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# **Carbon Sequestration in Soils: The Opportunities and Challenges**

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## **Abstract**

Recently, the contributions of the soil in various ecosystems have become more prominent with the recognition of its role as a carbon sink and the potential of that in reducing the concentration of carbon dioxide (CO<sub>2</sub>), which is a vital greenhouse gas, from the atmosphere. Conversely, the soil capacity to increase the concentration of CO<sub>2</sub> in the atmosphere through mineralization of organic matter is also a source of concern. Mineralization of only 10% of the soil organic carbon pool globally is believed to be equivalent to about 30 years of anthropogenic emissions. This underscores the need to preventing carbon loss (emission) from the soil resource. Globally, the soil contains a large carbon pool estimated at approximately 1500Gt of organic carbon in the first one meter of the soil profile. This is much higher than the 560 Gt of carbon (C) found in the biotic pool and twice more than atmospheric CO<sub>2</sub>. By holding this huge carbon stock, the soil is preventing carbon dioxide build up in the atmosphere which will confound the problem of climate change. There are a lot of strategies used in sequestering carbon in different soils, however, many challenges are being encountered in making them cost effective and widely acceptable.

**Keywords:** soil carbon sequestration, climate change, carbon dioxide, ecosystem services

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## **1. Introduction**

The role of soil the ecosystem is increasingly being recognized with the realization that it has the capacity of reducing the concentration of carbon dioxide (CO<sub>2</sub>) in the atmosphere (through sequestration of organic carbon in the soil) and also by releasing this CO<sub>2</sub> back into

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the atmosphere (through mineralization of soil organic matter). It has been reported that mineralization of only 10% of the soil organic carbon pool globally can be equivalent to about 30 years of anthropogenic emissions [1].

This underscores the need to preventing carbon loss (emission) from the soil resource. Globally, the soil contains a large carbon pool estimated at approximately 1500 Gt of organic carbon in the first 1 m of the soil profile [2–4]. This is much higher than the 560 Gt of carbon (C) found in the biotic pool [5] and twice more than atmospheric CO<sub>2</sub> [6]. By holding this huge carbon stock, the soil is preventing carbon dioxide build up in the atmosphere which will compound the problem of climate change.

There is huge opportunity of sequestering atmospheric carbon in the soil for a long period of time because already 24% of global soils and 50% of agricultural soils are degraded globally [7]. Because most of agricultural soils are already degraded, they are estimated to have the potential of sequestering up to 1.2 billion tonnes of carbon per year [8].

Carbon sequestration in soils can be a short term solution of reducing CO<sub>2</sub> concentration in the atmosphere until when more effective strategies are found [4].

Despite the huge carbon deposit in soil ecosystem globally, research efforts in sequestration has been primarily focused on geological and vegetation carbon capture and storage while giving less attention on the role of soil as a viable carbon sink [9].

This chapter will trace the origin of carbon sequestration idea as a potential climate mitigation measure as well as review the conceptual basis and mechanism of carbon capture and sequestration in soils. The benefits and challenges facing carbon sequestration in soils are also discussed extensively. Finally, some proven management practices and strategies used in enhancing the soil carbon stock under forest and agricultural ecosystems are outlined. The chapter concludes by emphasizing the need for the scientific community to resolve most the challenges making widespread adoption of this initiative difficult.

## 2. Genesis of the carbon sequestration idea in terrestrial systems

The idea that the concentration of CO<sub>2</sub> in the atmosphere can be minimized by sequestering it in terrestrial ecosystems, including the soil was first proposed by Dyson in 1977 [10]. He realized that the danger of rising CO<sub>2</sub> concentration in the atmosphere outweighs the benefits and that increased CO<sub>2</sub> into the atmosphere is inevitable in the light of continued dependence on fossil fuels. Therefore, a strategy was needed for reducing CO<sub>2</sub> emission without 'drastic shutdown of industrial civilization'. He proposed that the excess CO<sub>2</sub> could be absorbed by trees in a large scale plantation as a potential strategy for halting the continuous CO<sub>2</sub> build up in the atmosphere. This is in light of evidence that the photosynthetic turnover is 20 times larger than the annual increase in atmospheric CO<sub>2</sub> [10]. He therefore concluded that by planting of fast growing trees on a massive scale on marginal land or growing and harvesting swamp-plants and converting them into humus or peat the concentration of CO<sub>2</sub> in the atmosphere could be minimized. This could be a short gap measure to hold the atmospheric CO<sub>2</sub>

level down until alternatives to fossil fuels are found. Much later in 1989, Sedjo and Solomon also wondered whether CO<sub>2</sub> can be offset by increasing the size of forest areas globally [11].

