Chapter

Land Use Change Affects Soil Organic Carbon: An Indicator of Soil Health

Lucy W. Ngatia, Daniel Moriasi, Johnny M. Grace III, Riqiang Fu, Cassel S. Gardner and Robert W. Taylor

Abstract

Soil organic carbon (SOC) is a major indicator of soil health. Globally, soil contains approximately 2344 Gt of organic carbon (OC), which is the largest terrestrial pool of OC. Through plant growth, soil health is connected with the health of humans, animals, and ecosystems. Provides ecosystem services which include climate regulation, water supplies and regulation, nutrient cycling, erosion protection and enhancement of biodiversity. Global increase in land use change from natural vegetation to agricultural land has been documented as a result of intensification of agricultural practices in response to an increasing human population. Consequently, these changes have resulted in depletion of SOC stock, thereby negatively affecting agricultural productivity and provision of ecosystem services. This necessitates the need to consider technological options that promote retention of SOC stocks. Options to enhance SOC include; no-tillage/conservation agriculture, irrigation, increasing below-ground inputs, organic amendments, and integrated, and diverse cropping/farming systems. In addition, land use conversion from cropland to its natural vegetation improves soil C stocks, highlighting the importance of increasing agricultural production per unit land instead of expanding agricultural land to natural areas.

Keywords: agriculture, land use change, organic carbon, soil health

1. Introduction

The basis and essence of life on earth depends on soil health, and its main indicator is soil organic carbon (SOC) content [1, 2]. Soil health has been defined as the capacity of a soil to support ecosystem functions and sustain environmental quality and biological productivity, while promoting plant and animal health [3]. Through plant growth, soil health is connected with the health of humans, animals, and ecosystems within its domain [4]. The SOC is an indicator of soil health and is an important component of the soil ecosystem [5, 6]. Deb et al. [7] indicate that the presence of organic carbon (OC) in soil is a key determinant for soil quality and productivity. In addition, organic matter is a key influencer on physical, chemical, and biological soil attributes [8]. The SOC stock exhibit the long-term balance between additions of OC from different sources and its losses through different pathways [9].

The term SOC is defined as C in soil derived from organic origins and soil organic matter (SOM) is generally considered to contain approximately 58% SOC.
Soil organic matter is a mixture of materials including particulate organics, humus, fine plant roots, living microbial biomass as well as charcoal [10]. Two words have commonly been used in reference to SOC; C sequestration and C storage. Carbon sequestration is the process of transferring carbon dioxide (CO$_2$) from the atmosphere into the soil which can be achieved through plants, plant residues and other organic amendments which are retained in the soil as part of SOM [10, 11]. Carbon sequestration in soil can range from short-term to long-term [12]. However, carbon storage in soil is defined as increase in SOC stocks over time, but it is not necessarily associated with a net removal of CO$_2$ from the atmosphere [12]. Soil storage of OC for longer time periods is preferable in terms of greenhouse gases mitigation, however, mineralization of SOC is important in terms of soil fertility [12, 13]. Soil health reflects the capacity of a soil to support both the agricultural production and provision of other ecosystem services [14]. Therefore, evaluation of soil health is essential because soil is a critically important component of the earth's biosphere whose, functionality is critical in the production of food and fiber as well as maintenance of environmental quality [15, 16].

In the soil profile, approximately 615 Gt of OC is stored in the top 20 cm, 1500 Gt of OC stored in the first meter, and 2344 Gt of OC is stored in the top three meters of soil [17, 18]. However, approximately 9 Gt C is anthropogenically released to the atmosphere annually from fossil fuel sources and ecosystem degradation [10]. Previous studies have illustrated that conversion of forest or natural vegetation to agriculture leads to an overall loss of SOC [5, 6, 19]. Through soil supply of plant macro and micronutrients, soil health, mediated by SOC dynamics is a major determinant of global food and nutritional security [4]. The projected increase of human population by 2050 will double food demand and put immense pressure on natural resources [20]. Therefore, one of the greatest challenges will be to increase food production by maintaining ecosystem services [21].

2. Importance of soil organic carbon

Soil organic C provides ecosystem services that are essential to human well-being for example climate regulation, water supplies and regulation, nutrient cycling, erosion protection and enhancement of biodiversity [2, 22–24]. In addition, SOC exerts an influence on many soil properties, for example water holding capacity, aggregate stability, total nitrogen, pH and cation exchange capacity [5, 6]. Increasing SOC can mitigate GHG emissions, benefit agricultural productivity through improvements in soil health, and improve environmental quality [25].

