



Effect of Climate Change on Soil Health and Implications on Food Security: A Review



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Abstract: Climate change and soil health are intertwined complex processes that affect each other. The aim of this review was to find out the impact of climate change on soil health, its implication on food security and human welfare across the globe. The study found out that soil health is affected by land use practices and several anthropogenic activities carried out on landscapes; climate change and variability. Soil health also contributes to soil water retention, crop productivity, households' food and income security culminating into a large contribution towards achieving sustainable development goals across the globe. Soil components affect climate and climate affects soil health and human wellbeing. The review article concluded that climate change and soil health are complex and intertwined multidisciplinary processes that require multidisciplinary approaches for better understanding and improvement of crop production. Appropriate climate smart agricultural practices are recommended to enhance soil health and mitigate and adapt to the changing climate for the improved farmers' income, food security and human wellbeing across the globe.

Keywords: Soil health, Climate change, Food security, Crop production, Climate smart agriculture

1. Introduction

Climate change and soil health are closely interlinked, influence each other and food security globally. Climate change refers to the change in climate variables for a long period of time, usually 30 years or more [1]. The major variables of climate change being temperature and precipitation. Soil health is the ability of soil to perform various functions for the welfare of biodiversity and humanity. Figure 1 shows the three major processes affecting soil health. These include: physical, chemical and biological [2]. These processes influence the soil structure, nutrient-holding capacity and nitrogen mineralization among others. To better understand interaction of soil health and climate change, one needs to look at indicators that relate soil physical, chemical and biological properties to ecological functions and which can be monitored in the context of sustainable land management and climate change [3]. A healthy soil supports species diversity (flora, fauna and microorganisms), which in turn support crop production and human welfare. Climate smart soils are healthy in nature and provide

ecosystem services required for humans and their environment [4]. Soils in the tropics are more healthy, fertile and have deeper profile than soils in the temperate regions thus the former provides better requirements to support biodiversity at all levels (gene, species and ecosystem) [5]. Soils in the tropics are reported to be more developed with more horizons than soils in the temperate regions [6]. This is due the differences in temperature and moisture in the two landscapes. High temperature and heavy precipitation significantly affect soil health and healthy soils sequester more carbon (in form of soil organic carbon) and mitigate climate change. Heavy rainfall results into flooding, erosion and landslides that affect the soil structure hence its ability to support life [5]. Moreover, soil erosion washes away the top soil together with its nutrients that support plant growth and crop production for human survival. Heavy rains also enhance nutrient leaching which makes nutrients unavailable to plant utilization and assimilation hence poor plant growth and productivity.

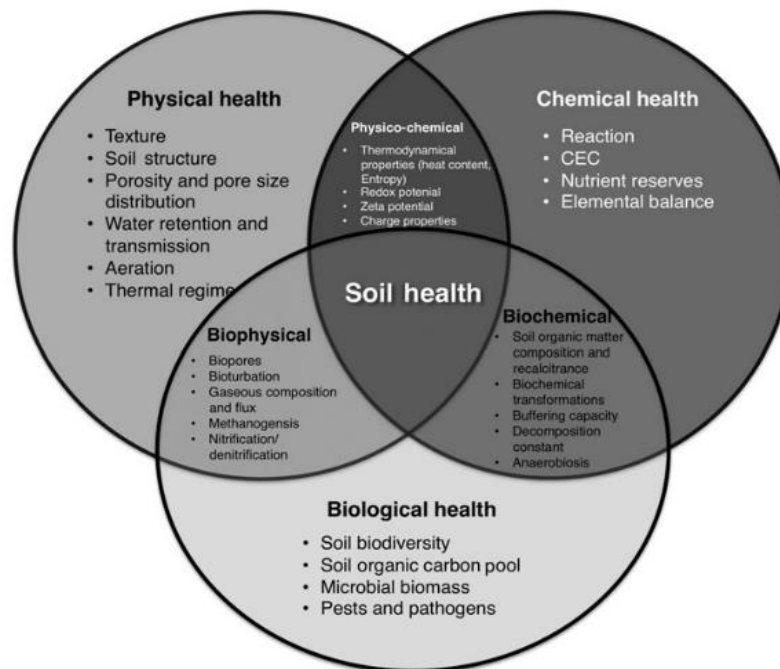


Figure 1. Soil health components (source: Bhupinder et al, 2011)

