Scientific Research Publishing

American Journal of Climate Change, 2024, 13, 140-162
https://www.scirp.org/journal/ajcc
ISSN Online: 2167-9509
ISSN Print: 2167-9495

Synergistic Interactions of Soil and Vegetation in Agroforestry Systems in Mitigating Climate Change in Upper East Region, Ghana

Joshua A. Adombire[1]*, Abdul-Wahab M. Imoro[2], Eunice Essel[3], Nang B. Douti[1]

[1]Department of Environmental Science, C. K. Tedam University of Technology and Applied Sciences, Navrongo, Ghana
[2]Department of Forestry and Forest Resources Management, University for Development Studies, Tamale, Ghana
[3]Department of Crop Science and Biotechnology, C. K. Tedam University of Technology and Applied Sciences, Navrongo, Ghana
Email: *Joshua_adombire@wvi.org, aimoro@cktutas.edu.gh, eessel@cktutas.edu.gh, binado1@yahoo.fr

How to cite this paper: Adombire, J. A., Imoro, A.-W. M., Essel, E., & Douti, N. B. (2024). Synergistic Interactions of Soil and Vegetation in Agroforestry Systems in Mitigating Climate Change in Upper East Region, Ghana. *American Journal of Climate Change, 13,* 140-162.
https://doi.org/10.4236/ajcc.2024.132008

Received: December 24, 2023
Accepted: May 27, 2024
Published: May 30, 2024

Abstract

Climate change has been a global pandemic with its adverse impacts affecting environments and livelihoods. This has been largely attributed to anthropogenic activities which generate large amounts of Green House Gases (GHGs), notably carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) among others. In the Upper East of Ghana, climate change manifests in erratic rainfalls, drought, high temperatures, high wind speeds, high intensity rainfall, windstorms, flooding, declining vegetation cover, perennial devastating bushfires etc. Practices such as burning farm residues, use of dung as fuel for cooking, excessive application of nitrogenous fertilizers, and deforestation that are prevalent in the region exacerbate the situation. Although, efforts made by governmental and none-governmental organizations to mitigate climate change through afforestation, agroforestry and promotion of less fuelwood consuming cook stoves, land management practices antagonize these efforts as more CO_2 is generated than the carrying capacity of vegetation in the region. Research findings have established the role of trees and soil in carbon sequestration in mitigating climate. However, there is limited knowledge on how the vegetation and soil in agroforestry interplay in mitigation climate change. It is against this background that this review seeks to investigate how vegetation and soil in an agroforestry interact synergistically to sequester carbon and contribute to mitigating climate change in Upper East region of Ghana. In this review, it was discovered soil stored more carbon than vegetation in an agroforestry system and is much effective in mitigating climate change. It was found out that in order to make soil and vegetation in an agroforestry system interact synergistically to effectively mitigate climate change, Climate Smart Agriculture practice which integrates trees, and perennials crops effectively mitigates climate. The review concluded that tillage practices that ensure retention and storage of soil organic carbon (SOC) could be much effective in carbon sequestration in the Savannah zones and could be augmented with vegetation to synergistically mitigate climate change in the Upper East region of Ghana.

Keywords

Climate Change, Carbon Sequestration, Agroforestry, Photosynthesis, Nutrient Mining, Synergistic

1. Introduction

Climate change is the long-term unfavorable changes in temperature and other weather patterns. Such changes can be caused by natural factors such as variations in the sun's activity or massive volcanic eruptions. Predominantly, human activities have been the cause of climate change since the 1800s, emanating from the use of fossil fuels such as coal, oil, and gas (Das et al, 2012).

The burning of fossil fuels produces greenhouse gas emissions, behaving as a blanket wrapped over the Earth, trapping heat from the sun and increasing temperatures. Carbon (IV) oxide and methane (CH_4) are the dominant greenhouse gases causing climate change (Fagodiya et al, 2023). These gases are produced because of using gasoline as fuel for heating buildings and driving vehicles. Agriculture, oil and gas enterprises are major methane emitters (Mir et al, 2017). Lamb et al. (2021) reported that energy, industry, transportation, buildings, agriculture, and land use are among the major contributors to greenhouse gas emissions. Anthropogenic activities such as those stated above emit greenhouse gases such as carbon (IV) oxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O) and Chlorofluorocarbons (CFC), which are causing an unprecedented warming of the earth, a phenomenon known as global warming (Warming & Rays, 2011).

The Inter-Governmental Panel on Climate Change (IPCC) reported the global mean annual temperature at the end of the twentieth century of 0.40˚C - 0.76˚C higher than at the end of the nineteenth century, with roughly two-thirds of the increase occurring in just the last three decades. Climate change is resulting in severe droughts, water scarcity, severe fires, increasing sea levels rise, flooding, melting polar ice, catastrophic storms, declining biodiversity and soil fertility, etc. This has threatened livelihoods with many developing countries becoming more vulnerable to its impacts.

Numerous findings (IPCC, 2007; Albrecht & Kandji, 2003; etc.) have substantiated the fact that agroforestry systems, even if not purposefully designed for carbon sequestration, have the tendency to increase carbon stocks in the terrestrial biosphere. Agroforestry systems are estimated to sequester between 12 and 228 mega grams/hectare ($Mg \cdot ha^{-1}$) with a median value of 95 $Mg \cdot ha^{-1}$ (Saha & Jha, 2012). Carbon is stored in the soil, tree biomass, crop biomass, and wood products components of an agroforestry system (Albrecht & Kandji, 2003). It has also been reported that worldwide, soils store more carbon than the amount of carbon stored in phytomass and the atmosphere (Saha & Jha, 2012). The efficacy of soil carbon sequestration on lands used for agriculture or forestry is largely determined by land management strategies or use as referred by the Kyoto Protocol as, "Land Use, Land-Use Change and Forestry (LULUCF)". The quantity of carbon stored in an agroforestry system is determined by the interplay of structure and function of different components within the systems (Albrecht & Kandji, 2003). Agricultural activities have been estimated to release 800 tera g C·yr^{-1} globally (Sohi et al., 2010).

It is therefore, indicative that the magnitude of carbon sequestered by an agroforestry system is the combined effect of the above ground (vegetation) and the below ground (soil) components of the system. This interaction can be either antagonistic, additive or synergistic depending on how the above ground and the soil components of the agroforestry system are managed. However, most researchers treat these components of agroforestry systems as mutually exclusive in carbon storage in mitigating climate change. There is paucity of knowledge on how the above ground and the below ground component of an agroforestry system complement each other to maximize carbon sequestration. It is against this background that this review seeks to synthesize the synergistic interaction of vegetation and soil components of an agroforestry system in sequestering the terrestrial carbon in mitigating climate change.

The review also seeks to explicitly demonstrate how soil and residues in an agroforestry can be managed to maximize carbon sequestration as well as crops that can be incorporated in an agroforestry to sustainably store soil organic carbon and ultimate carbon sequestration and tillage practices to be adopted to enhance carbon sequestration capacities of an agroforestry system.

2. Materials and Methods

2.1. Literature Search

A comprehensive literature review was carried out in this peer review. An initial scoping research was conducted online in MEDLINE to identify literature relevant to the topic. A search methodology, identifying keywords, search strings and the sources of accessible material in Baidu Scholar, SCOPUS, Worldwide Science, BASE, Microsoft Academic, Google books, CORE, Science Direct, Google Scholar, and Elsevier BIOBASE, among others to minimize selection bias.

The following approach was used to find scientific research publications: 1) the keywords including "Carbon", "sequestration", "Agroforestry", "Global warming, Green House gases", "methods of carbon capture", "soil carbon storage". Search strings such as land management and carbon sequestration, tillage and carbon storage" synergy of vegetation and soil in carbon sequestration was conducted. Also, agroforestry and climate change, tillage and carbon storage, land preparation and global warming, interaction of vegetation and soil in carbon sequestration, trees and carbon capture soil and vegetation in climate change were considered to be part of the title and abstract; and 2) scientifically indexed English papers published between 1983 and 2023 were used. A total of 150 papers were retrieved from the literature search.

2.2. Screening and Selection Criteria

The following variables were taken into account: 1) title, keywords, search strings, 2) abstract, 3) the journals' credibility, and 4) content analysis. Fifty (50) suitable literature sources were retained and considered for this review. Figure 1 below shows the search methodology employed in identifying relevant literature for this review.