Under long-term management practices SOC pools influence soil quality, C sequestration pathways, and crop productivity [9]. It has been demonstrated that high SOC levels can enhance soil fertility and health, improve water infiltration, improve soil structure, enhance moisture retention and increased crop yield [26, 27]. A positive relationship has been reported between SOC content and soil nutrient status and crop yield [28, 29]. Since SOC content influences almost all soil functions and it is easily measurable, it can be a suitable indicator of the soil capacity to supply ecosystem services [22, 23].

3. Effects of climatic conditions on soil organic carbon

Generally, SOC stocks increase with decreasing mean annual temperature [30], whereby, cold, humid climatic regions exhibit C rich soils [31]. Decomposition
releases to the atmosphere most of the C added to the soil through litter deposition, only a limited fraction becomes humus [10]. Both moisture and temperature influence the rate of litter decomposition through their effects on microbial activity [32]. In addition, both moisture and temperature also exhibit strong control of humus decomposition [10].

4. Land use change affects soil organic carbon and ecosystem services

Globally, there has been increased land use change from natural vegetation to agricultural land and urban areas as well as intensification of agricultural practices [33, 34]. These changes results in large increases in energy, water, and fertilizer consumption, as well as considerable losses of biodiversity [33]. The growing human population has driven both the land use change and land use intensification in order to meet global demand for food, water and energy [35]. However, conversion of forest or natural vegetation to agriculture leads to an overall loss of SOC [2, 5, 6, 19] (Figure 1), resulting in efforts to restore SOC in agricultural soils [36, 37]. Once soil is cultivated for agricultural production, SOM is rapidly decomposed as a result of modifications in conditions such as aeration, water content and temperature [38]. Land use change could affect soil functions that directly or indirectly relate to SOM, as a result of its capacity to retain water and nutrients as well as provide other ecosystem services [39, 40]. For example, changes in the SOC stock could result in significant impacts on the atmospheric C concentration [10]. Carbon dioxide is the main greenhouse gas responsible for global warming [41]. Soil organic C balances

![Figure 1](image)

*Figure 1.*
Averages concentrations of soil organic carbon in semiarid Chaco and Pampa's sub-regions. Full line indicates critical thresholds proposed for temperate regions, and dashed line is for topical regions. Modified from [2].
are associated with CO₂ sequestration [36]. As a result, SOC stock is considered an intermediate ecosystem service that contributes to climate regulation [10].

Agricultural production can be increased by increasing cropland area or increasing productivity per unit area. When agricultural production increases as a result of land use change from natural cover areas to crop production agriculture, overall SOC mediated ecosystem services supply decreases [2] (Figure 2A). It was indicated that land use change from native forest to pasture (+8%), crop to pasture (+19%), crop to plantation (+18%), and crop to secondary forest (+53%) increased total C stocks, as well as SOC mediated ecosystem services (Figure 2B and C) whereas changes from pasture to plantation (−10%), native forest to plantation (−13%), native forest to crop (−42%), and pasture to crop (−59%) reduced total C stocks [17]. Generally, land use change from all other uses to cropping or monocultures result in losses of SOC [10]. In addition, Montgomery [42] indicated that accelerated soil erosion associated with conventional agriculture could occur at rates up to 100 times greater than the rate at which natural soil formation takes place. Additionally, peatlands have been drained for agricultural purposes [43]. Peatland store much more organic C in form of different C functional groups compared to upland. For example; in Apalachicola National Forest, the wetlands dominated by cypress (Figure 3A) and spikerush and water lily (Figure 3B) contain more alkyl, methoxyl, O-alkyl, aromatic, phenolic and carboxyl C compared to upland (Figure 3C). However, globally, peatland drainage causes carbon-rich peat to disappear at a rate 20 times greater than the rate at which the peat accumulated [44]. As a result, SOC affect both climate change and crop production in agricultural soils [9].