Previous studies reported that soil organic matter, a proxy for soil health, increases with precipitation and decrease with increase in temperature hence affecting soil health [6-10]. Consequently, climate change directly affects the soil health and its ability to support biodiversity and food production. The effect of climate change on soil health is poorly documented hence the need for this review. The literature review focuses on the following objectives: the effect of climate change on soil formation; the effect of land management on soil health; the effect of climate change on soil chemistry; the effect of climate change on soil and ground water availability; the synergy between soil health, crop production and food security; the linkage between soil health and climate smart agriculture; the effect of Climate change on soil biodiversity; the contribution of soil health to Sustainable Development Goals (SDGs); and the strategies for improving soil health for improving crop production.

2. The Effect of Climate Change on Soil Formation

Climate affects soil formation and soil structure [11]. Healthy soils have appropriate levels of nutrients necessary for the production of healthy plants, moderately high levels of organic matter, a soil structure with good aggregation of the primary soil particles & macro-porosity, moderate pH, thickness sufficient to store adequate water for plants, a healthy microbial community, and absence of elements or

compounds in concentrations toxic for plant, animal, and microbial life [12]. High temperature breaks down the soil structure, reduced the ability for soil water retention and dissociates soil particles which making soil less productive and effectively support living organisms [13]. Warmer and wetter topical conditions have deeper and healthier soils than drier and colder temperate regions. Tropical soils, though healthier, have higher leaching of minerals and clay compared to the temperate soils. They require efficient management practices to keep them healthier and produce more crop yields for the populations [6]. At the same time, heavy rains result into compact soils that do not favour soil microorganisms thus making it unfavourable for their survival and soil respiration. Studies done in China revealed that Mineral-associated organic carbon (MOC), is dependent on soil type, soil texture and climate [14]. Soil organic carbon is used as an indicator for soil health and the higher the SOC, the healthier is the soil [8] and high temperature affects soil moisture and SOC [15] and soil structure.

3. The Effect of Land Management on Soil Health

Land management and agricultural practices affect soil health and climate change [16-17]. Slash and burn, for instance, destroys the soil structure, evaporates soil moisture and releases greenhouse gasses to the atmosphere thus enhancing climate change [18]. Additionally, heavy tillage destroys soil structure, decreases soil bulk density and exposes soils

to soil erosion agents such as wind and water thereby undermining soil productivity in a given agricultural landscape [19]. This is exacerbated by slopping agricultural landscapes where water erosion is facilitated by the slope. All soil processes can be affected by the type of land management practice [20]. Research conducted in the US, projected that growing biofuels on former corn large fields will increase greenhouse gases by 50% thus enhancing climate change [21]. Large scale production of biofuels attempts to reduce the impact of climate change by utilization of environmentally friendly energy source, but contrary to the intention of the operation, climate change is instead promoted.

4. The Effect of Climate Change on Soil Chemistry

Intensive agriculture results into loss of soil organic matter, mostly in tropical soils. The Soil Organic Carbon loss is usually due to climate change and management practices [22-23]. Climate change affects soil chemistry and several soil properties that are important for crop production [24-25]. Studies in Finland reported that reclamation of acid sulphate (AS) soils for agriculture resulted into increased metal cations that may expose the human population to increased metal intake. Mean Fe, Cr, Cu, Zn as well as C and N concentrations were higher in AS soils than their counterpart soils in the same region. This poses a threat to human health because swallowing heavy metals like Cr may cause diseases [21]. Further, study conducted in Canada revealed that increased temperature decreases SOC while increasing soil

microbial activity [26]. Type of cultivated crop also affect the nutrient cycle in soil such as leguminous green manure cropping systems were found to increase nitrogen concentration and improve soil health [27]. However, previous research pointed out that the risk of nitrate leaching in crops fertilized with minerals or organic N is weather and soil dependent and this affects crop productivity [28].