### **3. Evidence that carbon is sequestered in the soil and terrestrial ecosystems**

The soil is reputed to contain the largest terrestrial carbon pool estimated at approximately 2344 Gt (1 gigaton = 1 billion tonnes) of organic carbon in the first 3 m, 1500 Gt in the first 1 m and 615 Gt stored in the top 20 cm of the soil profile [2–4]. By holding this huge carbon stock, the soil is preventing or delaying carbon dioxide build up in the atmosphere which will compound the problem of climate change. Considering the fact that only 9 Gt of C is added to the atmosphere yearly through anthropogenic activities from fossil fuels and ecosystem degradation [4], the soil can be counted on as an effective carbon sink that renders vital climate regulation services.

Conversely, the soil also emits CO<sub>2</sub> back to the atmosphere due to SOM decomposition estimated at 150 Gt which leaves a vacuum that could be filled if the lost C can be recaptured back and stored in the soil [12].

The amount of carbon emitted annually into the atmosphere is estimated at 8.7 Gt C while only 3.8 Gt/year is found in the atmosphere at a given time [4]. This leaves an unaccounted balance of 4.9 Gt C/year that is believed to have been sequestered on terrestrial systems (oceans, forests, soils, etc.). The realization that the terrestrial systems (including soil) have the capacity to sequester this difference (4.9 Gt C/year) has generated interest in the potential of these systems to sequester and store carbon in long-lived pools thereby preventing its accumulation in the atmosphere [3, 4, 13–15]. Just like the way the soil sequesters and stores, organic carbon, thereby reducing the amount in the atmosphere, it can equally release carbon (through CO<sub>2</sub>) into the atmosphere and raise the concentration of carbon dioxide [12].

Over the last few decades, the soil has lost considerable quantity of carbon as a result of anthropogenic activities such as deforestation and agricultural activities. Managed ecosystems such as agriculture are believed to have already lost 30–55% of their original soil organic carbon stock since conversion [7]. The lost productivity of agricultural and degraded lands together offers an opportunity for recovering 50–60% of the original carbon content through adoption of carbon sequestration strategies [13]. This situation creates an opportunity for the replenishment of the lost carbon stock through adoption of deliberate strategies and policies of carbon sequestration. This may likely reduce the amount of CO<sub>2</sub> in the atmosphere.

#### **3.1. Mechanisms of carbon capture and sequestration**

Soil carbon is originally derived from the CO<sub>2</sub> assimilated by plants through photosynthesis and converted to simple sugars and eventually returned to the soil as soil organic matter. Photosynthesis is the process where plants produce organic compounds such as carbohydrate by using solar energy to convert CO<sub>2</sub> and water into organic compounds such as

carbohydrates. These organic compounds are then used in making the plants structural components (also known as biomass) and generating the energy needed for metabolic activities. The maximum amount of carbon that can be produced, otherwise known as gross primary productivity (GPP), depends on the plant's ability to produce these compounds through photosynthesis. The biomass produced through photosynthesis is utilized by the plants themselves in generating the energy needed for metabolic activities in a process called respiration. The difference between the GPP and respiration is called the net primary productivity (NPP). NPP is generally believed to be 45% of the GPP [16].

NPP is determined by the portion of solar radiation captured by the plants and used for the photosynthesis (also known as photosynthetically active radiation (PAR), the leaf area index, the light use efficiency (the ratio of primary productivity to absorbed PAR) of the vegetation and autotrophic respiration [12]. The higher the NPP the more carbon is transferred to stable pools in the soils [17].