Soil management practices that sustain and enhance carbon stocks are crucial if we are to overcome near-term challenges and conserve this valuable resource for future generations. As a result of soil C loss during the past 25 years, one-quarter of the global land area has suffered a decline in productivity and the ability to provide

---

**Figure 2.** Relations between ecosystem services mediated by SOC versus (A), agricultural production (B), natural cover (C), SOC and (D), relationship between agricultural production and natural cover. Modified from [2].
Land Use Change Affects Soil Organic Carbon: An Indicator of Soil Health
DOI: http://dx.doi.org/10.5772/intechopen.95764

ecosystem services [39]. However, it has been observed that land use change from cropland to pasture or cropland to permanent forest results in the greatest gains of SOC [10] (Table 1). For example, Conant et al. [45] indicated that land use conversion from cropland to grassland improve soil carbon stocks. However, over time grassland area has been shrinking and arable land area expanding, indicating continued conversion of grassland to croplands [46]. In some cases where natural land cover has increased in expense of agricultural land cover, agricultural production

Figure 3.
Quantification of carbon functional groups in Apalachicola National Forest; which includes (A) cypress wetlands, (B) spikerush+water lily wetlands and (C) upland.

| Treatment                      | Initial | Final | Change (%) |
|-------------------------------|---------|-------|------------|
| Conversion: Cultivation to grass | 0.97    | 1.35  | 39.2       |
| Conversion: native to grass   | 2.97    | 2.55  | −14        |
| Fertilization                 | 3.44    | 3.85  | 11.8       |
| Grazing                       | 2.62    | 2.89  | 9.99       |
| Reclamation                   | 8       | 15.9  | 98.8       |

Table 1.
Changes in soil carbon concentration presented by type of management change implemented. Modified from [45].
has been reported to decrease (Figure 2D). With increasing human population, this trend highlights the importance of increasing agricultural production by increasing crop yields per unit land area rather than expanding cropland and/or pasture over natural areas [2].

5. Increasing organic carbon stocks in agricultural soils

Agricultural systems are dependent on maintenance of four major functions; nutrients cycling, carbon transformations, soil structure maintenance, and regulation of pests and diseases [14]. Increasing SOM in agricultural soils contribute to food security and adaptation to climate change as well as mitigation of climate change [12]. SOM has a major role in soil fertility and water retention [47]. Therefore, SOM indirectly contributes to agricultural productivity and consequently to food security [12]. Management practices can influence SOC stocks by either decreasing SOC losses or increasing C inputs to soils. When OC input to a soil is larger than the OC outputs by mineralization or erosion, the SOC increases [12]. Below are technological options to manage SOC in agricultural ecosystem.

5.1 No-tillage and conservation agriculture

Soil organic matter is considered an important indicator of soil quality and health, which can be impacted by crop production practices such as tillage [48]. Tillage has the potential to increase the rate of C mineralization through breaking larger macro aggregates, mixing crop residues and exposing protected SOC in the aggregates to soil microorganisms [5, 6, 49, 50]. In general, tillage is considered to increase SOC mineralization as a result of mechanical and rain induced disruption of soil aggregates and the consequent release of CO$_2$. Hence, conservation tillage/no-tillage has been considered as a suitable practice to maintain or increase SOC stocks compared to conventional tillage [12, 51, 52]. Conservation tillage practices such as no till can enhance assimilation of SOC by decreasing soil disturbance and increasing crop residue accumulation in comparison to conventional tillage [12, 25, 48, 53]. For example; Blanco-Canqui and Lal [54] indicated an increase in SOC with increasing crop residue retention, whereby 16.0 t C ha$^{-1}$ of SOC was reported without straw additions, 25.3 t SOC ha$^{-1}$ with 8 t ha$^{-1}$ of straw added and 104.9 t C ha$^{-1}$ with 16 t ha$^{-1}$ of straw added.

Global meta-analyses and reviews have recently confirmed that SOC stock increases in the upper soil layers (0–15 or 0–20 cm) under no tillage, but generally has low to non-significant effects on SOC stocks over 30 cm depth or deeper [51, 55–58] (Figure 4). In addition to carbon sequestration, conservation tillage can reduce CO$_2$ emissions [60]. Accumulation of SOC exhibit a positive correlation with the sequestration of atmospheric CO$_2$, while oxidation of SOC, as a result of practices such as tillage, can contribute to CO$_2$ emission from agricultural fields [48]. For example, CO$_2$ emission in conventional tillage was 29% greater than in no till in a loamy soil as reported by Bista et al. [61].