5. The Effect of Climate Change on Soil and Ground Water Availability

Climate change is reported to have significant impact on availability of ground water in soils, which is important for plant growth and people's livelihood [29-30]. Increased temperatures cause by climate change in different climate scenarios, especially, Representative Concentration Pathway (RCP), RCP6.0 and RCP8.5 will negatively affect ground water availability and this will affect crop production, livestock and human lives [31]. Ground water deficiency affects plant growth and this in turn affect fauna species that depend on them for their feeding [24]. Rivers and lakes will decrease in their levels hence undermining irrigation systems for crop production. Simply put, reduction of ground water caused by climate change affects several ecosystems and food webs including humans [32].

Interaction of climate change, soil processes, plant primary production and land management at different intensities and magnitude affect soil health and crop production [33]. Details of possible impact of climate change on soil health indicators are provided in Table 1.

Table 1. Effect of climate change on soil health indicators

Soil Health Indicators	Climate Change Effect
Biological	
Soil organic matter (SOM)	High temperature affects soil moisture, Soil organic matter and soil structure [15]. Soil Organic matter increases microbial biomass and catabolic activity which may directly enhance nutrient mineralization and SOM stabilization [10]
Respiration	Increase in annual maximum and minimum temperature increased microbial respiration [26] hence releasing more greenhouse emissions to the atmosphere and further increasing climate (positive feedback)
Soil biota biomass	Microbial growth and activity generally decrease with decreased temperature. Extremely high temperatures, in general, are dangerous for many microorganisms [24] and affect their respiration, growth and biomass production.
Microbial biomass C & N	Increase in annual maximum and minimum temperature decreases SOC stocks [26] and decreases N leaching
Potentially mineralizable N	Increasing temperatures increase N mineralization thus have a positive effect on plant growth [8] and food production
Enzyme activity	Extreme high temperature denatures enzymes activity and very low temperature make enzymes inactive to support soil productivity and plant life. Moderate temperature required for maintaining healthy soils [21].

Chemical	
pH; rate of acidification or alkalization	Low pH leads to plant nutrient deficiency and unavailability except for Al and Mn to plant use and high pH, the solubility of many metals and trace elements is decreased, including essential nutrients for plants such as Fe, Mn, Cu or Zn [34]. Soil pH affects soil water retention capacity namely by impacting the biological and physical processes of the soil [35] and climate affects soil pH
Electrical conductivity	Soil electrical conductivity (EC) is a measure of the amount of salts in soil. High temperature interferes with soil microbial activity and affects EC of the soil [36]
leachable salts Adsorption & cation exchange capacity	Heavy rains increase nutrients leaching and make them less available to crop growth and food production [28].
Plant available N, P, K, S	Heavy rainfall causes nutrient leaching to far deep soil layers beyond which crops can reach them hence causing less crop production and reduced yields. Plants with no tap root system will also not reach the leached nutrients thus poor growth [8].
Physical	
Porosity	High temperature may result into large porosity with low specific areas resulting in rapid percolation to the aquifer [35] and high-water evaporation from the soil to the atmosphere
Soil Health Indicators	Effect of Climate Change
Aggregate stability	High temperature reduces aggregate stability and this exposes soil to soil erosion agents like wind and water [35]
Infiltration	Wet conditions and heavy rain fall favor leaching and mineral go in deeper soil layers where they cannot be reached by plants [6]
Bulk density	High temperature decreases soil bulk density and this exposes soil to both wind and water erosion thus washing away soil nutrients and making soil less supportive to plant growth [37].
Soil & rooting depths	High temperature makes soil compact and hard for soil roots to penetrate to deeper layers and this minimizes water absorption by those plants with tap roots.
Soil available water & distribution	High temperature decreases both surface and ground soil water availability which interferes with plant growth and other ecosystem services provided by soil [22].
Soil surface cover	Soil surface cover prevents moisture loss and this promotes soil health. It also adds SOM to the soil hence enhancing soil fertility, structure thus prevents soil erosion by wind or water [25].