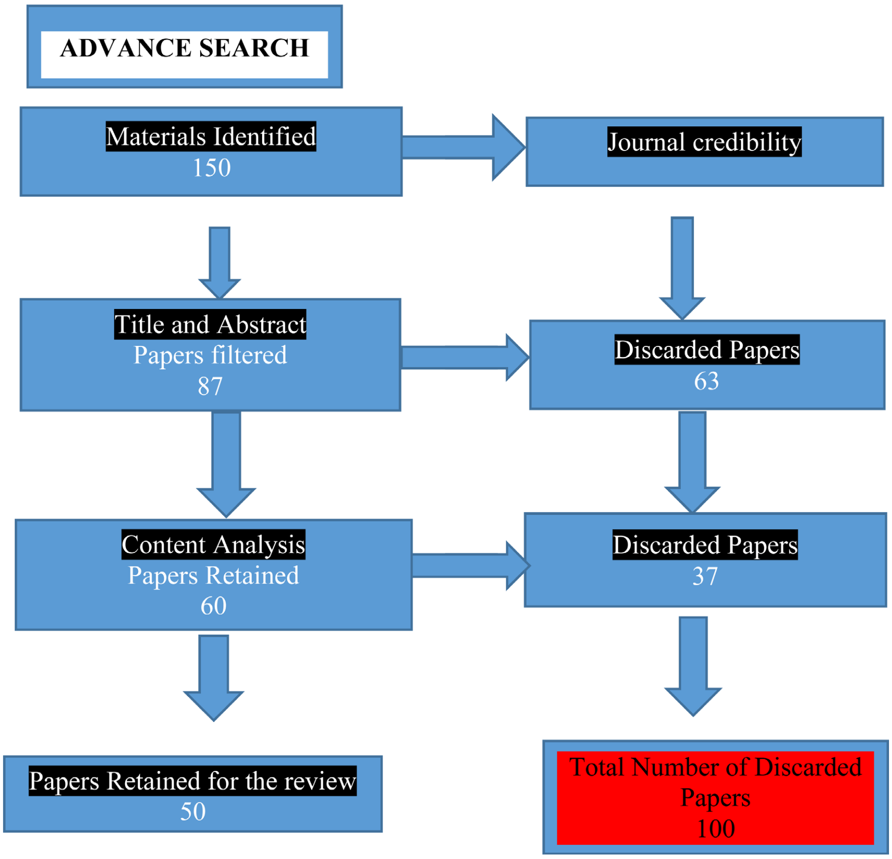

Figure 1. Screening process for selecting literature for review (Gentles et al., 2015).

3. Results

3.1. Agroforestry System (AFS)

International Centre for Research in Agroforestry (ICRAF) refers to agroforestry as a name for land-use practices that purposely combines trees and crops with or without livestock on the same piece of land (Nair et al., 2021). Agroforestry also refers to the intentional introduction or preservation of trees on farms to increase, diversify, and improve production for enhanced social, economic, and environmental benefits (Atangana et al., 2014). There are normally both ecological and economic interactions between trees and crops parts in agroforestry.

This definition has been helpful in agroforestry's recognition as a distinct field of agricultural research (Torquebiau, 2000).

It is approximated 1.6 billion hectares areas of land globally can be turned into agroforestry (Nair & Garrity, 2012). Agroforestry practices are considered the best "no regrets" approaches for helping communities adapt and become resilient to the effects of climate change because of their propensity to yield both economic and environmental benefits (Rao et al, 2007).

Agroforestry is generally practiced with the intention of developing a more sustainable form of land use that can improve farm productivity and the welfare of the rural community (Leakey, 1996). The contribution of agriculture to greenhouse gas (GHG) emissions has been estimated to be as low as 20% for CO_2, 50% for CH_4 and 70% for N_2O when compared to emissions from fossil fuels (Bedada & Goshu, 2021). CO_2 has been singled out as a highest GHGs being emitted to atmosphere from agriculture (FAO & ITPS, 2015).

As a means of sequestering carbon, agroforestry has attracted special attention, according to Kumar and Nair (2011). A major focus of the post-Kyoto Protocol discussions on climate change is an agenda for reducing the amount of CO_2 in the atmosphere by sequestering carbon in terrestrial plant systems (Gebre, 2016). Agroforestry is an environmentally sound and ecologically sustainable land use that retains carbon through sequestering it. This is expected to have a major positive impact on limiting the rise in atmospheric CO_2 levels Kumar and Nair (2011). Managed agroforestry systems store more carbon, but not as much as pure forest area (Bedada & Goshu, 2021). A significant amount of aboveground carbon stock, ranging from 10.7 to 57.1 mg $C \cdot ha^{-1}$ on average, is stored in agroforestry areas such as parklands, home gardens, and woodlots (Gebre, 2016).

There is an annual increase of CO_2 at a rate of 3.5 Pg (Pg = 1015 g or billion tons) to the atmosphere resulting largely from the burning fossil fuels and conversion of tropical forests to agricultural land (Paustian et al., 2000). According to Albrecht & Kandji (2003), the C sequestration capacity of agroforestry systems is estimated to range between 12 and 228 $Mg \cdot ha^{-1}$, with a median value of 95 $Mg \cdot ha^{-1}$ Albrecht & Kandji (2003). With an estimated area of (585 - 1215) × 10^6 ha suitable for agroforestry, 1.1 - 2.2 Pg C could be stored in the terrestrial ecosystems over the next 50 years Albrecht & Kandji (2003). Recent research conducted in a range of AFSs and ecological settings revealed that tree-based agriculture systems retained more carbon in deeper soil levels than treeless systems (Nair et al., 2010). According to Nair et al. (2010), system management and environmental factors have a major impact on how much carbon is sequestered in AFSs.

Agroforestry contributes to climate change mitigation and adaptation through:

> minimizing the destruction of nearby forests for the expansion of agricultural land, thereby lowering greenhouse gas emissions; providing fuelwood, which is also utilized as substitute for fossil fuel, and harvesting timber that

would otherwise be taken from the forest (Unruh et al., 1993) and enhancing soil C through litter, trimming, and root biomass improving agricultural output Albrecht & Kandji (2003). Mbow et al. (2014) demonstrated that agroforestry systems improve microclimate by decreasing the intensity of incident solar radiation while improving water conditions, gaseous exchange, and efficient water use.

3.2. Classification of Agroforestry

Agroforestry system can be categorized depending on vegetation structure, function of woody perennials in the system, levels of management input, and environmental conditions and ecological suitability of the system (Atangana et al., 2014).

Thus: agrisilviculture - combining trees/shrubs and crops, silvopastoral - keeping pasture/animals with trees and agrisilvopastoral - integration of crops, pasture/animals and trees. There is also a temporal agroforestry system called Taungya, which involves the cultivation of forestry tree crops and farmers' subsistence crops on a forest (Hemida et al., 2023).

3.3. Factors Affecting Carbon Sequestration in an Agroforestry System

3.3.1. The Type of Agroforestry System

There is ample data to indicate that the kind of agroforestry system has a significant impact on the trees' source or sink roles. For instance, agri-silvicultural systems are net sinks of greenhouse gases (GHGs), whereas agro-silvipastoral systems may be generators of GHGs (Kandji et al., 2006). The vegetative component of agroforestry contribute to carbon capture by using CO_2 for photosynthesis and depositing carbon above ground in tree stem, branches and twigs as well as underground in roots and the soil (Mahajan et al., 2021). Harvesting the tree for wood results in the permanent sequestration of the carbon for the life of products such as building materials or furniture created from the tree (Arehart et al., 2021).

Geography and tree species in an Agroforestry influence its ability to store carbon (Lasocki, 2001). Ma et al. (2020) reported that in order to improve biomass C sequestration in agroforestry systems, planting a variety of tree species is a key technic. A basic agroforestry which includes one specific tree species and a cash crop is capable of storing an average of, while complex agroforestry system with multiple tree species, shrubs, bushes and crops stores an average of 80.05 Mg C·ha^{-1} of carbon stock ranging from 71.99 - 85.45 Mg C·ha^{-1} (Toknok, 2013). Geographical climate also influences the response of soil to agroforestry practices Ma et al. (2020). Additionally, the amount of carbon stored in any agroforestry system is influenced by the structure and function of different parts within the system (Lorenz & Lal, 2014).

An agroforestry system with diverse tree species is able to sequester much carbon than a system with a single tree species (Parrotta, 1999). Agroforestry such as parklands, home gardens, and woodlots stored a substantial aboveground C stock of 10.7 to 57.1 Mg C·ha^{-1} with an average 19.4 Mg C·ha^{-1} (Gebre, 2016). Moreover, Ramachandran et al. (2009) have shown that the average abatement rates in tons of CO$_2$·ha^{-1}·year^{-1} are 7.6 for alley farming and 8.7 for improved fallow as indicated in **Table 1** below.

Table 2 and **Table 3** also indicate the mean above ground carbon sequestration by agroforestry system types in Africa and the carbon storage potential of agroforestry systems in different eco-regions of the world, respectively.

3.3.2. Soils

Research has substantiated that soils contain the largest terrestrial carbon (C) pool that is susceptible to changes in land use and agricultural management practices (Haddaway et al., 2017). Lal (2011) reported that soils at about 1-m depth contain approximately 2,500 Gt of C compared to the world biota which contains 750 Gt of C. Around 12% of soil C is stored in cultivated soils, which cover around 35% of the planet's terrestrial surface area (Betts et al., 2007).

Soils have the potential to sequester more carbon but are limited by bioclimatic factors (United Nations, 2011). These soils are susceptible to different types of degradation, including wind erosion and other bad management practices resulting in degradation. Dry lands need to sustainably manage to maintain their existing SOC levels and foster their SOC sequestration potential (United Nations, 2011). The type of soil is a very important determinant in carbon sequestration

Table 1. The C absorption capacity of different agroforestry models.