5.2 Irrigation

Irrigation may have similar effects on SOC decomposition in varying scenarios, but, its effects on primary production are likely to be much higher in arid and semi-arid areas compared to humid regions with dry summers [62]. It is reported that irrigation exhibited strong positive effects on SOC stocks in desert soils,
positive effects in semi-arid areas, but no consistent trend was observed in humid areas [12, 62]. Further, it is emphasized that SOC stocks are dependent on climate and initial SOC content [62].

5.3 Increasing below-ground inputs

Below ground OC inputs, which includes roots and associated inputs, contribute more to SOC compared with above ground inputs [59, 63, 64] (Figure 5). For example, Kätterer et al., [63] reported long-term experimental results which indicated that root derived C was 2.3 times higher than that derived from above ground plant residue. Rasse et al. [64] estimated that mean residence time in soils of root derived C is 2.4 times compared with that of shoot derived C, indicating that root C has a longer residence time in soil compared to the shoot C.

Figure 4.
Soil carbon content with depth. Shaded areas represent standard error of the mean. Data from long-term field experiment in Ultuna. Modified from [59].

Figure 5.
Mean annual carbon inputs through above-ground crop residues, roots including rhizodeposition to equivalent topsoil depth (1957–2008), and organic amendments (1956–2008). Modified from [63].
5.4 Organic amendments

Organic amendment inputs can promote a buildup of SOM and hence SOC [65] (Figure 6). Menichetti et al. [59] reported that application of organic amendments affected SOC in the topsoil resulting in fourfold increases in C stock. Organic residues and wastes can be applied to soil, as fresh organic matter, after composting, methanisation, or pyrolysis [12]. However, the effects of residue quality on long term SOC is still a matter of debate [12]. Previous studies have indicated that the most labile and easily degradable compounds contribute more to SOM in the long term than recalcitrant materials such as lignin, this is especially common in clayey soil [66]. There are three explanations to this finding, which include: 1) long lasting SOM are mainly derived from microbial materials [67, 68]; 2) substrates that are easily degradable are processed with a high microbial C use efficiency [69], and 3) soluble compounds could be protected between mineral surfaces [12].

5.5 Integrated, and diverse cropping/farming systems

Compared with monoculture, introduction of crop diversity increases SOC which improves soil health [70]. Whereby, a combination of diversification within a cropping system and no-till soil management can help to improve SOC [71]. Increased plant diversity can enhance positive soil feedbacks on residue decomposition and soil SOM stabilization and may contribute to C accumulation in soils with rotated crops [72]. Further, Maiga et al. [71] demonstrated that use of diverse 4-year crop rotations for longer duration (>24 years) enhanced SOC, overall C and nitrogen fractions, and soil aggregation in comparison with those under 2-year corn–soybean rotations.

6. Conclusion

Soil organic C is an important indicator of soil health. Soil health is a major component of one health, which encompasses human, animal, and environmental health [73].
Soil organic C promotes land productivity and provides ecosystem services. Since SOC content influences almost all soil functions and is easily measurable, it can be a suitable indicator of the soil capacity to supply ecosystem services. This hypothesis reinforces the suitability of SOC as an appropriate indicator for soil management decisions, land use planning, and regulation. However, the rapidly increasing global human population is exerting enormous pressure on natural resources, as a result of the need to provide food and fiber to supply demands from this growing population. Consequently, there has been conversion of natural land areas to agricultural land globally in pursuit of meeting the human demand for food and fiber. This land use change has resulted in losses of SOC, which negatively affects productivity and diminish ecosystem services. Previous work has demonstrated that conversion of agricultural land to its natural cover provides positive feedback in terms of increasing soil C stocks. This finding highlights the importance of increasing agricultural production by increasing crop yields per unit area rather than expanding cropland and/or pasture to natural areas for long-term sustainability. In addition, there is need to invest in technological options that enhance SOC stocks in agricultural land. These options include no-tillage/conservation agriculture, irrigation, increasing below-ground inputs, organic amendments and integrated, diverse cropping/farming systems.

