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Research Paper

Evaluating the crucial relationships between soil health and climate change

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ABSTRACT

This review examines the significant influence of soil health on global warming and climate stability. Soil affects the Earth's carbon cycle by acting as both a source and a sink of greenhouse gases. Climate is an important factor in soil formation, but soils also affect the climate; soils are therefore affected by current climate change, particularly because they may release excessive amounts of carbon dioxide (CO_2) and other greenhouse gases (GHGs) as a result of land-use change, poor management, or inappropriate human practices. The pressure that climate change places on soil ecosystems has a significant impact on agriculture, biodiversity, and ecosystem services, and understanding these relationships is essential for developing effective climate mitigation and adaptation policies. The most effective soil management practices for mitigating climate change focus on increasing soil organic matter content and water retention. Soil is an enormous store of carbon and nitrogen and a potential regulator of CO_2, N_2O, and CH_4, the three main greenhouse gases. Because biota carry organic matter into the soil, mature soils rich in life are frequently CO_2 sinks, but heterotrophic soil organisms are also net consumers of organic matter and release CO_2 through respiration. Climate change is altering the interactions between plants, soil organisms, and abiotic soil conditions, affecting plant performance, diversity, and community structure, while tillage and other disturbances of natural soils cause losses of soil organic matter to the atmosphere, and salinization is expected to expand with climate change. The review concludes that soil carbon sequestration can reduce greenhouse gas emissions.

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1. INTRODUCTION

Climate is a factor in soil formation, but soils also affect the climate. Soils are therefore affected by current climate change, particularly because they may release excessive amounts of CO_2 and other GHGs as a result of land-use change or poor management [1]. On the other hand, soil management has been shown to be one of the ways to store carbon and possibly slow global warming [2]. Soil is not a passive observer of climate change but a regulator of it, creating and managing a variety of positive and negative feedback loops [3]. Early studies attempted to quantify the carbon released to the atmosphere through soil cultivation and deforestation and the magnitude of anthropogenic impacts on the soil carbon reservoir and the carbon cycle [4], [5], [6] while modelling experiments evaluated the effects of extensive irrigation on regional hydrology and climate, concluding that soil moisture anomalies caused by irrigation have real effects in both areas [7]. In recent years, research on soil's role in regulating climate has grown significantly, showing that the most effective soil management practices for mitigating climate change focus on increasing soil organic matter content and water retention.

Soil is an enormous store of carbon and nitrogen [8], [9] and a potential regulator of CO_2, N_2O, and CH_4, the three main GHGs in the atmosphere; these soil stocks are significantly larger than the corresponding atmospheric pools. Because organic matter (OM) is generally stored in soil for long periods, soil can buffer atmospheric CO_2 concentrations: radiocarbon data indicate a mean age of about 4830 ± 1730 years for organic carbon in the top 1 m of soil globally [10]. There is a theoretical limit to the amount of OM that can accumulate in a soil, determined by its intrinsic and ecological features [11], and many soils, particularly agricultural soils, are far from this limit, so better management could greatly increase their carbon stock [12]. At the 2015 UN Climate Change Conference, the "4 per 1000" initiative encouraged practical measures such as agroforestry, agroecology, landscape management, and conservation agriculture, with the goal of increasing soil carbon stocks by 0.4% per year in the top 40 cm of soil [13]; however, questions have been raised about the true efficacy of this and other efforts to promote soil carbon sequestration at the global scale. Soil respiration is one of the largest fluxes in the global carbon cycle [14], so even small increases in soil respiration may be comparable to annual anthropogenic CO_2 emissions, producing a positive feedback to climate change [15].

This review discusses the physical and chemical properties of soil, the potential of carbon sequestration to reduce greenhouse gas emissions, the roles of biota and human activities, climate feedback loops, and soil organic carbon. The linkage between climate change and soil is illustrated in Figure 1.

