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Carbon Farming: A Solution to Climate Change

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Abstract

The significant challenge of the 21st century lies in mitigating climate change induced by elevated atmospheric carbon dioxide concentrations. The extensive use of biofuels, the destruction of wetlands, and the continuous burning of fossil fuels are alarming glimpses of human activities disrupting the global carbon cycle through greenhouse gas emissions. A concerning projection indicates a potential tripling of total emissions in the new millennium compared to the past half-century. Developing technological solutions for long-term carbon dioxide storage is necessary to combat climate change. Carbon farming offers a promising solution, empowering communities to participate actively in building a more sustainable future. Carbon farming uses agricultural practices to trap carbon dioxide from the air and store it in soil, plants, and trees, preventing it from contributing to global warming. In the terrestrial ecosystem, sequestering carbon is a win-win scenario. The current rise in atmospheric carbon dioxide could be halted with a yearly rise of 0.4% carbon content stored in the ground. Adopting low-carbon and renewable energy sources is an essential, accessible step towards a healthy planet. Some carbon sequestration techniques include conservation tillage, rotational cultivation, and woodland restoration on agricultural land. Expanding soil biological carbon stocks in agriculture holds immense potential for mitigating climate change by achieving carbon neutrality and removing carbon dioxide from the atmosphere.

Keywords: Climate change, carbon sequestration, carbon farming, carbon farming practices

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1. Introduction

Climate change has been affecting the natural environment, ecosystems, and their interactions has been considered the primary and most alarming world health concern of the 21st decade [1]. Extreme weather conditions and natural disasters are occurring more frequently, more intensely, and for longer periods due to global warming, which is changing the planet's climatic pattern. The world's warming climate, driven by global warming, intensifies extreme weather events, with greater frequency, intensity, and duration, posing a growing threat to communities worldwide. Numerous natural disasters continue to occur worldwide, including floods, tornadoes, cyclones, forest fires, and more prevalent heavy rains [2-5]. The health implications range from natural calamities causing early death to infectious disorders caused by inadequate hygiene and pathogen over-proliferation [1]. Inadequate temperatures were expected to be the cause of over five million fatalities per year between 2005 and 2019, accounting for 9.43% of all deaths globally. Furthermore, it is anticipated that in the coming 25 years, temperature-related excess mortality will continue to rise [6]. Aside from an increase in mortality, the temperature shift may result in various ailments. For instance, excessive heat increases your risk of hospitalizations for heart, lung, and metabolic problems [7]. Suicide, anxiety, and depression cases increase on hot days, suggesting that high heat may make behavioral and mental illnesses worse [8-9]. Activities like burning fossil fuels, clearing land for agriculture, raising livestock, using biogas, and draining wetlands are all contributing to a rise in greenhouse gases (GHGs), which in turn leads to higher air temperatures. Transportation and preservation (10.70%), farming (8%), Energy production (13.60%), electrical power (14.80%), development (11.40%), research (7.1%), water utilization, sanitation, disposal, and restoration processes (18.3%), domestic (4.4%), and other services sectors (11.7%), according to the Organization for Economic Cooperation and Development (OECD). Scientists believe human activities are the main reason behind rising global temperatures, driven by greenhouse gases like carbon dioxide (CO_2), methane

(CH_4), and nitrous oxide (N_2O) [10]. Table 1 shows electricity production tops the list as the biggest source of carbon emissions, contributing a quarter of the total. Energy Production and development follow closely behind [11]. Although not all GHGs are equally capable of causing warming, their potencies are influenced by the amount of radiative forcing they offer and the typical lifetime of a gas molecule in the atmosphere. Global Warming Potential (GWP) does not represent the "maximum amount of heat" produced by any combination of gases. It reflects the relative ability of one gas compared to another to trap heat in the atmosphere over a chosen timeframe. The GWP is therefore expressed as carbon dioxide equivalent. Among the principal sources of CO_2 emissions is the agricultural industry. About 6.1 gigatonnes of carbon dioxide equivalents (CO_2e) or approximately 11 percent of worldwide emissions of greenhouse gases are produced by agriculture each year, according to researchers [12-13]. The food system is impacted by climate change because it has decreased the quantity and condition of water, soil, and land resources. Eventually, the effect on crop performance has produced several detrimental effects on public health, including reduced food supply and crop variety, price swings, and political chaos [14]. Climate change is causing an increase in global hunger, and the human population is growing [15]. In a major setback for global food security, an estimated 1 billion people (11% of the world's population) faced hunger for the first time in 2016, marking a 15-year high. Researchers found that lowering atmospheric CO_2 levels is essential to prevent harmful climatic changes. The international community looked for low-cost ways to prevent atmospheric CO_2 concentrations from rising too quickly and to lessen their effects. The global community sought low-cost methods to slow the buildup of atmospheric CO_2 concentrations and lessen their effects. To halt the current rise of atmospheric CO_2 and address the existing burden, a "breathing space" is essential. This necessitates not only curbing emissions but also actively removing CO_2 through various methods [16].

Research suggests that a 0.4% annual increase in soil carbon storage may be sufficient to counteract the current upward trend in atmospheric CO_2 concentrations. A 2015 initiative, launched at the Climate Change Conference of Parties (COP 21), seeks to combat climate change by enhancing soil organic carbon (SOC) levels by 0.4% every year. This involves preserving or increasing carbon reserves in agricultural lands while safeguarding existing carbon-rich soils [17]. Large-scale tree planting offers a natural solution for capturing and storing terrestrial CO_2 (carbon farming). Carbon farming is a Climate Smart Agriculture land management approach that allows carbon absorption in soil and plants, reducing greenhouse gas emissions. Compared to other strategies, carbon farming appears less disruptive and potentially more manageable. Its reversibility and the potential to "green" degraded lands make it an attractive option. Carbon farming is emerging as a promising solution for the climate crisis, offering a natural way to reduce atmospheric carbon dioxide and its detrimental effects [18].

2. Climate realities:

With Western Australia experiencing a 1.6°C temperature increase above average and 40% less average rainfall than the rest of the world, 2019 was both the hottest and driest year on record for the entire planet. Since many years ago, climatic conditions have been researched and found to vary by location of the state. The southwest region of Washington has seen a decrease in average winter rainstorms of 26% since 1999 and an increase in average temperature of 1°C over the past century. In contrast, due to an increase in the power of tropical storms over the past 20 years, the northwest region's annual precipitation has increased. Stronger cyclones, which are fueled by rising land temperatures, result in more rainfall and longer dry spells [19]. These various conditions have an impact on West African residents' health and safety as well as agriculture and farming. The Millennium Drought (1996–2010) is a prime example. Similar to this, heavy rains in March 2021 caused extreme flooding in WA's northwest, separating Kimberley settlements and prompting helicopter-delivered resources. Such changes are anticipated to persist, posing problems like scarce water and food resources impacting dietary needs and ecosystems impacting the spread of disease. 2020's global average surface temperature is 0.94 °C warmer than it was between 1951 and 1980 [20]. Natural disasters have been occurring more frequently, more intensely, and for longer periods as a result of global warming. Studies have shown that the total number of severe heatwaves recorded between 2015 and 2020 was twice as high as the average for the period between 1951 and 1980. In addition, 46% of cyclones, 34% of hurricanes, 31% of famines, and 32% of forest fires have taken place [21]. Global warming has been accelerated by the melting of ice shelves and glaciers due to the warming atmosphere, which also reduces heat reflection. Sea level rise is primarily caused by the melting of ice sheets and glaciers as well as the thermal expansion of seawater. The rate of sea level rise between 1971 and 2010 was 1.7 mm per year, and it has more than doubled since 1993. The increase in atmospheric CO_2 levels is attributed to the expanding use of fossil fuels as well as the widespread deforestation that has occurred since the Industrial Revolution. Such CO_2 levels in the atmosphere have not been observed for ages [7].