Acknowledgements

This work was supported by USDA-Forest Service grant number 17-CA-11330140-027 and USDA-ARS grant number 58-3070-7-009. All NMR measurements were performed at the National High Magnetic Field Laboratory, which is supported by National Science Foundation Cooperative Agreement No. DMR-1644779 and the State of Florida.
Author details

Lucy W. Ngatia1*, Daniel Moriasi2, Johnny M. Grace III3, Riqiang Fu4, Cassel S. Gardner1 and Robert W. Taylor1

1 College of Agriculture and Food Sciences, Florida A&M University, Tallahassee, FL, USA

2 USDA-ARS Grazinglands Research Laboratory, USA

3 USDA-Forest Service, Southern Research Station, USA

4 National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL, USA

*Address all correspondence to: lucy.ngatia@famu.edu
References

[1] Lal, R. 2014. Societal value of soil carbon. J. Soil Water Conserv. 69:186A–192A.

[2] Villarino, S. H., Studdert, G. A., and Laterra, P. 2019. How does soil organic carbon mediate trade-offs between ecosystem services and agricultural production? Ecological Indicators, 103, 280-288. https://doi.org/10.1016/j.ecolind.2019.04.027

[3] Doran J.W., Safley M. 1997. Defining and assessing soil health and sustainable productivity, in: C.E. Pankhurst, B.M. Doube, V.S.R. Gupta (Eds.), Biological Indicators of Soil Health, CAB International, New York, 1997, pp. 1-28.

[4] Lal R. 2016. Soil health and carbon management. Food and Energy Security, 5(4):212-222

[5] Winowiecki, L., T.-G. Vägen, B. Massawe, N.A. Jelinski, C. Lyamchhai, G. Sayula, and E. Msoka. 2016a. Landscape-scale variability of soil health indicators: Effects of cultivation on soil organic carbon in the Usambara Mountains of Tanzania. Nutr. Cycling Agroecosyst. 105:263–274. doi:10.1007/s10705-015-9750-1

[6] Winowiecki, L., T.-G. Vägen, B. Massawe, N.A. Jelinski, C. Lyamchhai, G. Sayula, and E. Msoka. 2016b. Landscape-scale variability of soil health indicators: Effects of cultivation on soil organic carbon in the Usambara Mountains of Tanzania. Nutr. Cycling Agroecosyst. 105:263–274. doi:10.1007/s10705-015-9750-1

[7] Deb S., Bhadoria P.B.S., Mandal B., Rakshit A., Singh H.B. 2015. Soil organic carbon: Towards better soil health, productivity and climate change mitigation. Climate Change and Environmental Sustainability, 3(1): 26-34

[8] Bini D., Santos C.A.D., do Carmo K.B., Kishino N, Andrade G., Zangaro W., Marco Nogueira M.A. 2013. Effects of land use on soil organic carbon and microbial processes associated with soil health in southern Brazil. European Journal of Soil Biology 55:117-123

[9] Majumder, B., Mandal, B., Bandyopadhyay, P.K., Gangopadhyay, A., Mani, P.K. and Kundu, A.L., Mazumdar, D. 2008. Organic Amendments Influence Soil Organic Carbon Pools and Rice–Wheat Productivity. Soil Sci. Soc. Am. J. 72:775-785

[10] Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A.B., de Courcelles, V.D., Singh, K., Wheeler, I., Abbott, L., Angers, D.A., Baldock, J., Bird, M., Brookes, P.C., Chenu, C., Jastrowh, J.D., Lal, R., Lehmann, J., O’Donnell, A.G., Parton, W.J., Whitehead, D., Zimmermann, M., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. 164, 80-99.

[11] Olson, K.R., Al-Kaisi, M.M., Lal, R., Lowery, B., 2014. Experimental consideration, treatments, and methods in determining soil organic carbon sequestration rates. Soil Sci. Soc. Am. J. 78, 348.

[12] Chenu, C., Angers, D. A., Barré, P., Derrien, D., Arrouays, D., and Balesdent, J. 2019. Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. Soil and Tillage Research, 188, 41-52. https://doi.org/10.1016/j.still.2018.04.011

[13] Angers, D.A., Mehuys, G.R., 1989. Effects of cropping on carbohydrate content and water stable aggregation of a clay soil. Can. J. Soil Sci. 69, 373-380.
[14] Kibblewhite, M.G., Ritz, K., Swift, M.J. 2007. Soil health in agricultural systems. Philosophical Transactions of the Royal Society Series B, 363, 685-701.

[15] Doran, J. W., and M. R. Zeiss. 2000. Soil health and sustainability: managing the biotic component of soil quality. Appl. Soil Ecol. 15:3-11.