No.	Agroforestry Model	Carbon storage capacity (t·C·ha)
1.	Agrisilviculture system (11 years)	26.0
2.	Block Plantation (6 years)	24.1 - 31.1
3.	Silvopasture	31.71
4.	Agrisilviculture	13.37
5	Agri-horticulture	12.28

Source: Ramachandran et al. (2009).

Table 2. Mean above ground (vegetation) carbon by agroforestry system types in Africa.

Agroforestry system type	Mean	Variance	Number of Observations
Agrisilvicultural	0.88	0.14	5
Homegarden	0.52	0.07	5
Improved fallows	12.95	20.12	17
Shadow systems	2.27	2.36	18
Silvopastoral	0.15	–	1
Woodlots	3.36	1.85	14

Source: Feliciano et al. (2018).

Table 3. Carbon storage potential of agroforestry systems in different eco-regions of the world (Murthy et al., 2013).

Continent	Eco-region	System	Potential (megagram, Mg C/ha^{-1})	References
Africa	Humid tropical high	Agrosilvicultural	29 - 53	Dixon & Krankina, 1993
South America	Humid tropical low dry lowlands		39 - 102 39 - 195	
Southeast Asia	Humid tropical dry lowlands		12 - 228 68 - 81	Krankina & Dixon, 1994
Australia	Humid tropical low	Silvipastoral	28 - 51	
North America	Humid tropical high humid tropical low dry lowland		133 - 154 104 - 198 90 - 17	Schroeder, 1994
Northern Asia	Humid tropical low		15 - 18	Winjum et al., 1992

abilities of soil. Loamy soils, which include a balanced proportion of silt, sand, and clay, have a significant capacity to store CO_2 (Six et al., 2006). This is because of loam well-structured nature and promotes both adequate aeration and moisture retention thereby high ability to store organic materials (Rodrigues et al., 2023). Loamy soil provides conducive environmental conditions for biological activities promoting organic matter decomposition and thereby, contributing to carbon storage (Rodrigues et al., 2023).

Clayey soils due to their fine texture, high mineral content as well as high cation exchange capacity is able to store large amounts of CO_2 (Schimel et al., 1994). Sandy soils with their large particle size, rapid drainage, lower water holding capacity and low mineral content have lower carbon sequestration potential than loam and clay (Bai et al., 2019). Choudhury et al. (2014) reported carbon stock of 18.75, 19.84 and 23.83 $Mg \cdot ha^{-1}$ in the surface 0.4 m soil depth observed under zero tillage of 22.32, 26.73 and 33.07 $Mg \cdot ha^{-1}$ in 15 years in sandy loam, loam and clay loam soil respectively. This increase was highest in clay loam (38.8%) followed by loam (34.7%) and sandy loam (19.0%) soil. The carbon sequestration rate was found to be 0.24, 0.46 and 0.62 $Mg \cdot ha^{-1} \cdot yr^{-1}$ in sandy loam, loam and clay loam soil respectively under zero tillage. It is indicative that, fine textured soils have more potential for storing carbon and zero tillage practice enhances carbon sequestration rate in soils by providing better conditions in terms of moisture and temperature for higher biomass production and reduced oxidation (González-Sánchez et al., 2012).

According to Lal (2004), an estimated 25% - 75% of the carbon stocks in soils worldwide have been lost due to inappropriate vegetation management and tillage activities, among other things. Multiple studies investigating the conversion of natural forests to croplands discovered a considerable loss of soil carbon stores (Conant et al., 2001; Guo & Gifford, 2002). Soil organic carbon promotes climate change adaptation through enhancing physical characteristics of soil and boosting resistance to climatic extreme events. Land use practices that involve converting land from annual cropping to forest, grassland or perennial crops sequester C from atmospheric CO_2 and greatly contribute to climate change mitigation (Powlson et al., 2011).

Soil status as a net source or net sink of the atmospheric carbon dioxide greatly depends on management practices. Soil organic carbon loss is worsened by excessive soil drainage, bad ploughing techniques (e.g. ploughing across contours, deep ploughing), removal of residues and biomass, burning, inadequate soil amendment practices and soil erosion accelerative practices (Lal, 2011). Practicing recommended management practices (RMP) such as zero tillage farming with crop residue mulch, integration of forages in the rotation cycle, ensuring a positive nutrient balance, use of organic manures, turning arable lands to a perennial land use, and restoration of depleted soils can foster SOC pool.

Activities that promote potential increase in emission of CO_2 from soil, contribute to an increase in global warming (Rastogi et al., 2002). Land management strategies and fertilizer use that causes potential increase in emissions of N_2O and CH_4 from soils contribute to climate change as well (McDaniel et al., 2019). Boosting C (as CO_2) accumulation in soils leading to soil storage rate of about 3 Giga tons (GT) C/yr (Ontl & Schulte, 2012), prevent CO_2 increases in the atmosphere.

In addition to climate change, SOC plays beneficial vital physical, chemical and biological roles in the terrestrial biosphere as summarized in **Chart 1** below (Lal et al., 2013).

Soil carbon sequestration is catalyzed by management practices that incorporate more carbon into the soil and reduce soil respiration (Euliss et al., 2008). Research has proven that management practices that minimally disturb the soil and increase biomass production through soil amendments can avert soil carbon losses through oxidation and erosion. Appropriate land management can foster increase carbon inputs into the soil and this will consequently lead to appreciable decadal soil carbon storage due to long turn over times of soil carbon. Conservation tillage, which consists of no-tillage or reduced tillage, is one of the strategies, which promote carbon sequestration by reducing soil respiration (Euliss et al., 2008).

Soil characteristics, climate, land use, and other factors can make soil either a source or sink of carbon (Eglin et al., 2010). The collective objective of increasing global carbon stocks in forests, grasslands, and crops where human behavior is oriented toward C storage is projected to improve food security and mitigate climate change (Paustian et al., 2016). **Table 5** below shows the Carbon storage potentials of soils in different agroforestry systems and climatic zones.

Von Lützow et al. (2008) identified three soil conceptual C pools based on their rate of degradation. They included the labile OM with turnover between

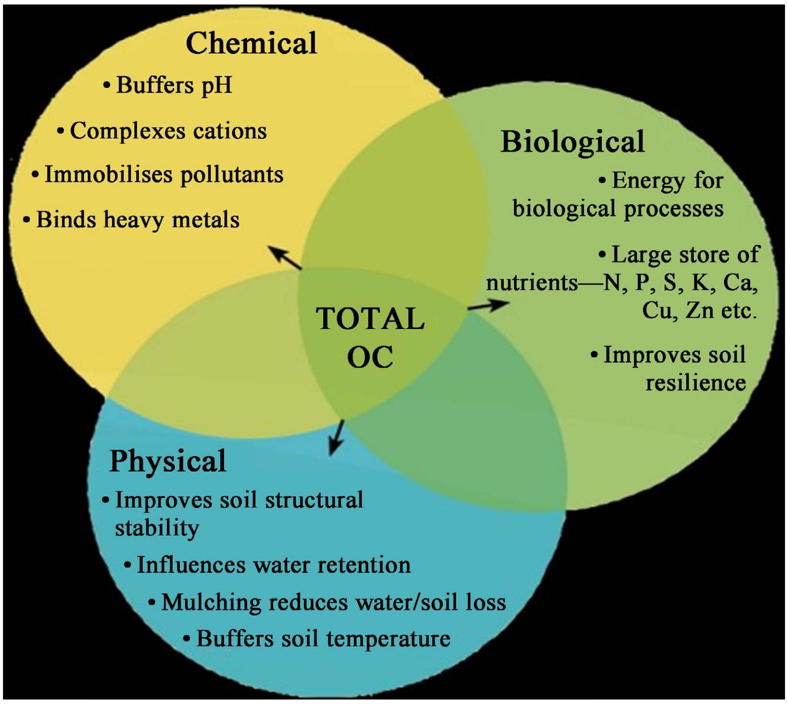

Chart 1. Soil Organic Carbon and its importance in Agriculture (Lal et al., 2013).

Table 5. Global Soil Carbon stocks in different agroforestry (AF) systems and Climatic zones.

Region	Agroforestry system	Soil C in AF (Mega gram, Mg C·ha^{-1})	Δ Soil C (Mg C·ha^{-1})
Tropics and subtropics	Alley cropping	38.6	5.3
	Homegardens	40.8	8.7/23.4
	Silvopasture	28.1	−1.8
	Windbreaks	30.1	6.3
Temperate	Alley cropping	17.7	2.2
	Homegardens	30.2	10
	Silvopasture	36.8	0.7
	Windbreaks	66.5	0.9

Δ: Soil C represents additional C sequestered in soils under AF compared to pure cropland (or pasture); *Δ: Soil C of homegardens highly varied between tropical and subtropical climates (8.7 vs 23.4 Mg C·ha^{-1}); Source: Shi et al. (2018); 1 Mg = 1 metric ton = 1,000,000 grams.

days to a year. The intermediate pool has a turn over within a few years to decades. The labile and intermediate pools consist of plant, animal, bacterial and fungal wastes. The stable OM pool has a turn over ranging from decades to centuries. It is derived from labile and intermediate pools and comprises most of the organic carbon in the soil (Torn et al., 2009). The stable OM also consists of plant, animal, bacterial, or fungal leftovers, as well as microbial metabolic products. The stable pool is present in aggregates and/or adsorbed on mineral surfaces.