Agriculture is heavily reliant on weather, climate change has resulted in food scarcity and malnutrition; there is fierce competition for scarce resources, even among humans and cattle. Changes in the climate have resulted in reduced biodiversity and animal or plant species are dying out at a frightening pace (Urban, 2015), as well as damage to croplands (Ikhuoso, 2015). These have posed an immense risk to the food supply and have sparked fierce competition. To assess mitigation needs, the global community has set temperature targets to mitigate the impact of global warming. These targets are set by the United Nations Framework Convention on Climate Change (UNFCCC), with countries meeting annually at the Conference of the Parties (COP) to agree on global targets for climate change mitigation. Before COP21 in November 2015 in Paris, France, the internationally agreed-upon goal for limit the increase in the global mean surface temperature to 2 degrees Celsius. The 2°C target is achieved by keeping GHG concentrations in the atmosphere below 450 ppm of CO_2 [22]. The goal of climate change mitigation is to reduce gross GHG emissions; preventing or minimizing emissions and storing C in the terrestrial environment are the two primary methods for doing so. The primary climate change adaptation options are increasing soil durability by increasing soil organic matter, implementing effective land-use systems, and increasing overall primary productivity. The conservation of carbon is a significant mitigation strategy for lowering atmospheric GHG concentrations, particularly CO_2. Fig 1 below paints a worrying picture of a planet where farms and ecosystems are struggling under the heat of climate change.

3. Sources of increase in the atmospheric concentration of gases:

The agriculture industry in the United States is a major source of CO_2 emissions, accounting for up to 9% of the overall emission of CO_2 [23]. The agricultural and land management sector contributes a significant 25% to global carbon dioxide emissions. The resulting emissions are caused by the following factors: forest clearance; biomass burning; agricultural management strategies that break down soil and nutrient management; and anthropogenic methane (CH_4) emissions from livestock operations[24]. Fertilizer production is one of the non-management activities that account for CO_2 emissions from energy use [25]. Deforestation occurs when wooded land that normally captures CO_2 is destroyed, typically for transformation to agreement or agricultural uses that don't capture as much CO_2. Despite covering 40% of the planet, agricultural land continues to expand by six million acres each year, converting natural habitats to meet growing food demands. Fig 2 shows the aspects of Earth that are being affected by climate change [26].

Cattle methane contributes most significantly to human-caused emissions, contributing to more than 14% of total emissions [27]. Cattle methane emissions equal the total emissions from all vehicles, automobiles, aircraft, and ships on the planet today. Population expansion and meat consumption are the main sources of methane emissions. The impact of agriculture and livestock on climate change is immense, with 135 gigatonnes of carbon released since the Industrial Revolution [28]. Compared to other populous nations, the United States risks having higher methane emissions from enteric fermentation by 2020, exceeding 108 million metric tonnes of CO2 equivalent and highlighting the need for action. By 2020, agricultural soil nitrous oxide emissions are expected to exceed 327 million metric tonnes of CO_2 equivalent, trailing in developing countries [29]. By 2055, livestock N_2O and the release of CH_4 are expected to more than triple [30]. Graph 1 illustrates the relative contributions of different activities to overall CO2 emissions [31].

4. Soil Carbon Sequestration:

According to research conducted by Joe Biden, the soil is the next frontier for storing carbon [32]. Among all land-based ecosystems**,** organically soil organic carbon (SOC) is considered the most significant carbon pool. SOC preservation is critical for global and societal sustainability [33]. Scientists are increasingly interested in soil organic carbon's role in the Earth's carbon cycle. It could be a major source of future carbon dioxide emissions due to warming temperatures, but also a potential natural sink for absorbing atmospheric carbon dioxide [34]. Advanced technologies like spectroscopy and isotopic analysis are revolutionizing the understanding of soil carbon storage and its dynamics over time [35]. Carbon Capture and Sequestration (CCS) indicates a group of methodologies designed for preserving a significant portion of carbon dioxide (CO_2) emissions, potentially mitigating climate change and reducing dependence on fossil fuels. Carbon dioxide is known as a greenhouse gas. CCS is a 3 step process: capturing CO_2, transferring CO_2, and securely conserving the carbon dioxide released deep below in drained natural gas and oil fields or deep saline aquifers. This innovative technology captures millions of tonnes of CO_2, transports it through various methods, and securely stores it in geological formations deep beneath the ground [36]. Rising temperatures and changes in precipitation can alter microbial activity in the soil, impacting decomposition rates and ultimately influencing the delicate balance between carbon sequestration and release [37].

Natural soil carbon sequestration occurs. It works by retaining some photosynthate in the soil and converting it into a carbon pool with prolonged residence. The process is natural and has several additional benefits, including reduced soil erosion hazards, sedimentation, and overall improved water quality**.** Soil carbon sequestration involves capturing CO2 from the air and storing it in the ground as plant residues, living plant tissues, and long-lasting organic matter [38-39]. Carbon dioxide is sequestered in the natural environment through photosynthesis, phytoplankton calcification, and underground mineralization [40].

5. Classification of carbon sequestration

5.1. *Biological carbon sequestration*

Biological carbon sequestration refers to the natural process where living organisms, such as trees and phytoplankton, absorb CO2 from the atmosphere and store it in their biomass and the surrounding soil or sediments [41]. Although it is critical to support such sinks and prevent carbon from being purposefully and unnecessarily released (through, for example, deforestation), the primary focus of climate change mitigation should be on practices that reduce greenhouse gas emissions. Because carbon capture and storage is believed to be a technique for neutralizing human-caused emissions of CO_2, the impact of nitrogen on ecosystem carbon budgets is critical[42]. In the biological sequestration of carbon, "nitrogen addition" coupled with "microbial" and "biochar" has been extensively employed [43-44].

5.2. Abiotic carbon sequestration

Abiotic sequestration, the process of storing carbon dioxide in geological formations like rocks, is a critical tool for mitigating climate change. Abiotic sequestration is a technique used in engineering. By 2025 and beyond, deep injection technology for use in oil spills, coal deposits, geological strata, and the ocean floor might be widely accessible. These methods are currently costly and injected carbon dioxide leaks easily. They are expensive as well as require the development and implementation of regulatory initiatives, detrimental ecological effects, and measurement and monitoring challenges. On the other hand, the enormous sink capacity of abiotic methods—thousands of Pg C—is frequently calculated to surpass the reserves of fossil carbon. Systems that are abiotic and biotic complement each other [45]. Fig 3 gives an overview of carbon sequestration practices.

6. Carbon sequestration practices

Strategies for boosting the soil carbon pool include soil restoration and woodland transformation, cover crops, no-till farming, nutritional requirements management, cultivation and sludge application, enhanced feeding, water processing, effective farming, agroforestry techniques, and growing energy-producing plants on unused land. Practices include reduced tillage, crop residue incorporation, field application of compost and sludge, and cover crop or leguminous crop rotation. A mutually beneficial strategy for enhancing livelihoods and reducing the impact of climate change in the area is carbon capture and storage through modified agricultural management techniques [46].