## 4. Carbon sequestration

Carbon sequestration is the process of transferring carbon dioxide ( $\text{CO}_2$ ) from the atmosphere into stable terrestrial carbon (C) pools.

The process can be driven naturally or anthropogenically. The anthropogenically driven sequestration ensures that there is no net gain in the atmospheric C pool because the  $\text{CO}_2$  sequestered comes from the atmosphere. There are basically two types of sequestration: abiotic and biotic. The abiotic techniques involve injection of  $\text{CO}_2$  into deep oceans, geological strata, old coal mines and oil wells. The biotic component on the other hand, involves managing higher plants and micro-organisms to remove more  $\text{CO}_2$  from the atmosphere and fixing this C in stable soil pools. Biotic sequestration is further subdivided into oceanic and terrestrial sequestration. Oceanic sequestration involves C capture by photosynthetic activities of organisms such as phytoplankton, which converts the C into particulate organic material and deposits such on the ocean floor. This type of sequestration is reported to fix about 45 Pg C/year [18].

Terrestrial sequestration involves the transfer of  $\text{CO}_2$  from the atmosphere into the biotic and pedologic C pools. This is accomplished by the transfer or sequestration of  $\text{CO}_2$  through photosynthesis and storage in live and dead organic matter. The major terrestrial C sinks include: forests, soils and wetlands.

### 4.1. Carbon sequestration in soil ecosystem

Soil carbon sequestration is defined by Olson et al. [19] as:

*the process of transferring carbon dioxide from the atmosphere into the soil of a land unit through plants, plant residues, and other organic solids, which are stored or retained in the unit as part of the soil organic matter (humus) [19].*

According to the Soil Science Society of America, it is the storage of carbon in a stable solid form in the soil as a result of direct and indirect fixation of atmospheric CO<sub>2</sub> [20]. The direct fixation involves natural conversion of CO<sub>2</sub> into soil inorganic compounds such as calcium and magnesium carbonates while the indirect sequestration takes place when plants produce biomass through the process of photosynthesis. This biomass is eventually transferred into the soil and indirectly sequestered as soil organic carbon after decomposition. Subsequently, some of this plant biomass is indirectly sequestered as soil organic carbon (SOC) during decomposition processes. The amount of carbon sequestered in the soil reflects the long term balance between carbon uptake and release mechanisms. Many agronomic, forestry and conservation practices, including best management practices lead to a beneficial net gain in carbon fixation in soil. The carbon sequestered under direct fixation is also referred to as soil inorganic carbon (SIC) while C fixed indirectly is called soil organic carbon (SOC) [5].

Carbon can also be sequestered in soil through the accumulation of humus onto the surface layers (usually 0.5–1 m depth) of soil or anthropogenically through land use change or adoption of right management practices (RMPs) in agricultural, pastoral or forest ecosystems [5]. Soils in managed ecosystems tend to have a lower SOC pool than those in natural ecosystems due to oxidation or mineralization, leaching and erosion [5]. Globally, soils are reported to have the capacity of sequestering 0.4–0.8 Pg [21].

The sequestration of carbon in soils depends on a number of factors depending on whether it is abiotic or biotic. Abiotic soil C sequestration depends on clay content, mineralogy, structural stability, landscape position, soil moisture and temperature regimes [22]. Biotic soil C sequestration on the other hand depends on management practice, climate and activities of soil organisms [23, 24].

#### **4.2. Carbon stock in forest soils**

Carbon is stored in forest ecosystems mainly in biomass and soil and to a lesser extent in coarse woody debris [25]. The carbon stock in forest soils play a large role in global carbon cycle due to the large expanse of forest ecosystems estimated at 4.1 billion hectares globally [26]. It has been estimated that, globally, the forest ecosystem contains about 1240 Pg C [27]. Out of this amount, the plants (vegetation) contain about 536 Pg C while the soil is believed to contain up to 704 Pg C. This is a very significant amount.

The forest ecosystems contain more than 70% of global soil organic carbon (SOC) and forest soils are believed to hold about 43% of the carbon in the forest ecosystem to 1 m depth [2].