To optimize the sustainability of increased carbon storage and extend the time that this additional carbon remains in the soil, the 4 per 1000 initiative aimed to increase the size of the intermediate and stable carbon pools (Dignac et al., 2017). Biotic and abiotic factors influence the storage and release of C from these pools (Dignac et al., 2017).

OM fluxes from plants to soils C inputs include not only above and belowground litter (leaves, branches, stems, roots), but also rhizodeposits and chemicals that are directly delivered to mycorrhizal fungus (Villarino et al., 2021). Root litter makes up around one-third of the total litter inputs in grassland soils and half in forest soils (Freschet et al., 2013). Rhizodeposition contributes appproximately 11% of carbon assimilated by plants and roots assimilate 27% of that carbon (Zhu et al., 2019).

Recent research proves belowground inputs play a major role in OM, which contribute to the intermediate to static pools of OM in deeper soil horizons (Mendez-Millan et al., 2012). Root litter breakdown is determined by root chemistry and happens at rate 30% slower than leaf decomposition (Birouste et al., 2012; Freschet et al., 2013).

Inputs of litter from above ground are partially incorporated into mineral soil with decomposition rates decreasing with increasing depth (Pries et al., 2018).

The structure of plant species and rooting system are very important characteristics that influence the quantity of carbon fixed into the soil (Luo et al., 2017). Species with lengthy root density such as monocots as well as annual which also have high root branching intensity on top soil minimizes surface runoff and therefore reducing carbon loss (Gyssels et al., 2005). Lange et al. (2015) reported that increased plant diversity enhanced rhizosphere carbon imports.

3.3.3. Processes Affecting Carbon Sequestration in Soils

The amount of carbon stored in the soil is determined by the rate and magnitude of the under listed processes which are influenced by Agricultural management practices (Follett, 2001).

Organic production

Through photosynthesis, the permanent vegetation can store significant amount of CO_2 thereby serving as a sink for the sequestration of CO_2. The carbon state of the soil system can be greatly impacted by farming methods and land use (Rabbi et al., 2014). Atmospheric carbon is sequestered and stored as carbon compounds in plants making plants the primary source of carbon.

Minimal organic carbon breakdown

Organic residue breakdown and oxidation increase carbon loss resulting in the production of greenhouse gases. Soil moisture, pH, temperature, chemical properties, and nutrient status influence this phenomenon. Minimal soil disturbance promotes carbon storage thereby improves the physical and chemical properties of soil and adds to nutrient pools. Appropriate soil management techniques protect the soil from erosion and improve microbial populations (Unger et al., 1991).

Soil erosion

Inappropriate soil and residue handling lead to accelerated water and wind erosion (Wilson et al., 2004). Soil erosion is a principal cause of soil degradation because of loss of organic matter, which is the "glue" or adhesive element in soil. The most effective way to lessen soil erosion is through conservation tillage (Seitz et al., 2019). The impact of no-tillage methods on improving soil quality with regard to the carbon content at the upper section of the soil profile is evident in situations where grasslands are turned to permanent vegetation. Tillage can result in appreciable carbon loss (as CO_2 bursts) immediately after tillage (Reicosky, 1995). Exposed soil organic carbon to aeration as a result of soil erosion emit more $CO_{2.}$ Erosion dislodges soil carbon and causes it to aggregate with soil sediments that is carried away causing loss of soil carbon pool. This consequently causes loss of soil fertility and aggregate stability. **Figure 2** below illustrates soil carbon loss through erosional processes.

Tillage

Although, tillage provides a number of benefits to farmers, it is also associated with the loss of carbon from agricultural soils (Haddaway et al., 2017). The recommendation and adoption of less intensive tillage practices and no tillage

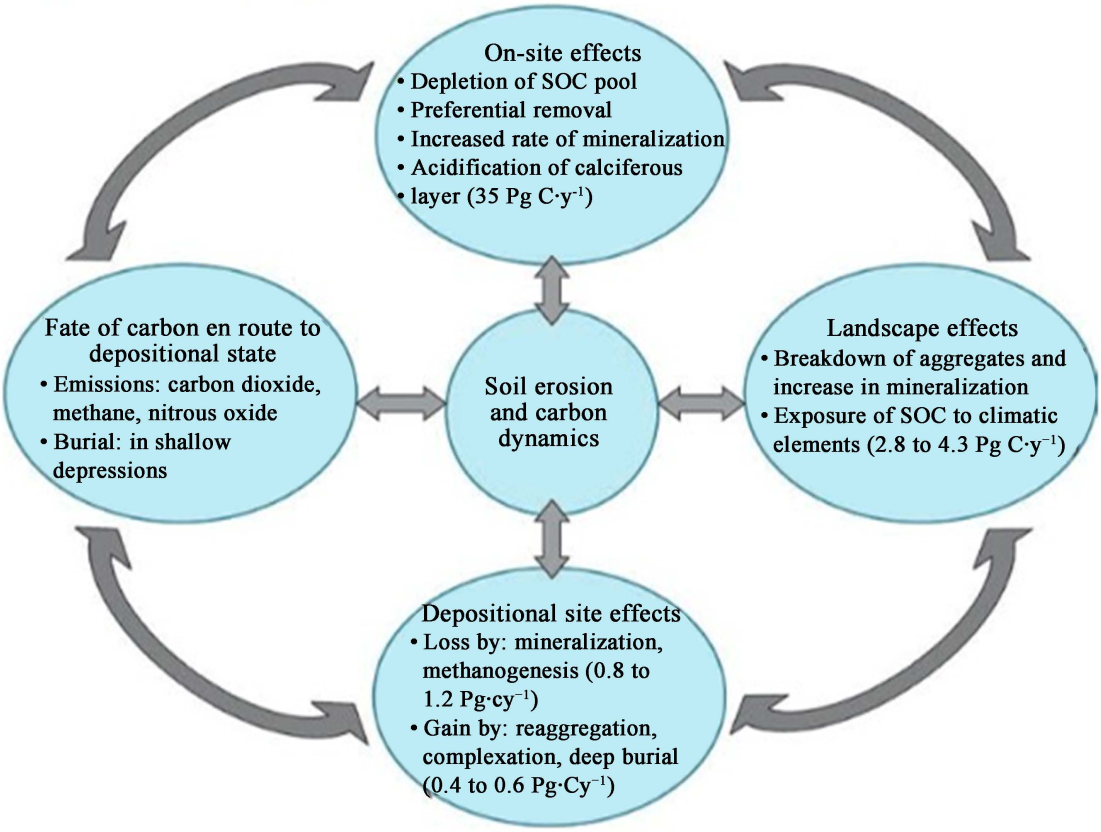

Figure 2. Fate of Soil Organic Carbon (SOC) transport by erosional processes modified and adapted from Lal (2003).

techniques helps prevent the adverse effects of tillage on soil quality and retain soil organic carbon (SOC) (Haddaway et al., 2017).

Conservation agriculture (CA), which encompasses little soil disturbance, plant residues retention, and crop rotations has proven to be beneficial to soil and farmers (Govaerts et al., 2009). A reduction in tillage practices tremendously reduces emissions, hence, mitigating climate change (González-Sánchez et al., 2012). CO_2 in the atmosphere is affected by changes in soil C (Schlesinger, 1995). Agriculture can be one of several potential solutions to the issue of greenhouse gas emissions if appropriate soil and residue management practices are practiced (Haddaway et al., 2017).

The oxidation and breakdown of plant residue will accelerate the loss of carbon as CO_2 (Olson et al., 2016). To completely store carbon in the soil system, there must be very little residue breakdown from conventional tillage and soil disturbance (Al-Kaisi et al., 2008).

Worldwide, the change in tillage practice from conventional tillage to no-tillage is effectively conserving soils in arable lands as well as reducing decline of soil organic matter and improving resilient agrarian systems (Mehra et al., 2018).

Reducing the need for mechanical tillage practices lessens energy consumption and C emissions through the use of fossil fuels (Holland, 2004). Increased Net Primary Productivity (NPP) through tillage methods may result in the storage of higher SOC stocks, which could mitigate the effects of climate change (Virto et al., 2012).

Effects of crop types and farming in carbon sequestration

According to Brakas and Aune (2011), tree crops sequester carbon at a higher rate than grasslands or annual crops because tree crops accumulate carbon through their roots, litter, and aboveground biomass, while annual crops only accumulate carbon through their roots and the retention of crop residue (Ramachandran et al., 2009; Jose, 2009).

According to Asbjornsen et al. (2013), perennial crops may be a viable choice for assisting climate-smart agricultural systems. Research has proven that perennial crops have the propensity to increase soil C stocks than annual crops (Ferchaud et al., 2016; Ledo et al., 2020).

Perennial crops in agroforestry systems have the potential to be significant carbon sinks, whereas annual crops in agroforestry systems under intensive management are more akin to conventional agriculture, which is a carbon source (Nair et al., 2010).