6.1. Agroforestry

As a carbon sequestration option, agroforestry has attracted a lot of attention. For "secure" storage, carbon sequestration in agroforestry primarily includes the absorption of atmospheric carbon dioxide during the process of photosynthesis and the subsequent incorporation of secured carbon into vegetation, debris, and particulates of soil. Agroforestry is the deliberate development of shrubs, crops, or animals in connected combinations [47]. It can boost soil organic matter by boosting carbon contributions from increased biomass efficiency and minimizing carbon losses, thus leading to an overall transfer of carbon from the atmosphere to the soil and thereby reducing climate change [48-49]. Agroforestry systems act as powerful carbon sinks, holding significantly more atmospheric CO2 than traditional croplands and pastures [50]. Agroforestry biomass production can reduce atmospheric CO_2 increases by substituting fossil fuels with renewable resources and biomass fuels [51]. It has also been incorporated into international initiatives like REDD+, which emphasizes the importance of preservation, beneficial forest management, and the improvement of forest carbon stocks in mitigating and adapting to climate change [52]. Its true power lies in its multifaceted approach to sustainability. It fosters healthy landscapes, protects biodiversity, and empowers communities [53-54]. Along with climatic benefits, it can aid in rural growth. improved habitat for wildlife, insects, and pollinators. Fig 4 provides a visual representation of both direct and indirect services of agroforestry [55-58].

6.1.1. Perennial plants

These include shrubs like Prosopis cineraria, Ricinus communis, and Simmondsia chinensis, as well as reeds and grasses like Arund and plants like Azadirachta indica, Eucalyptus microtheca, Acacia saligna, Moringa oleif era, Pongamia, Eucalyptus camaldulensis [59]. Lucerne and miscanthus are examples of perennial crops that can provide higher carbon inputs than annual varieties due to their prolonged vegetative life and continuous soil cover [60-61]. Compared to annual crops, perennials' longer growing seasons and higher photosynthetic rates allow them to capture and store much more carbon, and help mitigate climate change [62]. Integrating these crops into a diversified and sustainable system sprouts many positive outcomes such as enriching farmers' livelihoods, nurturing the environment, and cultivating vibrant communities [63].

6.1.2. Jatropha curcas

The plant genus Jatropha belongs to the Euphorbiaceae family. Although the plant can survive in sweltering arid regions and is particularly well suited to severe tropical and subtropical environments, irrigation is still necessary for optimal growth. It is a perennial wild plant that has received very little scientific research up to this point, in contrast to many annual crops that have been explored as a result of decades of domestication. Predictions of biomass generation and storage of carbon were obtained from evaluations made on a 100-hectare (ha) *Jatropha curcas* cultivation in Luxor, Egypt. Luxor's sewage water was used in the experiment [64]. In some humid, arid coastal regions, the consumption of such polluted water appears to be a possibility, because the water supply is inadequate to maintain the size of planned plantations. Extensive use of sewage water is not advised in particularly arid areas due to salinization. When it relates to Jatropha's susceptibility to salinity, existing research yields erratic results. However, According to the research conducted by Rajaona et al. (2012), the data suggests that salt exposure significantly impacted Jatropha plants, altering their canopy growth and CO_2 absorption [59-65]. Based on recent cultivation findings, the *Jatropha curcas* plant is well-suited in excessively severe ecosystems and can flourish independently or in conjunction with other forest and shrub types in hot deserts with sparse rain [66].

6.1.3. Bamboo

Bamboo is an important agricultural and forest plant that rural dwellers in many developing countries maintain and use to fulfill a wide range of economic and socio-environmental requirements. Woody bamboos act as a natural carbon sink, capturing and storing atmospheric carbon dioxide. Bamboo sprouts rapidly, with a growth cycle that lasts 120 to 150 days. Bamboo has incredible carbon capture and storage potential due to its rapid biomass growth and exceptional CO_2 fixation [67]. Woody bamboo should be extensively considered for carbon farming and dealing. Integrating woody bamboo into these markets promotes their cultivation and preservation in agroforestry and forest ecosystems, leading to a more sustainable landscape and additional income for rural populations. Bamboo is important at the forest ecosystem level for damaged land restoration, as a timber alternative, for deterioration administration, and for protecting watersheds [68].

6.1.4. Maintenance of existing forests

Forests contribute significantly to the Earth's carbon cycle by absorbing, conserving, and emitting carbon dioxide. The establishment and oversight of boreal, temperate, and tropical forest and agroforest systems can boost terrestrial biosphere carbon sequestration. Forests play an important role in the global carbon cycle. Forests contain approximately 60% of the terrestrial above-ground carbon and roughly 45 percent of the terrestrial soil carbon. In addition, woodlands account for roughly 90% of the annual carbon exchange between Earth's atmosphere and terrestrial habitats worldwide, or 90 petagrams (Pg) [69]. Forests cover approximately 30% of the entire land mass and act as important carbon sinks in both the upper atmosphere and the soil. In comparison to unmanaged woodlands, significantly maintained forests behave like powerful carbon sources after clearing forests and location-preparation procedures, reaching their maximum carbon-sink strength earlier than lightly managed or unmanaged forests. Forestation measures will increase productivity and may increase "carbon stocks" in the forest in the long run. Farmers use no-till, minimum-till, or conservation tillage to reduce soil disturbance, which typically involves leaving some or all of the residue from the previous crop in a field when planting the current crop [70]. Graph 2 provides data on the average carbon storage capacities of various biomes, such as forests, grasslands, and wetlands [71].

6.1.5. No tillage

These approaches boost the soil's adaptability to irrigation and loss of nutrients, minimize erosion risk, and maintain substantial quantities of carbon in the soil. Reduced tillage methods produce a continuous soil cover, which may reduce erosion [72-73]and mitigate the risk of fertilizer contamination of groundwater [74-75]. No-till agriculture has additional benefits over traditional farming [76]. Among them are reduced sediment loads, more predictable surface hydrology, and increased carbon sequestration. Conservation tillage has boosted efficiency during dry periods on farms in the Midwest region of the United States [24]. A comparative analysis of various agricultural practices revealed that no-tillage exhibited a marginally lower rate of carbon sequestration. Fig 5 visually explains how no-till farming contributes to climate mitigation.

6.1.6. Cover Cropping

Cover crops are used by farmers to improve carbon absorption. The term "cover crop" refers to "a crop that is predominantly employed to reduce erosion, improve soil health, enhance the accessibility of water, smother weeds, help control diseases and pests, and increase biodiversity."[77]. Cover crops, in addition to managing nutrients like nitrogen, offer several advantages for farms, including reduced erosion, improved water penetration, and consuming grazing animals. Additionally, by enhancing biological activity in the soil, cover crops grown on a large scale can trap a substantial quantity of carbon from the atmosphere. Along with cover crops, farmers use agricultural forestry to increase carbon storage. Farmers are turning to deep-rooted crops and natural soil amendments as a strategy to enhance carbon sequestration [78].

Farmers adopt a rotational grazing system where cover crops replace soybeans during fallow periods. Animals graze on these cover crops, returning valuable nutrients to the soil through their manure, creating a sustainable cycle that benefits both plant and animal health [79]. Potential cover crops include "sorghum, a cane-like grass with red-tinted tassels spilling from the tops, mung beans, and green-topped daikon radishes"; Each plant has an exclusive benefit for the soil. "Long radishes break up the soil and draw nutrients to the surface; tall grasses such as sorghum produce multiple fine rootlets, incorporating organic material to the earth's surface; and legumes such as mung beans harbor bacteria that add nitrogen to the soil [80].