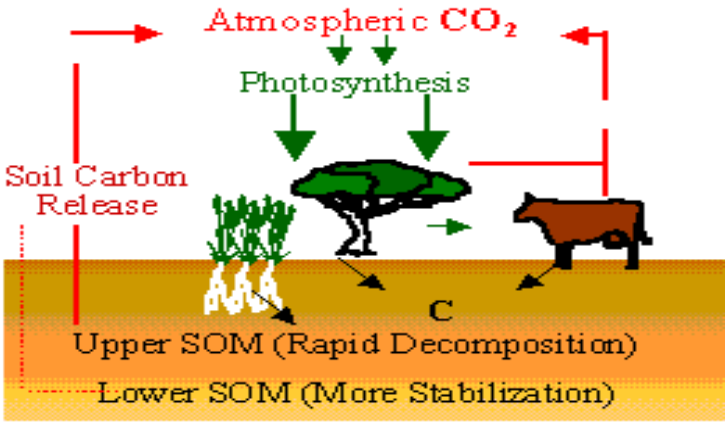


Figure 1. Linkage between Climate Change and Soil (Source: [16])

2. METHODOLOGY

This review is based on a literature search of research papers and books retrieved through Google Scholar, ResearchGate, and other online databases on the relationships between soil and climate change. The objectives of the review are:

1. To examine how carbon sequestration can decrease greenhouse gas emissions;
2. To evaluate the connection between soil health and climate;
3. To argue that climate change mitigation should be a key component of all soil management practices;
4. To identify the need to maximize soil water retention, soil organic matter content, and vegetation growth to achieve this goal.

2.1 Biota

In general, the ability of soil to provide essential ecosystem services, such as storing carbon and water and fostering plant growth, increases with the diversity and abundance of its living organisms [17]. There is mounting evidence that biodiversity, including that of the soil microbiome, which controls the biogeochemical cycling of elements, is declining as a consequence of environmental change [18]. Because biota carry OM into the soil, both as living organisms and through their decomposing remains, mature soils rich in life are frequently CO_2 sinks; but heterotrophic soil organisms are also net consumers of OM and release CO_2 to the atmosphere through respiration. Total soil respiration, the soil-to-atmosphere CO_2 flux, is highly variable in time and space [19], [20], [21], [22], [23]. Changes in plant community composition brought about by climate change shape the composition and functioning of the soil ecosystem, which in turn alters soil respiration rates [24], [25]. Reforestation of former agricultural land is typically viewed positively for climate mitigation because of carbon sequestration in biomass and soil, although the resulting decrease in surface albedo may offset part of this benefit [26].

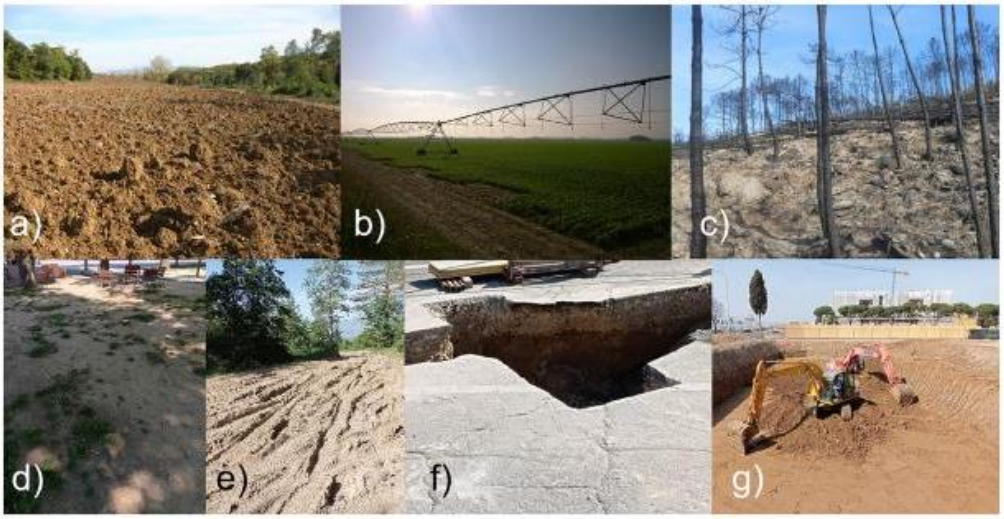


Figure 2. Examples of Human Disturbance of Soil: (a) Tillage for Agriculture; (b) Irrigation to Compensate for Crop Water Shortages; (c) fire, Which Leaves the Surface Bare and Prone to Erosion; (d) Compaction Through Repeated Trampling; (e) Heavy Machineryi Forest Operations; (f) Sealing with Impermeable Materials (Source: [3])