Depending on the type of growth, root morphology and physiology, leaf morphology, climate, soil texture, structure, and aggregation, dominant cropping system, and agronomic interventions during crop growth period, different plant species have different capacities for sequestering carbon and the amount of organic carbon (Jarecki & Lal, 2003). The aboveground plant biomass, plant leaves branches, stem, foliage, fruits, wood, litter-fall and below ground plant biomass such as dead roots, excretes substances from root exudates including rhizospheric deposition, and plant microbial biomass C, adding to the SOC buildup. Crop management practices that ensures increased nitrogen (N) availability is more sustainable and fosters C input in the soil ecosystem (Jarecki & Lal, 2003). Reduced tillage together with surface residue retention and integration of leguminous crops in a rotation reduce surface runoff and erosion and increase N availability and SOC sequestration (Meena et al., 2020). The application of organic manure, green manures, growing leguminous crops, cover crops, biological N-fixing microbes, and farm and kitchen waste materials adds nitrogen to the soil, which is essential for agricultural productivity and stores SOC (Meena et al., 2020). Practicing green manuring with leguminous crops (LGM) improves SOC, makes available nutrients, enhances physical, chemical and biological properties of soil thereby increasing crop productivity (Meena et al., 2018). When practiced with no-till farming practices, crop rotations can increase soil carbon storage, improve SOC concentration, and reduce soil erosion (Lal, 2011). Cover crops have the potential to store more carbon to enhance SOC and reduce climate change (Lal, 2004).

4. Discussion

Applied organic materials, respiration, plant residue removal and erosion determine the carbon balance in an agro-ecosystem (Brady & Weil, 1996). Tillage promotes good aeration in the soil, facilitates quick breaks down of organic matter, enhancing microbial decomposition to occur (Brady & Weil, 1996). Rapid organic matter decomposition has a positive correlation with CO_2 emissions, global warming and consequently, climate change (Kirschbaum, 2000). It is therefore indicative that processes that slow microbial decomposition of organic matter could be one of the sustainable approaches to sustained soil quality for agricultural productivity and also, mitigating climate change.

Eliminating soil tillage and inversion, maintaining crop residue cover, and ensuring proper crop rotation, have proven to improve SOM level and ensure carbon accumulation and sequestration in soils (Kassam et al., 2012). This has been termed as a Conservation or Climate Smart Agriculture practice. Fundamentally, conservation practices are linked to residue management, i.e., full, partial stubble retention on arable lands (Sommer et al., 2011). Conservation tillage facilitates surface residues accumulation leading to higher soil organic C storage.

Common land preparation methods in the Upper East of Ghana involve gathering all farm residues and burning to have a clean land for ploughing and other farm operations do not only contribute tremendously to the Green House effect but also antagonize the contribution of vegetation in mitigating climate change. These practices deteriorate soil carbon and make soils carbon sources than sinks.

With almost 79.0% of its inhabitants residing in rural areas and majority of them in dispersed villages, Ghana's Upper East region is the least urbanized (Ghana Statistical Service (GSS), 2014). The region is characterized by unimodal/ single rainfall pattern with a long dry season (no rains) seven months in a year. Due to this, the vegetation is savannah having sparse short fire resistant trees such as *Vitellaria paradoxa, Parkia biglobosa, Lannea micocarpa, Piliostigma thonningii, Diospyros mespiliformis, Combretum spp, Tectona grandis* with vast grasses understorey. As an agrarian region, livestock such as cattle, sheep, goats, donkey and birds (chicken, guinea fowls) are also kept dominantly on subsistence scale. Annual crops such as maize, sorghum, groundnuts, Bambara groundnuts, millet, guinea corn, rice are grown largely for family consumption.

Despite, efforts by the government and non-governmental organizations to minimize bushfires in the region, the rainfall pattern coupled with vast dry grasses in the dry season catalyzes bushfires. Hence, the region records bushfires on large hectares of land annually (Amoako et al., 2018). This undoubtedly contributes to global warming.

It is therefore, worth noting that if conservation land preparation methods are not adopted, no matter the hectares of agroforestry systems in the Upper East region of Ghana, they may not be able to contribute significantly to carbon sequestration and hence, mitigating climate change since CO_2 sources might outweigh the sinks.

It is logical to deduce from the above findings that no tillage land preparation methods leads to a buildup of soil organic carbon (SOC), storing substantial amount of carbon and consequently, sequestrating CO_2. Six et al. (2006) reported an increase in SOC stocks of both tropical and temperate soils under no tillage than with conventional tillage for the 0 - 10 cm layer. Conservation tillage is another feasible sustainable means of storing SOC and hence, contributing to CO_2 sequestration.

Busari et al. (2015) defines Conservation tillage as any tillage system that leaves at least 30% of the soil surface covered with crop residue after planting to reduce soil erosion by water splash and runoff. Conservation tillage, which encompasses maintenance of surface soil cover through retention of crop residues, is achievable by practicing zero tillage and minimal mechanical soil disturbance.

Retention of crop residue protects the soil from direct impact of raindrops and sunlight reducing soil erosion and evaporation, and processes that accelerate emission of CO_2 into the atmosphere (Busari et al., 2015). Bullock ploughing which is one of the land preparation methods in Upper East of Ghana ploughs a depth of 10 - 15 cm (Acharya et al., 2014) which is characteristic of climate smart agriculture practices should be a viable option in the savannah in fighting climate change since the rainfall pattern does not favour perennials growth including afforestation. Scharlemann et al. (2014) reported global soils store more C at average of 1500 Pg C in the top metre lone than vegetation and the atmospheric reservoirs combined.

Most of carbon in grassland ecosystems is stored in soils, where turnover durations are rather long (100 - 10,000 years). As a result, changes in the global carbon cycle have a major and long-term impact (Schimel et al., 1994). The slow turnover of the soil organic carbon (SOC) sink makes it a more secure carbon sequestration mechanism than plant biomass (Lugo & Brown, 1993).

5. Conclusion

From the results obtained in this review, tillage practices that ensure retention and storage of SOC could be much effective in carbon sequestration in the Savannah zones. Practices that enhance the rapid decomposition of soil organic carbon such as conventional tillage, gathering and burning of farm residues, bush burning etc. increase the buildup of CO_2 in the atmosphere. It is therefore, very imperative to consider soil organic carbon retention as a viable and sustainable approach in fighting climate change in this context since the rainfall pattern (unimodal) does not favour much vegetative (perennials) growth especially afforestation.

In the savannah, where annual plants are dominant, carbon sequestration could be enhanced by undertaking land management practices that ensure these grasses are not removed from the soil surface for fuels, thatch and other craft works while promoting bullocks ploughing and or no tillage practices. Promoting bullock ploughing alongside conserving the sparse indigenous and planted trees while discouraging mechanical ploughing with tractors could enhance CO_2 sequestration. This will consequently foster the synergistic mitigation of vegetation and soil of climate change mitigation in the Upper East region of Ghana.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Acharya, S., Mahapatra, N., & Ghosal, M. K. (2014). Draft Requirement of Bullock Drawn Mouldboard Ploughs in Sandy Loam Soil of Coastal Odisha. *Indian Journal of Dryland Agricultural Research and Development, 29,* 89-92. https://doi.org/10.5958/2231-6701.2014.01201.9

Albrecht, A., & Kandji, S. T. (2003). Carbon Sequestration in Tropical Agroforestry Systems. *Agriculture, Ecosystems and Environment, 99,* 15-27. https://doi.org/10.1016/S0167-8809(03)00138-5

Al-Kaisi, M. M., Kruse, M. L., & Sawyer, J. E. (2008). Effect of Nitrogen Fertilizer Application on Growing Season Soil Carbon Dioxide Emission in a Corn-Soybean Rotation. *Journal of Environmental Quality, 37,* 325-332. https://doi.org/10.2134/jeq2007.0240

Amoako, E. E., Kranjac-Berisavljevic, G., Ballu Duwieja, A., Misana, S., & Zizinga, A. (2018). Effect of the Seasonal Burning on Tree Species in the Guinea Savanna Woodland, Ghana: Implications for Climate Change Mitigation. *Applied Ecology and Environmental Research, 16,* 1935-1949. https://doi.org/10.15666/aeer/1602_19351949

Arehart, J. H., Hart, J., Pomponi, F., & D'Amico, B. (2021). Carbon Sequestration and Storage in the Built Environment. *Sustainable Production and Consumption, 27,* 1047-1063. https://doi.org/10.1016/j.spc.2021.02.028

Asbjornsen, H., Hernandez-Santana, V., Liebman, M., Bayala, J., Chen, J., Helmers, M., Ong, C. K., & Schulte, L. A. (2013). Targeting Perennial Vegetation in Agricultural Landscapes for Enhancing Ecosystem Services. *Renewable Agriculture and Food Systems, 29,* 101-125. https://doi.org/10.1017/S1742170512000385

Atangana, A., Khasa, D., Chang, S., Degrande, A., Atangana, A., Khasa, D., & Degrande, A. (2014). *Phytoremediation in Tropical Agroforestry* (pp. 343-351). Springer. https://doi.org/10.1007/978-94-007-7723-1_19

Bai, X., Huang, Y., Ren, W., Coyne, M., Jacinthe, P. A., Tao, B., Hui, D., Yang, J., & Matocha, C. (2019). Responses of Soil Carbon Sequestration to Climate-Smart Agriculture Practices: A Meta-Analysis. *Global Change Biology, 25,* 2591-2606. https://doi.org/10.1111/gcb.14658

Bedada, A. B., & Goshu, T. A. (2021). Farmland Trees for the Improvement of Crop Yield, Soil Fertilities, Soil and Water Conservation, and Carbon Sequestration: A Review. *Agricultural Science Research Journal, 11,* 154-168.