[16] Glanz, J.T., 1995. Saving Our Soil: Solutions for Sustaining Earth's Vital Resource. Johnson Books, Boulder, CO, USA.

[17] Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change. Global Change Biol. 8, 345-360.

[18] Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol. Appl. 10, 423-436.

[19] Don A., Schumacher J., Freibauer A. 2011. Impact of tropical land-use change on soil organic carbon stocks—a metaanalysis. Glob Change Biol 17:1658-1670. doi:10.1111/j.1365-2486.2010.02336.x

[20] Foley, J.A., 2011. Can we feed the world & sustain the planet? Scientific Am. 305, 60-65.

[21] Balmford, A., Green, R., Phalan, B., 2012. What conservationists need to know about farming. Proc. R. Soc./Biol. Sci. 279, 2714-2724.

[22] Lorenz, K., Lal, R., 2016. Soil organic carbon: an appropriate indicator to monitor trends of land and soil degradation within the SDG framework. Dessau-Roßlau, Germany (available at: http://www.umweltbundesamt.de/sites/default/files/medien/1968/publikationen/2016-11-30_soilorganic_carbon_as_indicator_final.pdf).

[23] Powlson, D.S., Gregory, P.J., Whalley, W.R., Quinton, J.N., Hopkins, D.W., Whitmore, A.P., Hirsch, P.R., Goulding, K.W.T., 2011. Soil management in relation to sustainable agriculture and ecosystem services. Food Policy 36, S72–S87.

[24] Victoria, R., Banwart, S., Black H. et al., 2012. Benefits of soil carbon. UNEP yearbook. United Nations Environmental Programme, New York, 33 p

[25] Hati, K. M., Biswas, A. K., Somasundaram, J., Mohanty, M., Singh, R. K., Sinha, N. K., & Chaudhary, R. S. 2020. Soil organic carbon dynamics and carbon sequestration under conservation tillage in tropical vertisols. In P.K Ghosh S.K Mahanta D. Mandal B. Mandal and R Srinivasan (Eds.), Carbon management in tropical and sub-tropical terrestrial systems (pp. 201-212). Singapore City, Singapore: Springer.

[26] Fan, Y., Hou, X., Shi, H., and Shi, S. 2013. Effects of grazing and fencing on carbon and nitrogen reserves in plants and soils of alpine meadow in the three headwater resource regions. Russian Journal of Ecology, 44, 80-88. https://doi.org/10.1134/S1067413612050165

[27] Xu, E., Zhang, H., and Xu, Y. 2020. Exploring land reclamation history: Soil organic carbon sequestration due to dramatic oasis agriculture expansion in arid region of Northwest China. Ecological Indicators, 108, 105746. https://doi.org/10.1016/j.ecoind.2019.105746

[28] Hashimi, R., Komatsuizaki, M., Mineta, T., Kaneda, S., and Kaneko, N. 2019. Potential for no-tillage and clipped-weed mulching to improve soil quality and yield in organic eggplant production. Biological Agriculture and Horticulture, 35, 158-171. https://doi.org/10.1080/01448765.2019.1577757

[29] Xu, J., Han, H., Ning, T., Li, Z., and Lal, R. 2019. Long-term effects of tillage and straw management on soil
organic carbon, crop yield, and yield stability in a wheat-maize system. Field Crops Research, 233, 33-40. https://doi.org/10.1016/j.fcr.2018.12.016

[30] Post, W.M., Emanuel, W.R., Zinke, P.J., Stangenberger, A.G., 1982. Soil carbon pools and world life zones. Nature 298, 156-159.

[31] Hobbie, S.E., Schimel, J.P., Trumbore, S.E., Randerson, J.R., 2000. Controls over carbon storage and turnover in high-latitude soils. Global Change Biol. 6, 196-210.

[32] Meentemeyer, V., 1978. Macrolimate the lignin control of litter decomposition rates. Ecology 59, 465-472.

[33] Foley J.A., DeFries R., Asner G.P., et al. 2005. Global consequences of land use. Science, 309:(5734): 570-574.

[34] Vanwalleghem, T., Gómez, J.A., Infante, Amate J., González de Molina, M., Vanderlinden, K., Guzmán G., Laguna A., Giráldez J.V. 2017. Impact of historical land use and soil management change on soil erosion and agricultural sustainability during the Anthropocene. Anthropocene 17:13-29. https://doi.org/10.1016/j.ancene.2017.01.002.