6.2. Biochar production

Partially burning resources such as logging slash or crop residue under total or partial air exclusion" is the process that produces biochar. The pyrolysis process transforms biomass into a long-lasting carbonaceous material, effectively trapping carbon dioxide in the soil for 10 to 100 times longer than the original material could manage. [81]. It can be embedded or sprayed on fields; biochar is another method of soil enrichment that has been shown to enhance plants' carbon storage ability. By incorporating biological material that is resistant to microbial decomposition, biochar helps to preserve carbon in agricultural soils [82]. Biochar doesn't boost microbes like other carbon sources, but its impact on soil carbon keeps growing even after you stop adding it. In addition, biochar improves soil aggregation and slows decomposition [83].

A study revealed that incorporating biochar into soil was the most effective method for increasing carbon sequestration, with a mean increase of 41.28%. The effectiveness varied from 33.75% to 49.26%, demonstrating the significant potential of biochar for mitigating climate change. Due to increased carbon dioxide flow, a decline in the rate of carbon breakdown, and soil organic carbon stabilization, the incorporation of biochar into soil resulted in the most prominent carbon sequestration [84]. According to the findings of the research, using biochar increased soil organic carbon by 23% when compared to a control [85]. Fig 6 depicts the production process of biochar, highlighting key steps such as biomass feedstock selection, pyrolysis or gasification conditions, and char optimization techniques. Additionally, it illustrates various applications of biochar, including soil amendment for improved fertility and water retention, water filtration for contaminant removal, and potential use as a renewable energy source or industrial feedstock [86].

6.3. Silvopasture

Silvopasture is an approach to feeding livestock in the woods rather than on farms to improve agricultural efficiency and carbon capture and storage. Silvopasture soil incorporates up to five times the carbon content of managed grazing soil. "Recent times have seen a rise of silvopasture in Latin America," with government financial assistance. Strategic selection of diverse plant species in silvopasture, characterized by their ability to rapidly accumulate biomass, develop extensive root systems, and efficiently store carbon belowground, can significantly enhance the system's overall carbon absorption capacity. Management practices like maintaining stocking rates, rotating livestock, and applying fertilizer can all contribute to increased carbon sequestration in grazing lands [87].

According to the assertions made in the research, converting 3.6 million hectares to silvopasture could capture 5.6 teragrams of carbon per year initially, then 1.1 teragrams for the next 25 years**.** If this land is left to grasslands, it will sequester 3.1 Teragram of CO_2 per year. Among the many established advantages of silvopasture are: reduced nutrient leaching, including phosphate loss; elevated fodder growth and quality, particularly in summer; and minimized heat exposure for animals and forage [88]. Other positive outcomes include increased resource efficiency, reduced fire risk, increased biodiversity, and lower outbreaks of crop diseases and greenhouse gas emissions [89].

6.4. Rotational Grazing

Animals can help with carbon capture and storage. When farmers use rotational feeding, "animals are regularly moved between paddocks, with the period between grazings establishing plant recovery." Permitting crops to recover allows them more time to absorb and process sunlight via the process of photosynthesis. Facilitating cattle to feed suggests "manure and plant debris are dumped into the soil," to decompose and improve the soil's network of microorganisms. Increasing soil carbon percentage may facilitate the development of plants, increase biological matter, and enhance water retention capability, eventually resulting in lower fertilizer input use. Studies have shown that properly managed rotational grazing systems lead to improvements in animal performance, including weight gain, milk production, and overall health [90].

6.5. Geological storage of carbon dioxide

Carbon dioxide is typically stored geologically by injecting it densely into formations of rock below the surface of the Earth. Permeable rock formations that maintain or have previously held fluids such as petroleum, natural gas, or brines, such as depleted oil and gas reservoirs are potential CO_2 storage candidates. Storage formations can be found in both onshore as well as offshore sedimentary reservoirs (natural large-scale depressions in the Earth's crust filled with sediments). The first research on the global potential for carbon dioxide preservation in rock formations was carried out by the IPCC Special Report on CO2 Capture and Storage [91]. Three different rock formation categories that have previously been the subject of extensive research for carbon dioxide geological storage were thoroughly examined by the IPCC SRCCS. The three options included, storing carbon in gas and oil reserves; storing in deep saline dumps; and storing in unmineable coal beds. Despite being a highly attractive option for global carbon dioxide preservation, deep saline deposits remain largely undiscovered in most of the world. Fig 7 gives the different categories or types of carbon sequestration practices.

7. Carbon farming

A Climate Smart Agriculture approach that meets the Intergovernmental Panel on Climate Change (IPCC) Report target by using plants to capture and preserve atmospheric carbon dioxide in the soil. Agroecosystems that maximize economic, ecological, and carbon richness can be created through the application of various carbon-beneficial techniques, and carbon farming is a comprehensive approach to doing so. Temporary carbon storage is the approach in which carbon is stored in the biosphere for certain periods and then released before the onset of the most catastrophic consequences of climate change. After the worst effects of climate change have passed, carbon can be permanently stored [92]. Regenerative agriculture techniques are used in carbon farming, which is a carbon-negative practice, to absorb more carbon from the surrounding atmosphere than it releases. A set of non-destructive farming techniques known as "regenerative agriculture" works to restore soil while managing an area. Carbon farming is effective when carbon losses are outweighed by carbon benefits from better agricultural practices and/or conservation techniques [67]. The approach itself doesn't require additional power, hence carbon farming is more practical and has the potential to remove substantial quantities of carbon dioxide from the atmosphere [93].

By paying farmers to use climate-friendly farm management practices, carbon farming is another business model that aims to increase the mitigation of climate change on a larger scale. Funding sources for supply chains and carbon markets include the organization as well as the administration, as seen in the case of the Common Agricultural Policy. In addition to offering a range of opportunities and risks, these different funding sources also help achieve climate goals for farmers. The rise in popularity of carbon farming in recent years is evidence that agriculture needs to adapt to the changing climate as well as help the European Union meet its environmental objectives. To encourage broader adoption of carbon farming practices, the European Commission announced a "Carbon Farming Initiative" in December 2021 and a legislative framework for certifying carbon reductions by 2022 [94]. To scale up carbon farming in a manner that fulfills resilient climate adaptation and other European Union Green Deal objectives, this research identified possibilities and boundaries related to carbon farming, along with unanswered questions [95]. By employing photosynthesis, carbon farming preserves carbon on Earth so that less carbon leaves a given environment than enters it. The theory behind carbon farming is that plants can increase the amount of biological matter in the soil by absorbing more carbon dioxide through the process of photosynthesis. Carbon farming could be applied to both kinds of landscapes. The deficiency of freshwater supplies or rainfall has made dry coastal areas more catastrophic over the years. The development of resilient plants in harsh weather, technological advancements in the desalination of seawater, and knowledge of how greening deserts affect weather and climate are all considered in our updated assessment of carbon farming. Fig 8 gives a visual exploration of carbon farming capture and storing carbon [59].

8. Carbon farming practices

Growing numbers of farmers in well-developed countries are realizing that agriculture can absorb substantial quantities of carbon from the surrounding environment [24]. Instead of preparing the land before and after the crop cycle, they use Angus cattle, hogs, Katahdin sheep, and chickens to trample and consume the crop residue into their field and to plant seeds in the residue that is still on the soil's surface. Carbon-based farming minimizes the effects of the changing climate on Earth by sequestering carbon and enhancing and sustaining soil, which in turn improves yields for individual farmers. A wide range of regenerative farming techniques [24]can be used to increase a crop's photosynthetic intake, which will help captured carbon move into and stay in the soil. To enhance the land, carbon farmers concentrate on five primary regenerative agriculture techniques that prioritize soil health [96].