However, unfortunately this high carbon content inherent in natural forest soils is easily depleted by decrease in the amount of biomass (above and below ground) returned to the soil, changes in soil moisture and temperature regimes and degree of decomposability of soil organic matter (due to difference in C:N ratio and lignin content) [14]. Anthropogenic activities such as conversion of forests to agricultural land also deplete the soil organic carbon (SOC) stock by 20–25% [28]. Deforestation is reported to emit about 1.6–1.7 Pg C/year (about 20% of anthropogenic emission [29]).



### 4.3. Carbon stock in agricultural soils

According to the IPCC agricultural soils have the potential of sequestering up to 1.2 billion tonnes of carbon per year. However, it has been estimated that already about 50% of agricultural soils have been degraded globally, a situation that creates an opportunity for sequestering atmospheric carbon in the soil for a long period of time [8].

The potential of sequestering carbon in agricultural land is huge as over one third of the world's arable land is in agriculture [30]. Agricultural land could sequester at least 10% of the current annual emissions of 8–10 Gt/year [31].

## 5. The role of soil carbon in different ecosystems

The carbon in soil plays significant roles in different ecosystems. Some of these include:

### 5.1. Mitigation of climate change

The continuous increase in the concentration of carbon dioxide ( $\text{CO}_2$ ) and other GHGs in the atmosphere largely due to anthropogenic sources is believed to be responsible for climatic changes and related consequences being experienced across the globe [21, 23].

This situation has generated interest in developing strategies for reducing GHGs build up in the atmosphere.

Out of the approximately 8.7 Gt C/year being emitted into the atmosphere, from anthropogenic sources, only 3.8 Gt C/year remains [5, 32]. The unaccounted difference of 4.9 Gt C/year is believed to be sequestered in terrestrial (oceans, forests, soils, etc.) bodies which is referred to as the 'missing sink' [32, 33]. This realization has generated interest on the potential of terrestrial sector (including soil) to sequester carbon in long-lived pools thereby reducing the amount that is present in the atmosphere [3, 4, 13, 14].

### 5.2. Sustainable land management

Apart from reducing the concentration of greenhouse gases (GHGs) in the atmosphere, soil carbon sequestration also complements efforts geared at improving land (forest or agricultural land) productivity. This is because all strategies that sequester carbon in soil also improve soil quality and land productivity by increasing the organic matter content of the soil. Organic matter improves soil's structural stability, water-holding capacity, nutrients availability and provide favorable environment for soil organisms [13].

Carbon sequestration activities offer an opportunity for regaining lost productivity especially under agricultural systems. It has been reported that managed ecosystems such as agriculture have lost 30–55% of their original soil organic carbon stock since conversion [7]. The lost productivity of agricultural and degraded lands together offers an opportunity for recovering 50–60% of the original carbon content through adoption of carbon sequestration strategies [13].

### 5.3. Ancillary benefits

Apart from climate change mitigation and improving forest land productivity, carbon sequestration in soils (of different ecosystems) also have several ancillary benefits. Some of these include: improvement in water holding capacity and infiltration, provision of substrate for soil organisms, serving as a source and reservoir of important plant nutrients, improvement of soil structural stability among others [13]. According to [34] the environmental benefits associated with soil carbon sequestration is 40–70% higher than the productivity benefits. Based on these reasons, therefore, any policy, strategy or practice that increase soil carbon sequestration also generates these benefits.

### 5.4. Carbon inventories

The obligation on countries, that are parties to the UNFCCC, to deposit their independent nationally determined contributions (INDCs) requires a comprehensive estimation and valuation all carbon sink and sources in the terrestrial and other sectors. These estimation and valuation of carbon in the LULUCF sector will be incomplete if the contribution of soil carbon is excluded due to its large percentage (36–46%). Carbon inventory is a process of estimating changes in the stocks (emission and removals) of carbon in soil and biomass periodically for various reasons [35].