Betts, R. A., Falloon, P. D., Goldewijk, K. K., & Ramankutty, N. (2007). Biogeophysical Effects of Land Use on Climate: Model Simulations of Radiative Forcing and Large Scale Temperature Change. *Agricultural and Forest Meteorology, 142,* 216-233. https://doi.org/10.1016/j.agrformet.2006.08.021

Birouste, M., Kazakou, E., Blanchard, A., & Roumet, C. (2012). Plant Traits and Decomposition: Are the Relationships for Roots Comparable to Those for Leaves? *Annals of Botany, 109,* 463-472. https://doi.org/10.1093/aob/mcr297

Brady, N. C., & Weil, R. R. (1996). *The Nature and Properties of Soils.*

Brakas, S. G., & Aune, J. B. (2011). Biomass and Carbon Accumulation in Land Use Systems of Claveria, the Philippines. In B. Mohan Kumar, & P. K. Ramachandran Nair (Eds.), *Carbon Sequestration Potential of Agroforestry Systems: Opportunities and Challenges* (pp. 163-175). Springer. https://doi.org/10.1007/978-94-007-1630-8_9

Busari, M. A., Kukal, S. S., Kaur, A., Bhatt, R., & Dulazi, A. A. (2015). Conservation Tillage Impacts on Soil, Crop and the Environment. *International Soil and Water Conservation Research, 3,* 119-129. https://doi.org/10.1016/j.iswcr.2015.05.002

Choudhury, S. G., Srivastava, S., Singh, R., Chaudhari, S. K., Sharma, D. K., Singh, S. K., & Sarkar, D. (2014). Tillage and Residue Management Effects on Soil Aggregation, Organic Carbon Dynamics and Yield Attribute in Rice-Wheat Cropping System under Reclaimed Sodic Soil. *Soil and Tillage Research, 136,* 76-83. https://doi.org/10.1016/j.still.2013.10.001

Conant, R. T., Paustian, K., & Elliott, E. T. (2001). Grassland Management and Conversion into Grassland: Effects on Soil Carbon. *Ecological Applications, 11,* 343-355. https://doi.org/10.1890/1051-0761(2001)011[0343:GMACIG]2.0.CO;2

Das, B., Khara, U., & Bandyopadhyay, A. (2012). *Main Physical Causes of Climate Change and Global Warming—A General Overview.*

Dias Rodrigues, C. I., Brito, L. M., & Nunes, L. J. R. (2023). Soil Carbon Sequestration in the Context of Climate Change Mitigation: A Review. *Soil Systems, 7,* Article No. 64. https://doi.org/10.3390/soilsystems7030064

Dignac, M. F., Derrien, D., BarrÉ, P., Barot, S., CÉCillon, L., Chenu, C., & Basile-Doelsch, I. (2017). Increasing Soil Carbon Storage: Mechanisms, Effects of Agricultural Practices and Proxies. A Review. *Agronomy for Sustainable Development, 37,* 1-27. https://doi.org/10.1007/s13593-017-0421-2

Dixon, R. K., & Krankina, O. N. (1993). Forest Fires in Russia: Carbon Dioxide Emissions to the Atmosphere. *Canadian Journal of Forest Research, 23,* 700-705. https://doi.org/10.1139/x93-091

Eglin, T., Ciais, P., Piao, S., BarrÉ, P., Bellassen, V., Cadule, P., Chenu, C., Gasser, T., Koven, C., Reichstein, M., & Smith, P. (2010). Historical and Future Perspectives of Global Soil Carbon Response to Climate and Land-Use Changes. *Tellus B, 62,* 700-718. https://doi.org/10.1111/j.1600-0889.2010.00499.x

Euliss, N. H., Smith, L. M., Wilcox, D. A., & Browne, B. A. (2008). Linking Ecosystem Processes with Wetland Management Goals: Charting a Course for a Sustainable Future. *Wetlands, 28,* 553-562. https://doi.org/10.1672/07-154.1

Fagodiya, R. K., Verma, K., & Verma, V. K. (2023). Climate Resilient Agricultural Practices for Mitigation and Adaptation of Climate Change. In *Social Science Dimensions of Climate Resilient Agriculture* (pp. 1-14). ICAR-National Dairy Research Institute.

FAO and ITPS (2015). *Status of the World's Soils Resources.*

Feliciano, D., Ledo, A., Hillier, J., & Nayak, D. (2018). Which Agroforestry Options Give the Greatest Soil and above Ground Carbon Benefits in Different World Regions? *Agriculture, Ecosystems and Environment, 254,* 117-129. https://doi.org/10.1016/j.agee.2017.11.032

Ferchaud, F., Vitte, G., & Mary, B. (2016). Changes in Soil Carbon Stocks under Perennial and Annual Bioenergy Crops. *Global Change Biology Bioenergy, 8,* 290-306. https://doi.org/10.1111/gcbb.12249

Follett, R. F. (2001). Soil Management Concepts and Carbon Sequestration in Crop-Land Soils. *Soil and Tillage Research, 61,* 77-92. https://doi.org/10.1016/S0167-1987(01)00180-5

Freschet, G. T., Cornwell, W. K., Wardle, D. A., Elumeeva, T. G., Liu, W., Jackson, B. G., & Cornelissen, J. H. (2013). Linking Litter Decomposition of Above- and Below-Ground Organs to Plant-Soil Feedbacks Worldwide. *Journal of Ecology, 101,* 943-952. https://doi.org/10.1111/1365-2745.12092

Gebre, A. B. (2016). Potential Effects of Agroforestry Practices on Climate Change Mitigation and Adaptation Strategies: A Review. *Journal of Natural Sciences Research, 6,* 83-89.

Gentles, S. J., Charles, C., Ploeg, J., & McKibbon, K. A. (2015). Sampling in Qualitative Research: Insights from an Overview of the Methods Literature. *The Qualitative Report, 20,* 1772-1789. https://doi.org/10.46743/2160-3715/2015.2373

Ghana Statistical Service (GSS) (2014). *Ghana Living Standards Survey Round 6 (GLSS 6), Main Report, 2012/2013.* GSS.

González-Sánchez, E. J., Ordóñez-Fernández, R., Carbonell-Bojollo, R., Veroz-González, O., & Gil-Ribes, J. A. (2012). Meta-Analysis on Atmospheric Carbon Capture in Spain through the Use of Conservation Agriculture. S*oil and Tillage Research*, *122*, 52-60. https://doi.org/10.1016/j.still.2012.03.001

Govaerts, B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K. D., Dixon, J., & Dendooven, L. (2009). Conservation Agriculture and Soil Carbon Sequestration: Between Myth and Farmer Reality. *Critical Reviews in Plant Sciences, 28,* 97-122. https://doi.org/10.1080/07352680902776358

Guo, L. B., & Gifford, R. M. (2002). Soil Carbon Stocks and Land Use Change: A Meta-Analysis. *Global Change Biology, 8,* 345-360. https://doi.org/10.1046/j.1354-1013.2002.00486.x

Gyssels, G., Poesen, J., Bochet, E., & Li, Y. (2005). Impact of Plant Roots on the Resistance of Soils to Erosion by Water: A Review. *Progress in Physical Geography, 29,* 189-217. https://doi.org/10.1191/0309133305pp443ra

Haddaway, N. R., Hedlund, K., & Jackson, L. E. (2017). How Does Tillage Intensity Affect Soil Organic Carbon? A Systematic Review. *Environmental Evidence, 6,* Article No. 30. https://doi.org/10.1186/s13750-017-0108-9

Hemida, M., Yasin, E. H., Kheiry, M. A., Hammad, Z. M., & Vityi, A. (2023). Assessment of Taungya Agroforestry System in Dryland Forests Rehabilitation in Sudan. *Journal of Degraded and Mining Lands Management, 10,* 4495-4507. https://doi.org/10.15243/jdmlm.2023.103.4495

Holland, J. M. (2004). The Environmental Consequences of Adopting Conservation Tillage in Europe: Reviewing the Evidence. *Agriculture, Ecosystems & Environment, 103,* 1-25. https://doi.org/10.1016/j.agee.2003.12.018

Intergovernmental Panel on Climate Change (IPCC) (2007). *Fourth Assessment Report. Climate Change (AR4).* http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml

Jarecki, M. K., & Lal, R. (2003). Crop Management for Soil Carbon Sequestration. *Critical Reviews in Plant Sciences, 22,* 471-502. https://doi.org/10.1080/713608318

Jose, S. (2009). Agroforestry for Ecosystem Services and Environmental Benefits: An Overview. *Agroforestry Systems, 76,* 1-10. https://doi.org/10.1007/s10457-009-9229-7

Kandji, S. T., Verchot, L.V., Mackensen, J., Boye, A., Van, N.M., *et al.* (2006). Opportunities for Linking Climate Change Adaptation and Mitigation through Agroforestry Systems. In D. P. Garrity, A. Okono, M. Grayson, & S. Parrott (Eds.), *World Agroforestry into the Future* (pp. 113-121). World Agroforestry Centre (ICRAF).