[35] Foresight 2011. The Future of Food and Farming: Challenges and choices for global sustainability. Final Project Report. The Government Office for Science, London.

[36] Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623-1627.

[37] Tittonell P., Giller K.E. 2013. When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crops Res 143:76-90. doi:10.1016/j.fcr.2012.10.007

[38] Ashagrie, Y., Zech, W., Guggenberger, G., Mamo, T., 2007. Soil aggregation and total and particulate organic matter following conversion of native forests to continuous cultivation in Ethiopia. Soil and Tillage Research 94: 101-108.

[39] Bai, Z.G., Dent, D.L., Olsson, L. and Schaepman, M.E. 2008. Proxy global assessment of land degradation. Soil Use and Management, 24, 223-234

[40] Guimarães, D. V., Gonzaga, M. I. S., da Silva, T. O., da Silva, T. L., da Silva Dias, N., and Matias, M. I. S. 2013. Soil organic matter pools and carbon fractions in soil under different land uses. Soil and Tillage Research, 126:177-182. https://doi.org/10.1016/j.still.2012.07.010

[41] IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[42] Montgomery, D.R. 2007. Soil erosion and agricultural sustainability. Proceedings of the National Academy of Sciences, 104, 13268-13272

[43] Ojanen P. and Minkkinen K., 2020. Rewetting Offers Rapid Climate Benefits for Tropical and Agricultural Peatlands But Not for Forestry-Drained Peatlands. Global Biogeochemical Cycles, 34, e2019GB006503. https://doi.org/10.1029/2019GB006503

[44] Joosten, H. 2009. The Global Peatland CO2 Picture. Peatland status and drainage associated emissions in all countries of the World. Wetlands International, Ede, the Netherlands

[45] Conant, R.T., Cerri, C., Osborne, B., Paustian, K., 2017. Grassland management impacts on soil carbon
stocks: a new synthesis. Ecol. Appl. 9, 73-76.

[46] FAO. 2015. FAO STAT Statistical Database 2013. Food and Agriculture Organization of the United Nations, Rome, Italy. Follett, R. F., J. M. Kimble, and R. Lal. 2001. The potential of US grazing lands to sequester carbon and mitigate the green-house effect. CRC Press, Chelsea, Michigan, USA.

[47] Lal, R., 2008. Carbon sequestration. Philos. Trans. R. Soc. Lond. B Biol. Sci. 363, 815-830.

[48] Govindasamy, P., Liu, R., Provin, T., Rajan, N., Hons, F., Mowrer, J., Bagavathiannan, M. 2020. Soil carbon improvement under long-term (36 years) no-till sorghum production in a sub-tropical environment. Soil Use Manage. 2020;00:1-12.

[49] Kan, Z.-R., Ma, S.-T., Liu, Q.-Y., Liu, B.-Y., Virk, A. L., Qi, J.-Y., Zhang, H.-L. 2020. Carbon sequestration and mineralization in soil aggregates under long-term conservation tillage in the North China Plain. Catena, 188, 104428. https://doi.org/10.1016/j.catena.2019.104428

[50] Singh, S., Nouri, A., Singh, S., Anapalli, S., Lee, J., Arelli, F., and Jagadamma, S. 2020. Soil organic carbon and aggregation in response to thirty-nine years of tillage management in the southeastern US. Soil and Tillage Research, 197, 104523. https://doi.org/10.1016/j.still.2019.104523

[51] Haddaway, N.R., Hedlund, K., Jackson, L.E., Kätterer, T., Lugato, E., Thomsen, I.K., Jørgensen, H.B., Isberg, P.-E., 2017. How does tillage intensity affect soil organic carbon? A systematic review. Environ. Evid. 6, 2-48.

[52] VandenBygaart, A. J., Gregorich, E. G. and Angers, D. A. 2003. Influence of agricultural management on soil organic carbon: A compendium and analysis of Canadian studies. Can. J. Soil Sci. 83: 363-380.

[53] Jha, P., Hati, K. M., Dalal, R. C., Dang, Y. P., Kopittke, P. M., & Menzies, N. W. 2020. Soil carbon and nitrogen dynamics in a vertisol following 50 years of no-tillage, crop stubble retention and nitrogen fertilization. Geoderma, 358, 113996.

