). Soil biodiversity and soil community composition determine ecosystem multifunctionality. Proceedings of the National Academy of Sciences, 111(14), 5266–5270. https://doi.org/10.1073/pnas.1320054111

Zhang, N., Wang, M., & Wang, N. (2002). Precision agriculture—a worldwide overview. Computers and Electronics in Agriculture, 36(2-3), 113-132. https://doi.org/10.1016/S0168-1699(02)00096-0