Kassam, A., Friedrich, T., Derpsch, R., Lahmar, R., Mrabet, R., Basch, G., & Serraj, R. (2012). Conservation Agriculture in the Dry Mediterranean Climate. *Field Crops Research, 132,* 7-17. https://doi.org/10.1016/j.fcr.2012.02.023

Kirschbaum, M. U. (2000). Will Changes in Soil Organic Carbon Act as a Positive or Negative Feedback on Global Warming? *Biogeochemistry, 48,* 21-51. https://doi.org/10.1023/A:1006238902976

Krankina, O. N., & Dixon, R. K. (1994). Forest Management Options to Conserve and Sequester Terrestrial Carbon in the Russian Federation. *World Resource Review, 6,* 88-101.

Kumar, B. M., & Nair, P. K. R. (2011). *Carbon Sequestration in Agroforestry Systems: Opportunities and Challenges*. Springer. https://doi.org/10.1007/978-94-007-1630-8

Lal, R. (2003). Soil Erosion and the Global Carbon Budget. *Environment International, 29*, 437-450. https://doi.org/10.1016/S0160-4120(02)00192-7

Lal, R. (2004). Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science, 304,* 1623-1627. https://doi.org/10.1126/science.1097396

Lal, R. (2011). Soil Carbon and Climate Change. In D. Hillel, & C. Rosenzweig (Eds.), *Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation* (pp. 287-305). World Scientific Publishing. https://doi.org/10.1142/9781848166561_0016

Lal, R., Lorenz, K., Hüttl, R., Schneider, B., & Von Braun, J. (2013). *Ecosystem Services and Carbon Sequestration in the Biosphere*. Springer. https://doi.org/10.1007/978-94-007-6455-2

Lamb, W. F., Wiedmann, T., Pongratz, J., Rew, R., Crippa, M., Olivier, J. G., & Minx, J. (2021). A Review of Trends and Drivers of Greenhouse Gas Emissions by Sector from 1990 to 2018. *Environmental Research Letters, 16,* Article ID: 073005. https://doi.org/10.1088/1748-9326/abee4e

Lange, M., Eisenhauer, N., Sierra, C. A., Bessler, H., Engels, C., Griffiths, R. I. G. P., Malik, A. A., Roy, J., Scheu, S., Steinbeiss, S., Thomson, B. C., Trumbore, S. E., & Gleixner, G. (2015). Plant Diversity Increases Soil Microbial Activity and Soil Carbon Storage. *Nature Communications, 6,* Article No. 6707. https://doi.org/10.1038/ncomms7707

Lasocki, T. J. (2001). Climate Change Mitigation through Forestry: Theory and Practice. *Journal of Sustainable Forestry, 14,* 147-166. https://doi.org/10.1300/J091v14n02_09

Leakey, R. R. B. (1996). Definition of Agroforestry Revisited. *Agroforestry Today, 8,* 5-7. https://doi.org/10.1016/B978-0-12-805356-0.00001-5

Ledo, A., Smith, P., Zerihun, A., Whitaker, J., Vicente-Vicente, J. L., Qin, Z. C., McNamara, N. P., Zinn, Y. L., Llorente, M., Liebig, M., Kuhnert, M., Dondini, M., Don, A., Diaz-Pines, E., Datta, A., Bakka, H., Aguilera, E., & Hillier, J. (2020). Changes in Soil Organic Carbon under Perennial Crops. *Global Change Biology, 26,* 4158-4168. https://doi.org/10.1111/gcb.15120

Lorenz, K., & Lal, R. (2014). Soil Organic Carbon Sequestration in Agroforestry Systems. A Review. *Agronomy for Sustainable Development, 34,* 443-454. https://doi.org/10.1007/s13593-014-0212-y

Lugo, A. E., & Brown, S. (1993). Management of Tropical Soils as Sinks or Sources of Atmospheric Carbon. *Plant and Soil, 149,* 27-41. https://doi.org/10.1007/BF00010760

Luo, Y. Q., Zhao, X.-Y., Wang, T., & Li, Y.-Q. (2017). Characteristics of the Plant-Root System and Its Relationships with Soil Organic Carbon and Total Nitrogen in a Degraded Sandy Grassland. *Acta Prataculturae Sinica, 26,* 200-206.

Ma, Z., Chen, H. Y., Bork, E. W., Carlyle, C. N., & Chang, S. X. (2020). Carbon Accumulation in Agroforestry Systems Is Affected by Tree Species Diversity, Age and Regional Climate: A Global Meta-Analysis. *Global Ecology and Biogeography, 29,* 1817-1828. https://doi.org/10.1111/geb.13145

Mahajan, A., Sojitra, A., Gupta, H., & Arora, D. (2021). Carbon Sequestration in Forest and Agroforestry—A Global Perspective. In *Advances in Forestry and Agro-Forestry* (p. 437). Stella International Publication.

Mbow, C., Smith, P., Skole, D., Duguma, L., & Bustamante, M. (2014). Achieving Mitigation and Adaptation to Climate Change through Sustainable Agroforestry Practices in Africa. *Current Opinion in Environmental Sustainability, 6,* 8-14. https://doi.org/10.1016/j.cosust.2013.09.002

McDaniel, M. D., Saha, D., Dumont, M. G., HernÁNdez, M., & Adams, M. A. (2019). The Effect of Land-Use Change on Soil CH_4 and N_2O Fluxes: A Global Meta-Analysis. *Ecosystems, 22,* 1424-1443. https://doi.org/10.1007/s10021-019-00347-z

Meena, B. L., Fagodiya, R. K., Prajapat, K., Dotaniya, M. L., Kaledhonkar, M. J., Sharma, P. C., & Kumar, S. (2018). Legume Green Manuring: An Option for Soil Sustainability. In R. S. Meena, *et al.* (Eds.), *Legumes for Soil Health and Sustainable Management* (387-408). Springer. https://doi.org/10.1007/978-981-13-0253-4_12

Meena, R. S., Kumar, S., & Yadav, G. S. (2020). Soil Carbon Sequestration in Crop Production. In R. S. Meena (Ed.), *Nutrient Dynamics for Sustainable Crop Production* (pp. 1-39). Springer. https://doi.org/10.1007/978-981-13-8660-2_1

Mehra, P., Baker, J., Sojka, R. E., Bolan, N., Desbiolles, J., Kirkham, M. B., & Gupta, R. (2018). A Review of Tillage Practices and Their Potential to Impact the Soil Carbon Dynamics. *Advances in Agronomy, 150,* 185-230. https://doi.org/10.1016/bs.agron.2018.03.002

Mendez-Millan, M., Dignac, M. F., Rumpel, C., Rasse, D. P., Bardoux, G., & Derenne, S. (2012). Contribution of Maize Root Derived C to Soil Organic Carbon throughout an Agricultural Soil Profile Assessed by Compound Specific 13C Analysis. *Organic Geochemistry, 42,* 1502-1511. https://doi.org/10.1016/j.orggeochem.2011.02.008

Mir, K. A., Purohit, P., & Mehmood, S. (2017). Sectoral Assessment of Greenhouse Gas Emissions in Pakistan. *Environmental Science and Pollution Research, 24,* 27345-27355. https://doi.org/10.1007/s11356-017-0354-y

Murthy, I. K., Gupta, M., Tomar, S., Munsi, M., Tiwari, R., Hegde, G. T., & Ravindranath, N. H. (2013). Carbon Sequestration Potential of Agroforestry Systems in India. *Journal of Earth Science & Climatic Change, 4,* 1-7. https://doi.org/10.4172/2157-7617.1000131

Nair, P. K. R., & Garrity, D. (2012). *Agroforestry—The Future of Global Land Use.*

Springer. https://doi.org/10.1007/978-94-007-4676-3

Nair, P. R., Kumar, B. M., Nair, V. D., Nair, P. R., Kumar, B. M., & Nair, V. D. (2021). Definition and Concepts of Agroforestry. In P. K. R. Nair, B. M. Kumar, & V. D. Nair (Eds.), *An Introduction to Agroforestry: Four Decades of Scientific Developments* (pp. 21-28). Springer. https://doi.org/10.1007/978-3-030-75358-0_2

Nair, P. R., Nair, V. D., Kumar, B. M., & Showalter, J. M. (2010). Carbon Sequestration in Agroforestry Systems. In *Advances in Agronomy* (Vol. 108, pp. 237-307). Elsevier. https://doi.org/10.1016/S0065-2113(10)08005-3

Olson, K. R., Al-Kaisi, M., Lal, R., & Cihacek, L. (2016). Impact of Soil Erosion on Soil Organic Carbon Stocks. *Journal of Soil and Water Conservation, 71,* 61A-67A. https://doi.org/10.2489/jswc.71.3.61A

Ontl, T. A., & Schulte, L. A. (2012). Soil Carbon Storage. *Nature Education Knowledge, 3,* 35.