## 6. Challenges of carbon sequestration in soils

Although there are a lot of opportunities in leveraging carbon stock and sequestration potential in the soil of different ecosystems, there are numerous challenges making this difficult in reality. Some of these challenges include:

- a. *Measurement and verification*: the stock of carbon in soils is difficult, time-consuming and expensive to measure. Changes within the range of 10% are very difficult to detect due to sampling errors, small-scale variability and uncertainties with measures and analysis [36]. The annual incremental stock of carbon in soil is very small usually within 0.25–1.0 t/ha [37]. It is even more difficult to account for little gains or losses in soil carbon at various scales due to methodological difficulties such as monitoring, verification, sampling and depth [38]. Even if these small changes (gains or losses) are detected, it is not easy to link such changes to management or land use practice in a given context. The capacity of the soil to sequester and retain carbon is also finite as it reaches a steady state after sometime.
- b. *Carbon pools*: sequestered carbon exists in the soil in different pools with varying degree of residence time in the ecosystem. These pools include:
  - i. Passive, recalcitrant or refractory pool: organic carbon held in this pool has a very long residence time ranging from decades to thousands of years.
  - ii. Active, labile or fast pool: carbon held in this pool stays in the soil for much shorter period due to fast decomposition. The residence time normally ranges from 1 day to a year.



- iii. **Slow, stable or humus pool:** carbon held in this pool has long turnover time due to slow rate of decomposition. The residence time typically ranges from 1 year to a decade.
- d. *Permanence:* another challenge of carbon sequestration in soil is non-permanence of the sequestered carbon as it can be released back to the atmosphere as easily as it is gained as a result of decomposition or mineralization. It is for this reason that sequestered carbon is considered a short-term option for removing carbon from the atmosphere. The rate of carbon loss depends on several climatic, land use and management factors.
- e. *Separation:* it is very difficult to isolate and differentiate the portion of carbon sequestered in the soil as result of management activities or land use and that which occurred naturally. The principle of separation requires that the carbon sequestered or GHGs emission prevented as a result of management intervention be distinguished from that which would have occurred due to natural causes. Methods are therefore needed that can differentiate naturally sequestered carbon from that captured due to human management [39].

## 7. Strategies of increasing carbon stock in soils

There are proven practices and strategies that lead to increase in soil carbon stock in different terrestrial ecosystems. Most of these strategies increases the carbon stock in biomass through photosynthesis and indirectly builds up below ground and soil carbon through increased deposition of organic matter. According to Post and Kwon in 2000, organic carbon level of soil can be improved by increasing the amount of organic matter input, changing the decomposability of organic matter, placing organic matter in deep layer and enhancing better physical protection of the soil aggregates or formation of organo-mineral complexes [14].

In the forest ecosystem, the following have been widely reported.

- Afforestation
- Reforestation
- Natural regeneration
- Enrichment planting
- Reduced impact logging (RIL)
- Increasing the carbon stock of existing forests using several silvicultural techniques among others [40–43].

In the agricultural ecosystem, some strategies that enhance carbon capture and storage in the soil include:

- Manuring and fertilizing
- Conservation tillage (minimum, zero/no-till)

- Crop residue management
- Cover cropping
- Application of farmyard manure
- Application of inorganic fertilizers
- Rotational grazing
- Perennial cropping systems
- Etc.

## 8. Conclusion

There has been increasing interest on carbon capture and storage in the soils of different ecosystems as a climate mitigation measure. However, enhancing the carbon stock of soils also have ancillary benefits such as improving soil health and productivity, water retention, fertility enhancement among others. Although, theoretically this idea sounds appealing, however it is difficult to operationalize it in practice due to a number of challenges. Some of these include difficulties in measurement of soil carbon stock, permanence, carbon pools with different carbon residence times, separation, the tendency of the soil to reach saturation level when the maximum attainable carbon that could be captured is reached. Advances have been made in tackling most of these challenges, however, deliberate actions to enhance carbon capture and sequestration in the soil ecosystem is yet to get wide acceptance by practitioners and policy makers alike. This chapter is written in an attempt to create more awareness on the potential of soils in capturing and storing atmospheric CO<sub>2</sub> in long lived pools thereby mitigating climate change in the process. Researchers should also work assiduously in finding solutions to the challenges making widespread adoption of this initiative difficult.

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