Recent research on the production of carbon emphasizes the active role of living plants in removing carbon, as opposed to earlier studies that concentrated on the physical requirements for dead organic matter to physically enter the soil. By directly sustaining soil ecosystems, living plants increase soil carbon. When plants die, their roots store carbon below ground. perhaps more importantly, when plants take carbon from the atmosphere, their roots introduce carbon into the soil, feeding fungi and microbes that enrich the soil [24]. To offset the additional costs associated with switching to carbon farming techniques, funding is needed. The primary expenses incurred by farmers are the time it takes to realize the advantages of carbon farming and the energy required to use organic matter [97].

According to Colorado's carbon producers, there is a three-year "till penalty" that prevents agriculturalists and ranchers from producing at their usual level for the first three years. Since paying back the expenses of converting land to specialized practices like silvopasture can take three to four years, access to finance and knowledge are essential for specialized activities like silvopasture. The energy-intensive process of creating compost and the need for large machinery to shred the material and keep it aerated are further reasons against its use. In addition, it's unclear how much greenhouse gas composting produces or if compost, like synthetic fertilizer, can pollute land when applied [98].

9. Steps needed

A carbon management policy that incorporates trading soil carbon based on regulations must be created. In a similar vein, resource-poor tropical farmers must adopt Risk Management Programs (RMPs) widely. The recognition that soils are vital natural carbon sinks and that land degradation and unsustainable farming and grazing practices release carbon into the atmosphere is growing. Although oceans hold more carbon, soil plays a crucial role as the second biggest reservoir on Earth. While farmers play a critical role in carbon sequestration, they need the right tools. Implementing United States Department of Agriculture (USDA) backed carbon farming practices empowers them to actively contribute to a sustainable future [99].

10. Farmers Approach

Soil organic matter (SOM), also known as soil organic carbon (SOC), is a crucial component that plays a vital role in enhancing soil health through various direct and indirect mechanisms. Farmers need to be convinced to improve soil preservation and resource utilization to reap the full benefits of agriculture. Equipping farmers with the means to assess their soil health empowers them to identify issues, find solutions, and refine their management strategies, leading to improved outcomes. Two instances of farmer-led soil analysis are earthworm counts [100]and visual inspection of soil framework [101]. It is common to see pioneer land managers conducting independent experiments to identify underlying issues [102]. Engaging farmers directly leads to improved soil health, regardless of financial incentives [103].

11. Implementation methods of carbon farming

11.1. Establishing a Volunteer Farmer Network

A small band of agricultural workers who explore green-farming techniques in their chosen areas and communicate with investigators to address further investigations is an essential tool in the Carbon Action effort. An article in Maaseudun tulevaisuus, the most influential agricultural journal in the country, and the newsletter of the Central Union of Agricultural Producers and Forest Owners (MTK) helped to choose cooperative cultivators in December 2017. Approaches were received from 130 enthusiastic cultivators in a few days, exceeding the initial target of 100 farms. The final selection of 105 farmlands represented 0.2% of all landowners in Finland, as 25 of the enthusiastic landowners were not willing to participate in multiyear research. The 105 volunteer farmlands exemplified the variety found in Finnish farming. Both organic (46%) and traditional (54%), agricultural practices included raising animals and producing grains and vegetables. The most prevalent kind of soil was clay (55%) and was followed by organic soils (4%), silt and sand (41%), and clay [104]. Larger farms than typical farms were represented in the group, as were more organic farmers. These farmers excel at both active production and strategic growth, making them a model for others. Based on the suggestions, farmers would need to take the following actions [105].

11.2. Empowering farmers with carbon plans

The volunteer farmers enthusiastically tested new methods, paving the way for others. Before they put their intentional carbon-farming plan into action, some time was taken to develop it. Background information, including their existing knowledge, intentions, approaches, and daily routines, was provided. In 2018, Peasants learned about carbon farming in a two-day course. Participants not only learned the science but also gained practical skills in carbon farming through hands-on training with experienced farmers. Farmers had the chance to form connections with researchers and other farmers on several levels during the session. The training empowered farmers to choose their unique "carbon pathway" considering their desired outcomes, soil health, and available carbon sequestration strategies [106].

After the workshop, peasants were given a list of measurements and directed to choose the one that best suited their trial field and approach. To facilitate learning from participating researchers as well as from one another, farmers were randomized to learning groups depending on the metrics they had selected. The online platform Slack was utilized to manage the groups and conversations. Lastly, the peasants were directed to come up with a plan for raising the field plot's carbon stock over the following five years. All Carbon Farming Plans emphasized boosting soil carbon through crop rotation, cover crops, organic practices, and targeted management techniques. Farmers actively assessed and analyzed their soil health to modify their Carbon Farming Plans [107].

Professionals from various sectors reviewed the plans in early 2019. The panel comprised experts from the Carbon Action steering group [104]. Approximately fifty percent of the steering group was present for the review process. 15 participants, representing academia, research, and on-the-ground expertise, participated. The experts worked while attending their five sessions together. The panel reviewed all 105 Carbon Farming strategies, proposing adjustments for effective carbon emission tracking and achievement.