Parrotta, J. A. (1999). Productivity, Nutrient Cycling, and Succession in Single- and Mixed-Species Plantations of *Casuarina equisetifolia*, *Eucalyptus robusta*, and *Leucaena leucocephala* in Puerto Rico. *Forest Ecology and Management, 124,* 45-77. https://doi.org/10.1016/S0378-1127(99)00049-3

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

Paustian, K., Six, J., Elliott, E. T., & Hunt, H. W. (2000). Management Options for Reducing CO_2 Emissions from Agricultural Soils. *Biogeochemistry, 48,* 147-163. https://doi.org/10.1023/A:1006271331703

Powlson, D. S., Whitmore, A. P., & Goulding, K. W. (2011). Soil Carbon Sequestration to Mitigate Climate Change: A Critical Re-Examination to Identify the True and the False. *European Journal of Soil Science, 62,* 42-55. https://doi.org/10.1111/j.1365-2389.2010.01342.x

Pries, C. E. H., Sulman, B. N., West, C., O'Neill, C., Poppleton, E., Porras, R. C., & Torn, M. S. (2018). Root Litter Decomposition Slows with Soil Depth. *Soil Biology and Biochemistry, 125,* 103-114. https://doi.org/10.1016/j.soilbio.2018.07.002

Rabbi, S. F., Tighe, M., Cowie, A., Wilson, B. R., Schwenke, G., Mcleod, M., & Baldock, J. (2014). The Relationships between Land Uses, Soil Management Practices, and Soil Carbon Fractions in South Eastern Australia. *Agriculture, Ecosystems and Environment, 197,* 41-52. https://doi.org/10.1016/j.agee.2014.06.020

Ramachandran Nair, P. K., Mohan Kumar, B., & Nair, V. D. (2009). Agroforestry as a Strategy for Carbon Sequestration. *Journal of Plant Nutrition and Soil Science, 172,* 10-23. https://doi.org/10.1002/jpln.200800030

Rao, K., Verchot, L., & Laarman, J. (2007). Adaptation to Climate Change through Sustainable Management and Development of Agroforestry Systems. *Journal of SAT Agricultural Research, 4,* 1-30.

Rastogi, M., Singh, S., & Pathak, H. (2002). Emission of Carbon Dioxide from Soil. *Current Science, 82,* 510-517. https://doi.org/10.4141/S02-SI

Reicosky, D. C. (1995). Impact of Tillage on Soil as a Carbon Sink. In *Farming for a Better Environment* (pp. 50-53). Soil and Water Conservation Society.

Saha, R., & Jha, P. (2012). Carbon Sequestration Potentials of Agroforestry Systems under Climate Change Scenario—Brief Review with Special Emphasis on North-Eastern Hill Regions. *Journal of Agricultural Physics, 12,* 100-106.

Scharlemann, J. P., Tanner, E. V., Hiederer, R., & Kapos, V. (2014). Global Soil Carbon: Understanding and Managing the Largest Terrestrial Carbon Pool. *Carbon Manage-*

ment, 5, 81-91. https://doi.org/10.4155/cmt.13.77

Schimel, D. S., Braswell, B. H., Holland, E. A., McKeown, R., Ojima, D. S., Painter, T. H., Parton, W. J., & Townsend, A. R. (1994). Climatic, Edaphic, and Biotic Controls over Storage and Turnover of Carbon in Soils. *Global Biogeochemical Cycles, 8,* 279-293. https://doi.org/10.1029/94GB00993

Schlesinger, W. H. (1995). Soil Respiration and Changes in Soil Carbon Stocks. In G. M. Woodwell, & F. T. Mackenzie (Eds.), *Biotic Feedbacks in the Global Climatic System: Will the Warming Feed the Warming* (pp. 159-168). Oxford University Press. https://doi.org/10.1093/oso/9780195086409.003.0010

Schroeder, P. (1994). Carbon Storage Benefits of Agroforestry Systems. *Agroforestry Systems, 27,* 89-97. https://doi.org/10.1007/BF00704837

Seitz, S., Goebes, P., Puerta, V. L., Pereira, E. I. P., Wittwer, R., Six, J., & Scholten, T. (2019). Conservation Tillage and Organic Farming Reduce Soil Erosion. *Agronomy for Sustainable Development, 39,* Article No. 4. https://doi.org/10.1007/s13593-018-0545-z

Shi, L., Feng, W., Xu, J., & Kuzyakov, Y. (2018). Agroforestry Systems: Meta-Analysis of Soil Carbon Stocks, Sequestration Processes, and Potential. *Land Degradation and Development, 29,* 3886-3897. https://doi.org/10.1002/ldr.3136

Six, J., Frey, S. D., Thiet, R. K., & Batten, K. M. (2006). Bacterial and Fungal Contributions to Carbon Sequestration in Agroecosystems. *Soil Science Society of America Journal, 70,* 555-569. https://doi.org/10.2136/sssaj2004.0347

Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). A Review of Biochar and Its Use and Function in Soil. *Advances in Agronomy, 105,* 47-82. https://doi.org/10.1016/S0065-2113(10)05002-9

Sommer, R., Ryan, J., Masri, S., Singh, M., & Diekmann, J. (2011). Effect of Shallow Tillage, Moldboard Plowing, Straw Management and Compost Addition on Soil Organic Matter and Nitrogen in a Dryland Barley/Wheat-Vetch Rotation. *Soil and Tillage Research, 115,* 39-46. https://doi.org/10.1016/j.still.2011.06.003

Toknok, B. (2013). Carbon Stock of Agroforestry Systems at Adjacent Buffer Zone of Lore Lindu National Park, Central Sulawesi. *Journal of Tropical Soils, 16,* 123-128. https://doi.org/10.5400/jts.2011.v16i2.123-128

Torn, M. S., Swanston, C. W., Castanha, C., & Trumbore, S. E. (2009). Storage and Turnover of Organic Matter in Soil. In N. Senesi, *et al.* (Eds.), *Biophysico-Chemical Processes Involving Natural Nonliving Organic Matter in Environmental Systems* (pp. 219-272). John Wiley & Sons, Inc. https://doi.org/10.1002/9780470494950.ch6

Torquebiau, E. F. (2000). A Renewed Perspective on Agroforestry Concepts and Classification. *Comptes Rendus De L'Academie Des Sciences-Series III-Sciences De La Vie, 323,* 1009-1017. https://doi.org/10.1016/S0764-4469(00)01239-7

Unger, P. W., Stewart, B. A., Parr, J. F., & Singh, R. P. (1991). Crop Residue Management and Tillage Methods for Conserving Soil and Water in Semi-Arid Regions. *Soil and Tillage Research, 20,* 219-240. https://doi.org/10.1016/0167-1987(91)90041-U

United Nations (2011). *Global Drylands: A UN System-Wide Responses.* United Nation Environment Management Group.

Unruh, J. D., Houghton, R. A., & Lefebvre, P. A. (1993). Carbon Storage in Agroforestry: An Estimate for Sub-Saharan Africa. *Climate Research, 3,* 39-52. https://doi.org/10.3354/cr003039

Villarino, S. H., Pinto, P., Jackson, R. B., & Piñeiro, G. (2021). Plant Rhizodeposition: A Key Factor for Soil Organic Matter Formation in Stable Fractions. *Science Advances, 7,* Eabd3176. https://doi.org/10.1126/sciadv.abd3176

Virto, I., BarrÉ, P., Burlot, A., & Chenu, C. (2012). Carbon Input Differences as the Main Factor Explaining the Variability in Soil Organic C Storage in No-Tilled Compared to Inversion Tilled Agrosystems. *Biogeochemistry, 108,* 17-26. https://doi.org/10.1007/s10533-011-9600-4

Von Lützow, M., Kögel-Knabner, I., Ludwig, B., Matzner, E., Flessa, H., Ekschmitt, K., & Kalbitz, K. (2008). Stabilization Mechanisms of Organic Matter in Four Temperate Soils: Development and Application of a Conceptual Model. *Journal of Plant Nutrition and Soil Science, 171,* 111-124. https://doi.org/10.1002/jpln.200700047

Warming, C. R. F. T. G., & Rays, G. C. (2011). *INCCA: Indian Network for Climate Change Assessment*.

Wilson, G. V., Dabney, S. M., McGregor, K. C., & Barkoll, B. D. (2004). Tillage and Residue Effects on Runoff and Erosion Dynamics. *Transactions of the ASAE, 47,* 119-128.

Winjum, J. K., Dixon, R. K., & Schroeder, P. E. (1992). Estimating the Global Potential of Forest and Agroforest Management Practices to Sequester Carbon. *Water, Air, and Soil Pollution, 64,* 213-227.

Zhu, X., Hu, Y., Wang, W., & Wu, D. (2019). Earthworms Promote the Accumulation of Maize Root-Derived Carbon in a Black Soil of Northeast China, Especially in Soil from Long-Term No-Till. *Geoderma, 340,* 124-132.