2.2 Human Activities

Humans, possessing culture and reason, are unique among organisms in that they can choose to act in the best interests of soil quality and climate change mitigation. Humans have almost universally become a factor that directly or indirectly influences pedogenesis [27], [28], and the balance between the soil disturbed or destroyed and the soil whose formation human activity has supported is considered highly negative. Since the advent of agriculture thousands of years ago, humans have affected the climate through the soil, altering its temperature, moisture, evaporation, and runoff regimes [29], [30]. The loss of soil OM to the atmosphere quickly became a significant effect of tillage and any other activity that disturbs natural soils (Figure 2) [31]. Organic matter contributes to soil water retention both directly and by improving soil structure [32], [33]. Animal manure has been added to arable soils for millennia to keep their OM content reasonably high, although its widespread use could have detrimental long-term consequences for the

environment [34]. Widespread irrigation, which temporarily reduces land surface albedo, is another anthropogenic factor that affects the climate through agriculture [7], and fires can prevent cloud formation by releasing soot-rich smoke into the atmosphere [35], [36]. Areas affected by salinization are expected to increase with climate change [37], [38], [39]. Military operations can have some of the most severe effects on soils, drastically altering soil biology, composition, and morphology to the point where full recovery takes a very long time or is impossible; the most frequent effects include compaction, excavations, blast craters, and chemical contamination [40], [41], [42]. The term "anthropogenic soils" refers to soils significantly affected by human activity, such as extensive addition of artefacts or fertilizers, sealing by impermeable materials, or serious contamination [43]. With growing urbanization, more land is sealed by asphalt and other impermeable surfaces, which prevents rainwater from infiltrating the soil and alters evaporation [44], [45].

2.3 Climate Feedback Loops

A warmer atmosphere caused by increased GHG concentrations holds more water vapour, which traps more heat and further warms the globe [46]. Climate controls the biogeochemical reactions in soil and, consequently, the pace of pedogenesis through temperature and moisture, and climate change is disrupting pedoclimatic regimes in most places, with clear effects on soil biota and the transformation of their remains [3]. There may be positive and negative feedback loops between the biogeochemical cycles of several elements and climate change [3]. The links between extreme weather, a warming climate, and the carbon cycle are illustrated in Figure 3 and Figure 4.

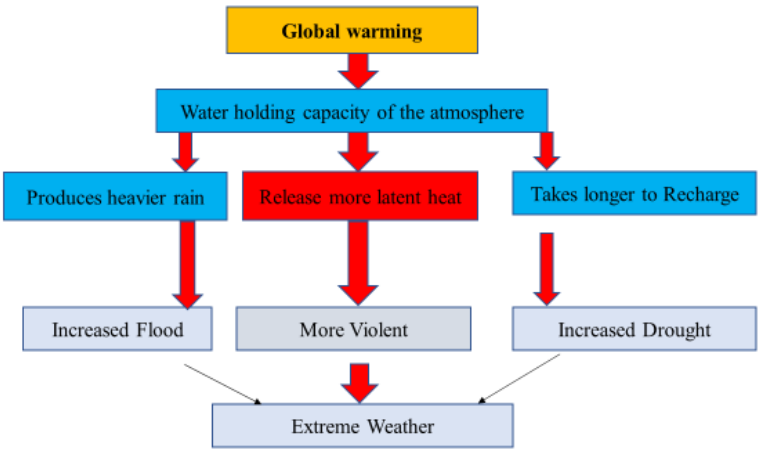


Figure 3. Conceptual Connection between Extreme Weather and a Warming Climate (Source: [47])

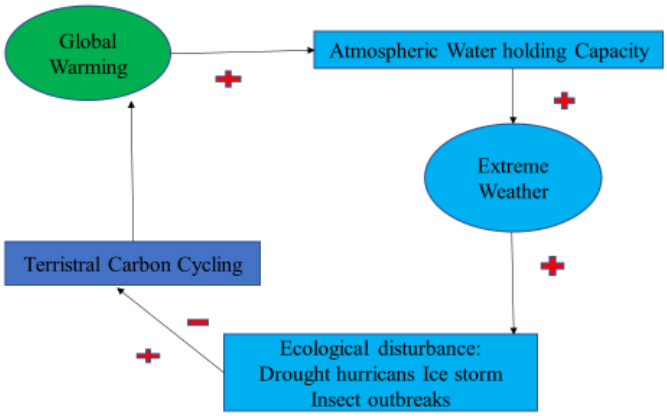


Figure 4. Climate–Carbon Feedback Loop: Links between Extreme Weather and the Carbon Cycle (Source: [47])