[54] Blanco-Canqui, H., and Lal, R. 2007. Soil structure and organic carbon relationships following 10 years of wheat straw management in no-till. Soil and Tillage Research, 95, 240-254. https://doi.org/10.1016/j.still.2007.01.004

[55] Luo, Z.K., Wang, E.L., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric. Ecosyst. Environ. 139, 224-231.

[56] Meurer, K.H.E., Haddaway, N.R., Bolinder, M.A., Kätterer, T., 2018. Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil—A systematic review using an ESM approach. Earth Sci. Rev. 177, 613-622.

[57] Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, Ca., Sanchez, Pa., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Change 4, 678-683.

[58] Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agric. Ecosyst. Environ. 220, 164-174.

[59] Menichetti, L., Ekblad, A., Kätterer, T., 2015. Contribution of roots and amendments to soil carbon
accumulation within the soil profile in a long-term field experiment in Sweden. Agric. Ecosyst. Environ. 200, 79-87.

[60] Hernanz, J. L., Sánchez-Girón, V., and Navarrete, L. 2009. Soil carbon sequestration and stratification in a cereal/leguminous crop rotation with three tillage systems in semiarid conditions. *Agriculture, Ecosystems and Environment*, 133, 114-122. https://doi.org/10.1016/j.agee.2009.05.009

[61] Bista, P., Norton, U., Ghimire, R., & Norton, J. B. 2017. Effects of tillage system on greenhouse gas fluxes and soil mineral nitrogen in wheat (Triticum aestivum, L.) -fallow during drought. Journal of Arid Environment, 147, 103-113. https://doi.org/10.1016/j.jaridenv.2017.09.002

[62] Trost, B., Prochnow, A., Drastig, K., Meyer-Aurich, A., Ellmer, F., Baumecker, M., 2013. Irrigation, soil organic carbon and N2O emissions. A review. Agron. Sustain. Dev. 33, 733-749.

[63] Kätterer, T., Bolinder, M.A., Andrén, O., Kirchmann, H., Menichetti, L., 2011. Roots contribute more to refractory soil organic matter than above-ground crop residues, as revealed by a long-term field experiment. Agric. Ecosyst. Environ. 141, 184-192.

[64] Rasse, D.P., Rumpel, C., Dignac, M.F., 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant Soil 269, 341-356.

[65] Follett, R.F., 2001. Soil management concepts and carbon sequestration in cropland soils. Soil and Tillage Research 61: 77-92.

[66] Cotrufo, M.F., Wallenstein, M.D., Boot, C.M., Denef, K., Paul, 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? Glob. Change Biol. 19, 988-995.

[67] Kallenbach, C.M., Grandy, A.S., Frey, S.D., Dieffendorf, A.F., 2015. Microbial physiology and necromass regulate agricultural soil carbon accumulation. Soil Biol. Biochem. 91, 279-290.

[68] Miltner, A., Bombach, P., Schmidt-Brücken, B., Kästner, M., 2012. SOM genesis: microbial biomass as a significant source. Biogeoosciences 11, 41-55.

[69] Wieder, W.R., Grandy, A.S., Kallenbach, C.M., Bonan, G.B., 2014. Integrating microbial physiology and physio-chemical principles in soils with the MiCrobi-al-Mineral Carbon Stabilization (MIMICS) model. Biogeoosciences 11, 3899-3917.

[70] McDaniel M., Grandy A., Tiemann L., Weintraub M. 2016. Eleven years of crop diversification alters decomposition dynamics of litter mixtures incubated with soil. Ecosphere 7, e01426. doi:10.1002/ecs2.1426

[71] Maiga, A., Alhameid, A., Singh, S., Polat, A., Singh, J., Kumar, S., and Osborne, S. 2019. Responses of soil organic carbon, aggregate stability, carbon and nitrogen fractions to 15 and 24 years of no-till diversified crop rotations. Soil Research,57, 149-157

[72] McDaniel, M. D., L. K. Tiemann, and A. S. Grandy. 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecological Applications 24:560-570.

[73] Mackenzie J.S. and Jeggo M., 2019. The One Health Approach—Why Is It So Important? Tropical medicine and infectious disease. *Trop. Med. Infect. Dis*.4:88; doi:10.3390/tropicalmed4020088