Soil health indicators (Table 1) respond to climate change effect differently in different landscapes and soil types.

6. The Synergy Between Soil Health, Crop Production, Climate Change and Food Security

Food security refers to a situation where all the people have access and affordability to all their required foods to meet their dietary needs for better health and livelihoods [38-40]. Climate change affects soil structure, water holding capacity and nutrient cycling culminating into low crop production, thereby affecting food security of populations across the globe. Climate change promotes soil erosion, affects soil structure hence food and fibre production, which are necessary for human welfare [8]. Anthropogenic activities

associated with land use that negatively affect soil health do not only affect climate but they also affect crop production which undermines food security across the globe. Unhealthy soils do not only produce less crop yields but also less nutritious foods for human consumption. Table 1 shows most crops that need healthy soils for providing important nutrients for human health required for enhancing food security. Climate change that affects soil health also affects food production and peoples' livelihoods.

Table 1 shows the daily global food sources and their respective Calories they provide thus contributing to food security. With exception of fish and aquatic products, the rest of foodstuffs, require good and healthy soils for improved productivity and will be either directly or indirectly affected by climate change. Heavy rains caused by climate change, cause soil erosion, affect crop production and result into food insecurity [8].

Table 1. Daily per capita food intake as a worldwide average, 2001–2003
(Adopted from Brevik, 2014)

Food Source	Calorie	Percent of Calories
Rice	557	25.5
Wheat	521	23.9
Maize	147	6.7
Sorghum	33	1.5
Potatoes	60	2.7
Cassava	42	1.9
Sugar	202	9.3
Soybean Oil	87	4.0
Palm Oil	50	2.3
Milk	122	5.6
Animal Fats (raw and butter)	62	2.8
Eggs	33	1.5
Meat (pig)	117	5.4
Meat (poultry)	46	2.1
Meat (bovine)	40	1.8
Meat (sheep and goats)	11	0.5
Fish and other aquatic products ^b	52	2.4
TOTAL	2182	

^a Aquatic products data from 2003. All other data from 2001–2003; ^b Includes both marine and freshwater products.

7. The Linkage Between Soil Health and Climate Smart Agriculture (CSA)

Climate smart agriculture stands on three pillars i.e., increasing productivity and income; building resilience and adaptation to climate change and reducing greenhouse emissions to the atmosphere [41]. Healthy soils support the three pillars by promoting crop production thus increasing farmers' income; enhancement of adaptation and mitigation to climate change through carbon sequestration and building crop resilience to climate stresses. CSA approach is a climate smart soil health approach that aim at improving the wellbeing of the populations across the globe, especially in developing countries. Smart soils are those that sequester more carbon and mitigate climate change [42-43].

8. The Effect of Climate Change on Soil Biodiversity

Healthy soils are habitats for macrofauna which play a big role in carbon cycle [44]. They include pro, nematodes and collembola that play essential roles in a variety of ecosystem services including turnover of organic matter, nutrient mineralization and regulation of population densities. Neither too high nor too low temperature or rainfall favour such processes and moderate temperature and rainfall are required to preserve soil biodiversity and health so as to keep providing ecosystem services required for a healthy environment [45-46]. Chen et al (2019), pointed out that

agricultural practices such as minimum or no till, addition of agriculture amendments and crop rotation have potential to enhance soil biodiversity thus keeping soils healthy and mitigating impacts of climate change [48].