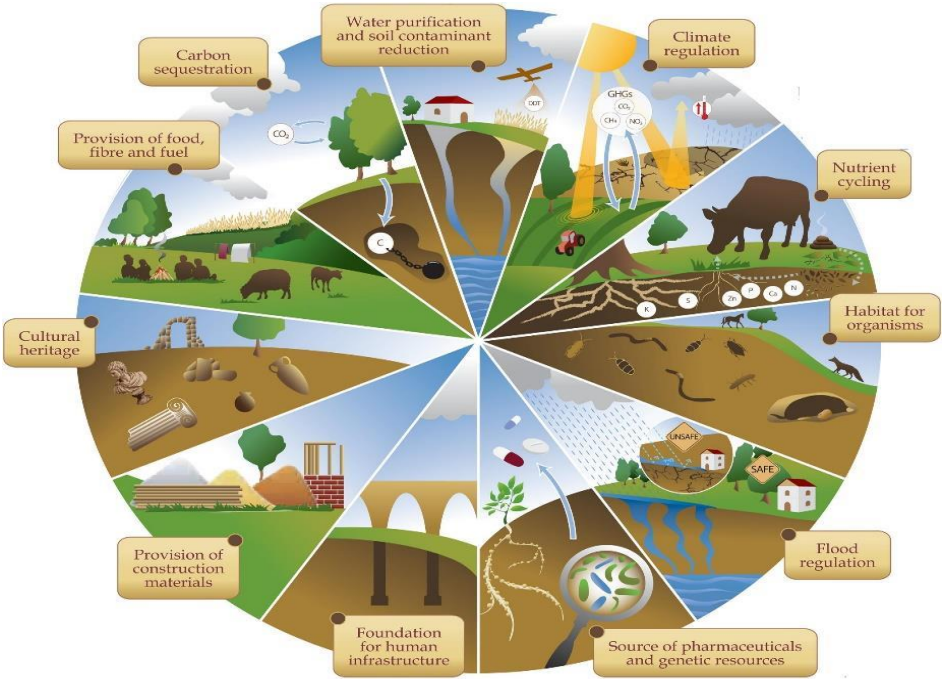


Figure 5. Soil Functions Delivering Ecosystem Services, Including Carbon Sequestration and Climate Regulation (Adapted From [51])

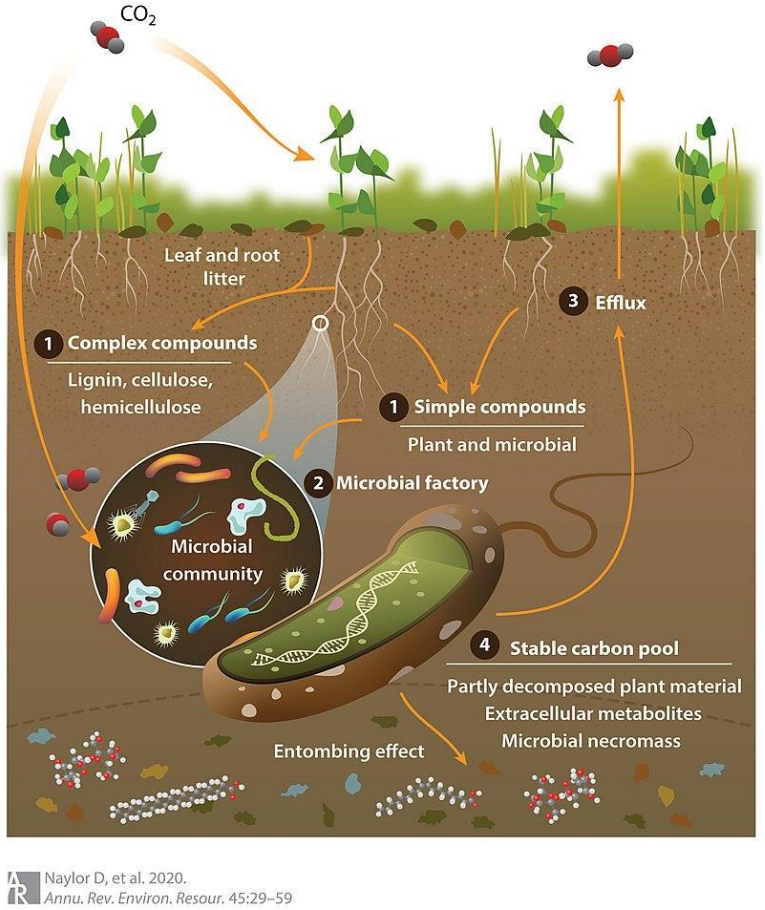


Figure 6. Carbon Cycling in Soil Via the Microbial Loop: Plants Fix Atmospheric CO_2 and Add Carbon to the Soil as Root Exudates and Litter, Which Microbes Either Respire to the Atmosphere or Convert into Stable Carbon as Microbial Necromass (source: [19])