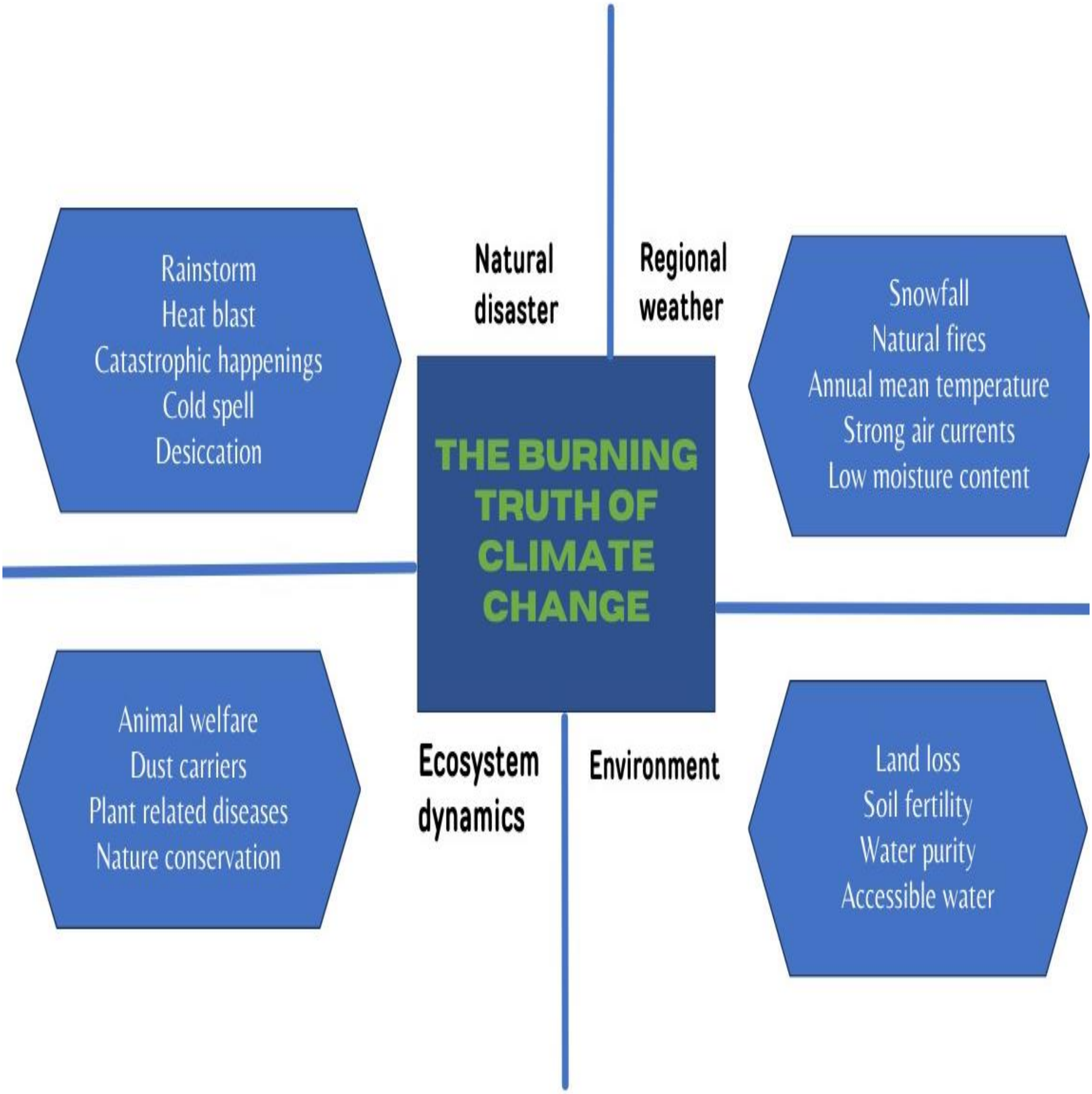


Figure 1. Our Planet in Peril: Climate Change and its Consequences

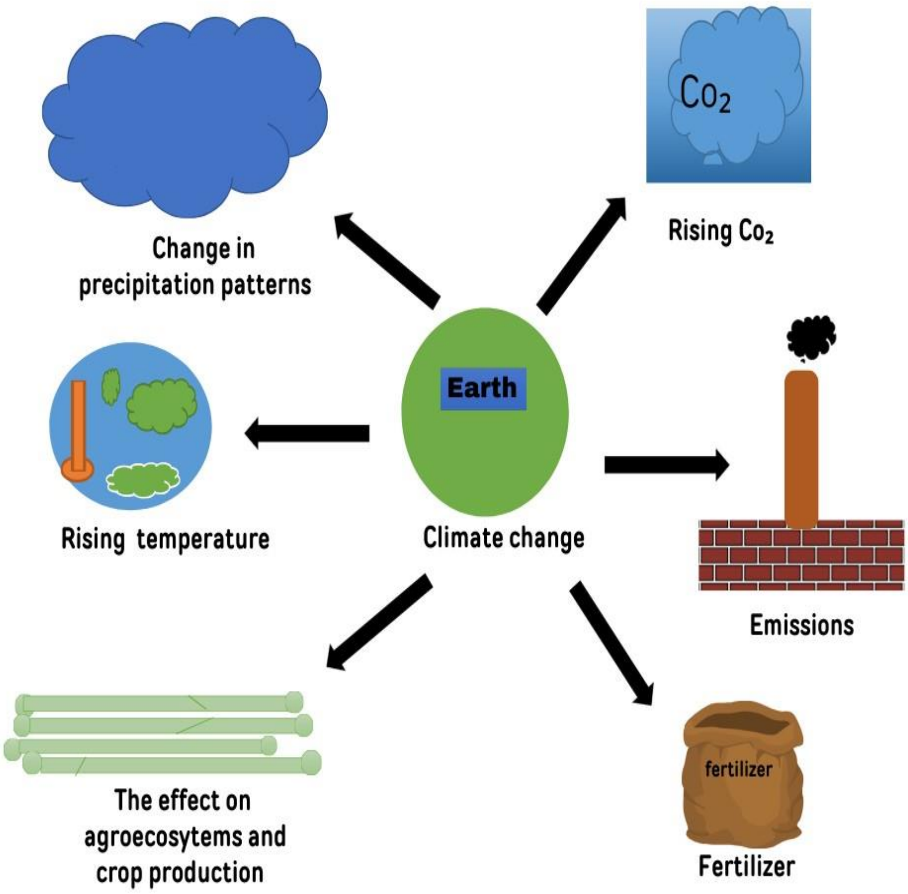


Figure 2. Heatwaves & Climate: A Threat to Agriculture

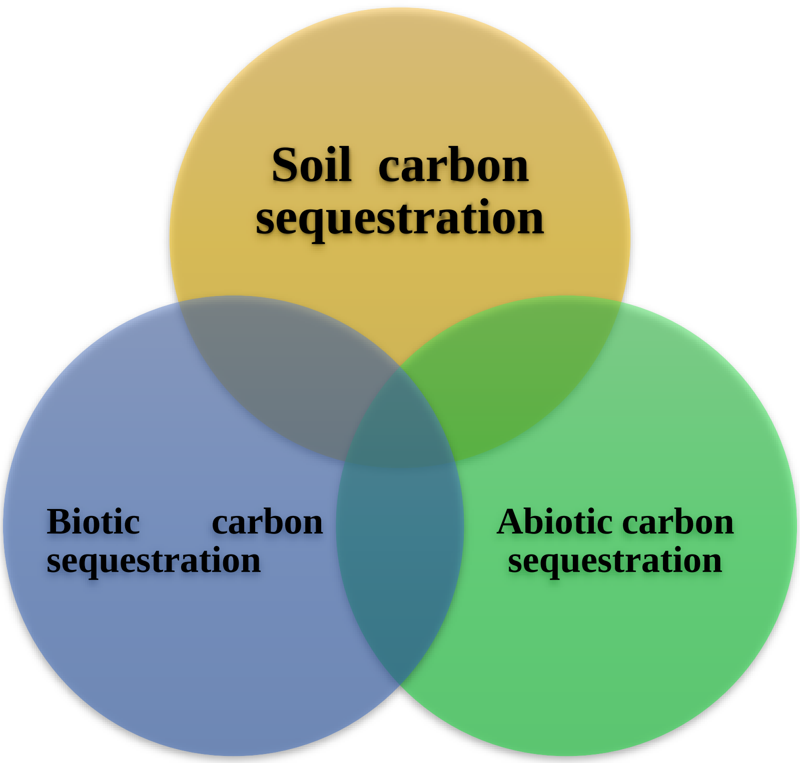


Figure 3. Types of soil carbon sequestration