9. The contribution of soil health to Sustainable Development Goals (SDGs)

Healthy soils Table 2 substantially contribute to the UN SDGs in regard to economic development, poverty eradication, clean water, reverse land degradation, conserve biodiversity loss and climate change adaptation and mitigation, and food security enhancement [49].

10. Proposed strategies for improving soil health

The European Commission [35] recommends the following management practices in agricultural landscape to maintain water retention capacity and keep soils healthy:

- i. mitigating the impacts of the use of heavy machinery and heavy tillage to reduce soil compaction and avoid disturbance of soil structure
- ii. mitigating the impact of tillage, through reduced tillage or tillage adapted to environmental conditions, such as contour tillage on slopes

Table 2. Contribution of healthy soils to Sustainable Development Goals (adopted and modified from UNDP, 2015)

Goal	Contribution of healthy soils
SDG 1. End poverty in all its forms everywhere	Over 80% of most developed countries are employed in the agriculture sector. Healthy soils enhance crop production and boosts employment opportunities especially for development counties thus contributing to poverty eradication [50]
SDG 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture	Agriculture is the food basket for the billions of people across the globe. It requires health soils to feed the world's population projected to be 9.1 billion people by 2050 and meet their nutritional demands [51]
SDG 6. Ensure availability and sustainable management of water and sanitation for all	Healthy soils play an important role in water filtration, improve water quality and contribute to provision of safe water for domestic use thus enhancement of hygiene among global communities [52]
SDG 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	Agriculture is a major source of income and household development for most developing countries. Healthy soils provide sustainable economic development and employment for households in many countries [53]
SDG 13. Take urgent action to combat climate change and its impacts	Health soils sequester more carbon from the atmosphere and store it hence reducing concentration of CO ₂ from the atmosphere thus mitigating climate change impact. They strengthen the resilience and adaptation capacity of landscapes to climate-related hazards and natural disasters [49]
SDG 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	Healthy soils provide better ecosystem services such as regulating and provisioning to the populations. They reduce soil erosion and floods and support many flora and fauna species. They contain better macro and micronutrients, and have higher water holding capacity for supporting biodiversity and enhance plant growth and development [54, 55]

- iii. promoting the return of organic matter to the soil, through organic amendment and crop residue management
- iv. better integrating the issue of soil water retention when designing crop rotations and include legume-cereal rotations to enhance nutrients retention in degraded soils
- v. maintaining landscape features such as hedges and buffer strips along rivers, which allow slowing down water flows, and reducing the size of patches to optimize the hydrological functioning of the catchment application of sustainable land management to boost crop production without damaging the environment through pollution
- vi. growing cover crops and leaving land under permanent vegetation cover to enhance water retention and nutrient cycling for better productivity
- vii. application of mulching that keeps soil moisture and soil structure for effective soil respiration and microbial activity
- viii. application of fallowing to allow soils to rest and regain nutrients before the next growing seasons so as to boost crop yields
- ix. application of integrated crop-livestock farming that provide organic manure to the soils and keep them healthy for improved productivity
- x. reduced application of artificial fertilizers and herbicides to minimize the effect on soil micro biodiversity which are essential in soil respiration

11. Conclusions and Recommendations

Climate change significantly affects soil health and peoples' livelihoods across the globe. High temperature and heavy precipitation affect soil health indicators and processes such as soil formation, soil structure, soil chemistry, soil porosity and soil biodiversity. This influences soil water holding capacity, soil fertility, crop production and consequently food security and improved livelihoods. Soil health contributes to the UN Sustainable Development Goals and peoples' wellbeing. Both soil health and climate change are complex phenomena that affect each other. Proper land management is essential for improving soil health, climate change mitigation and improvement of human well-being. Both developed and developing countries need to put deliberate efforts on improving

soil health, crop yields for improved livelihoods. The effect of soil health on human health and development needs to be studied.

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Conflict of interest

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