2.4 Soil Organic Carbon

Recent research indicates that the predicted catastrophic losses of soil carbon may not occur, because of balancing interactions among mechanisms through which climate change affects soil organic carbon reserves [48], [49]. When litter bags in a temperate grassland were exposed to drought for six weeks over an 11-month period, decomposition was affected by climate change, and frequent cutting significantly accelerated decomposition [50]. Soil moisture stress can considerably reduce healthy soil function and plant productivity [32], [50]; changes in precipitation may affect water supply, drier and warmer soil conditions may increase organic carbon turnover, and decomposition is accelerated in wet settings, with long-term consequences for soil hydro-physical properties [50]. The functions of soil, including carbon sequestration and climate regulation, and the microbial loop through which carbon cycles in soil are illustrated in Figure 5 and Figure 6.

2.5 Soil Chemical Properties and Climate Change

Soil pH, soluble salt content (measured as electrical conductivity), nutrient and carbonate levels and their distribution in the profile, cation exchange capacity (CEC), and base saturation (BS) are among the most important soil chemical properties [52]. This review is restricted to some of the direct effects of climate change on them. Because soil pH is regulated by the rate of weathering, parent material, vegetation, and climate, it is not expected to change quickly as an immediate consequence of climate change, although soil acidity may increase under wetter conditions if buffering pools are exhausted [53]. Soils exposed by glacial retreat showed that, once vegetation establishes, soil pH may decrease significantly and calcium carbonate levels drop rapidly, whereas on bare surfaces pH change may be negligible for decades [54]. Conversely, rising temperatures combined with decreasing precipitation may drive capillary water movement and groundwater evaporation, causing salt to accumulate in the soil (salinization) [55]. Base saturation often rises with soil pH: very acidic soils may contain high levels of H^+ and Al^{3+}, whereas Ca^{2+} and Mg^{2+} predominate in neutral and moderately alkaline soils. Treatments with higher electrical conductivity and organic matter have been found to give aggregates greater tensile strength, whereas treatments with a higher sodium adsorption ratio reduce it [56], [57], [58].

3. RESULTS AND DISCUSSION

Several important findings emerge from this evaluation of the relationships between soil health and climate change. First, the ability of healthy soil to sequester carbon is crucial for reducing the effects of climate change. Second, soil quality is closely linked to water retention capacity, which directly influences climate resilience.

3.1 Soil Carbon is Crucial for Reducing the Effects of Climate Change

Soil is the world's largest terrestrial carbon store and is essential for the global carbon cycle and the fight against climate change [59], [60]. Soil organic carbon is central to the functioning of terrestrial ecosystems and the global carbon cycle, and projected warming and changes in soil water content may cause SOC losses [61]. Adopting alternative rice farming practices could reduce GHG emissions and increase carbon sequestration [62], and soil carbon sequestration and biochar have been proposed as negative-emission technologies [63], [64]. Ecological criteria and process models can be used to prioritize the preservation of forest landscapes to reduce GHG emissions and maintain biodiversity [65], and mangroves, as significant organic carbon sinks, attract great interest for mitigating greenhouse gas emissions [66].

3.2 Agricultural Practices that Improve Soil Health and Lower Greenhouse Gas Emissions

Organic farming practices can enhance carbon sequestration, and there are several ways to decrease GHG emissions from agricultural soils [67]. Although the capacity of conservation agriculture to sequester carbon has been debated, reduced tillage can lower greenhouse gas emissions [68]; however, some interventions, such as biochar application, may also have adverse effects on the soil environment [69]. Raising public awareness and education are essential to establishing a shared commitment to

improving soil health to help mitigate climate change. Overall, the relationships between soil health and climate change are intricate and varied, highlighting the need for coordinated action to protect the ecosystem.

4. CONCLUSION

The analysis of the connections between soil health and climate change shows how complex and multidimensional these linkages are. The interaction of soil water retention, carbon sequestration, and soil quality is a key component of climate change mitigation, and sustainable farming techniques are required to promote soil health and lower greenhouse gas emissions. Policy development and ongoing research are essential to address these relationships, and tackling climate change and protecting the environment require coordinated efforts, public awareness, and education.

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Authors Contributions Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Khan Waqar Ahmad	✓	✓	✓		✓	✓		✓	✓		✓		✓	
Gang Wang	✓		✓	✓	✓		✓			✓		✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

Conflict of Interest Statement

No conflict of interest.

Informed Consent

Not Applicable.

Ethical Approval

Not Applicable.

Data Availability

This study draws on publicly available data. No new datasets were created.

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