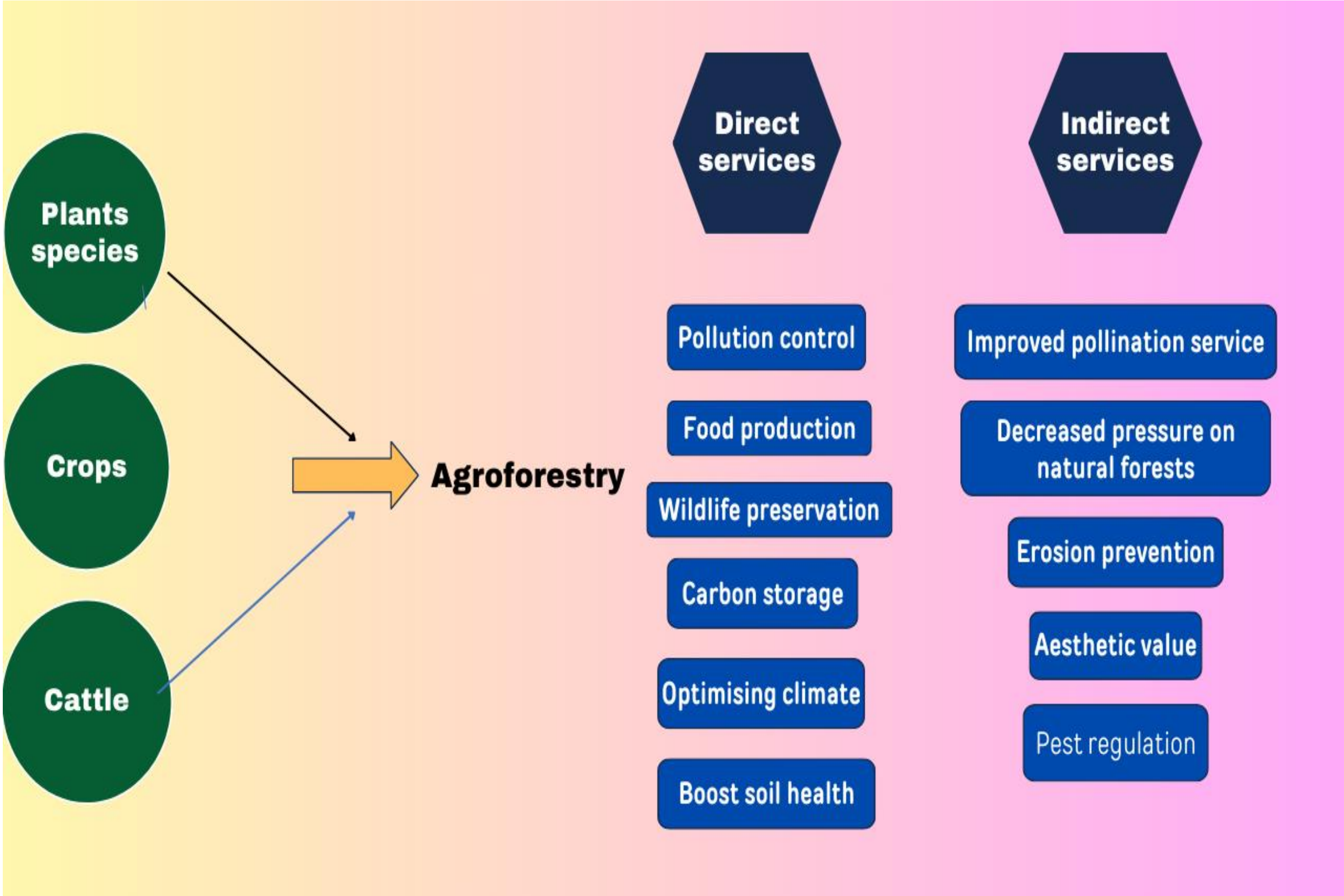


Figure 1. Farming with Nature: Agroforestry's Direct and Indirect Rewards

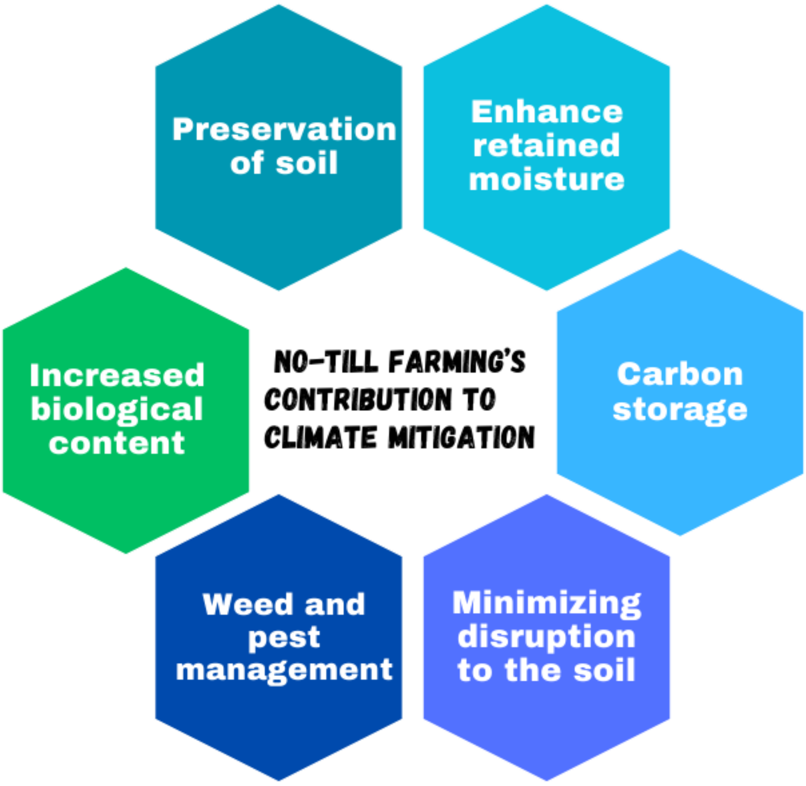


Figure 5. No-Till's Climate-Smart Revolution

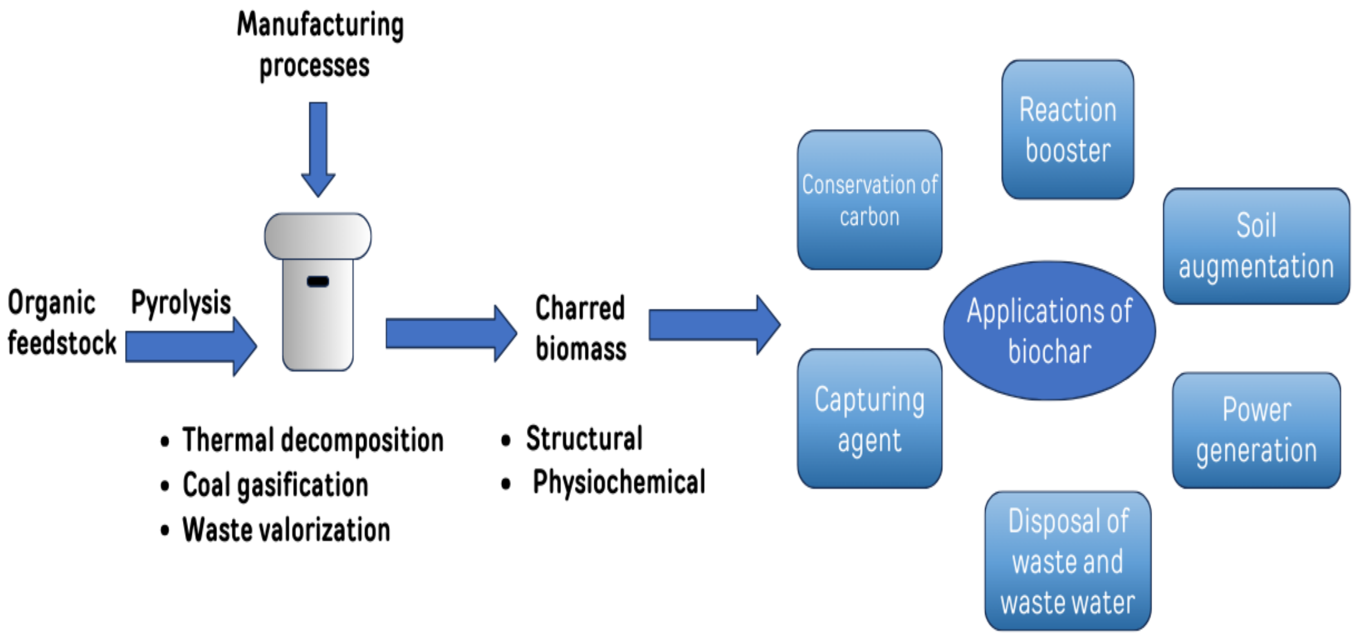


Figure 6. Biochar's Transformation from Waste to Resource

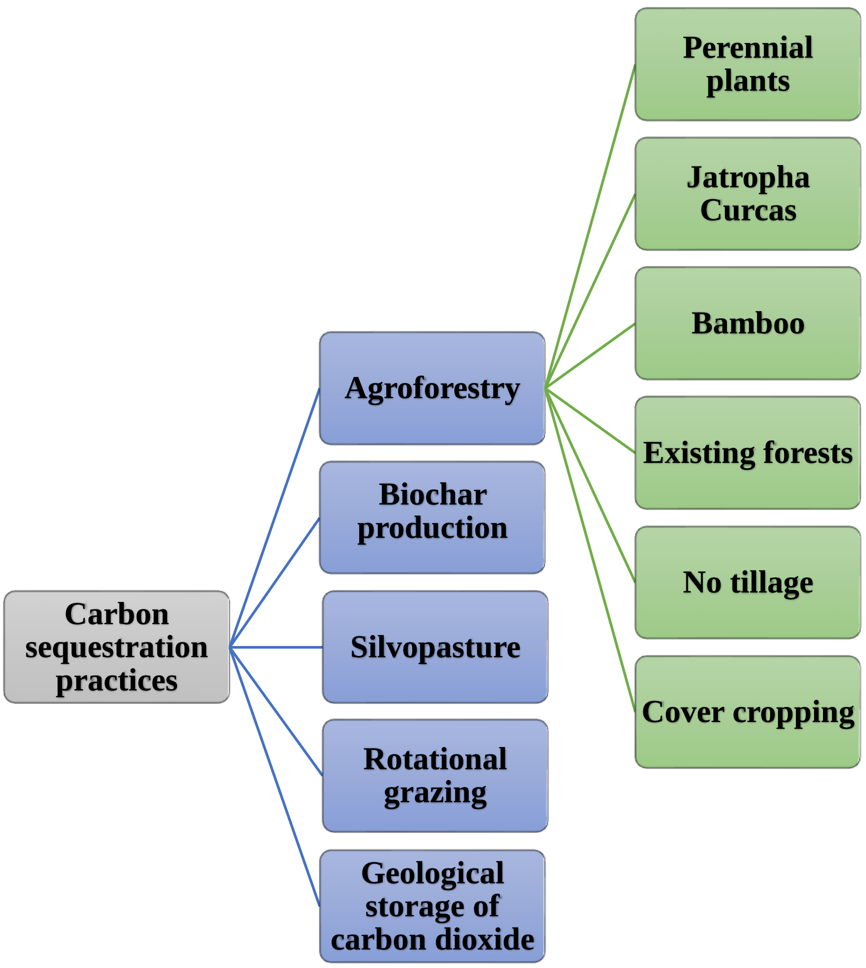


Figure 7. The Diversity of Carbon Sequestration Strategies

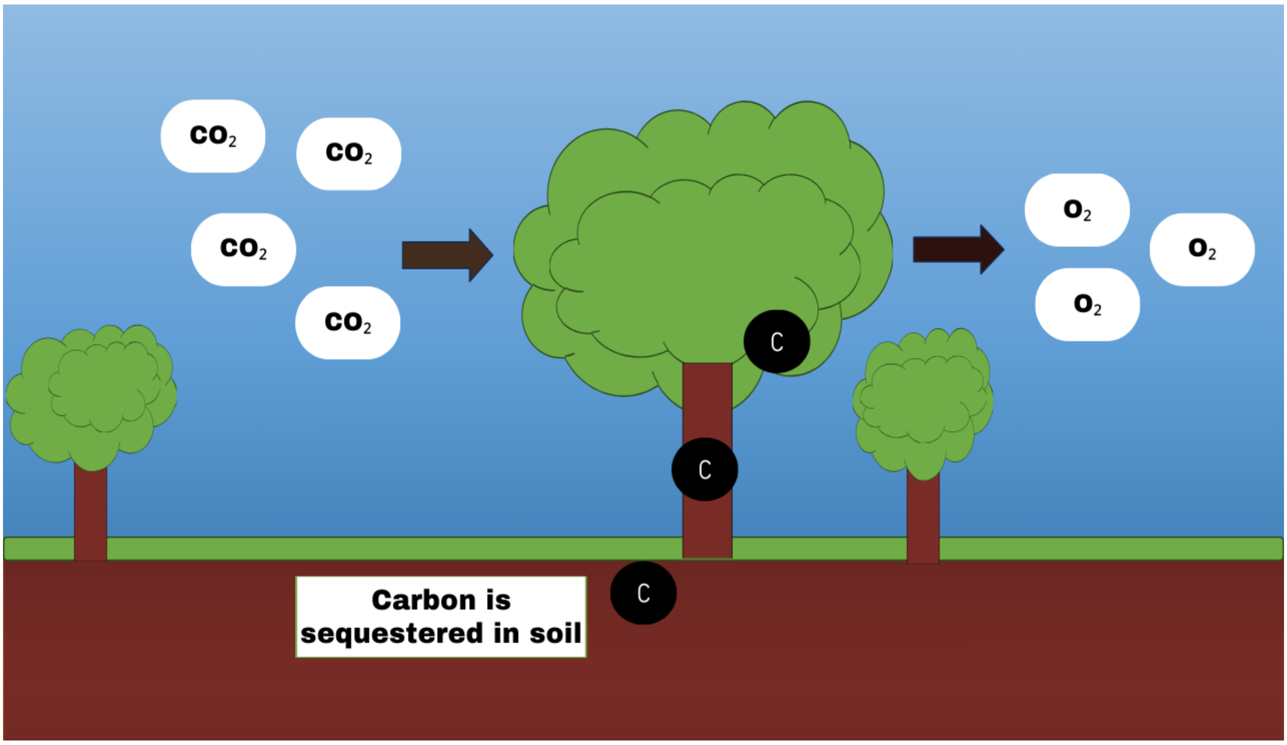


Figure 8. Carbon storage process in carbon farming

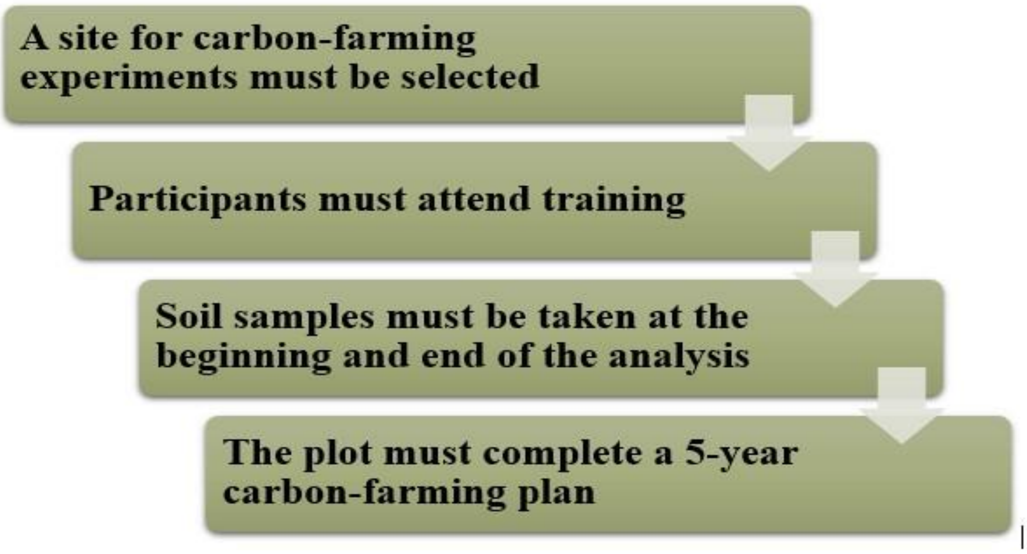


Figure 9. Farmers' Role in Carbon Sequestration

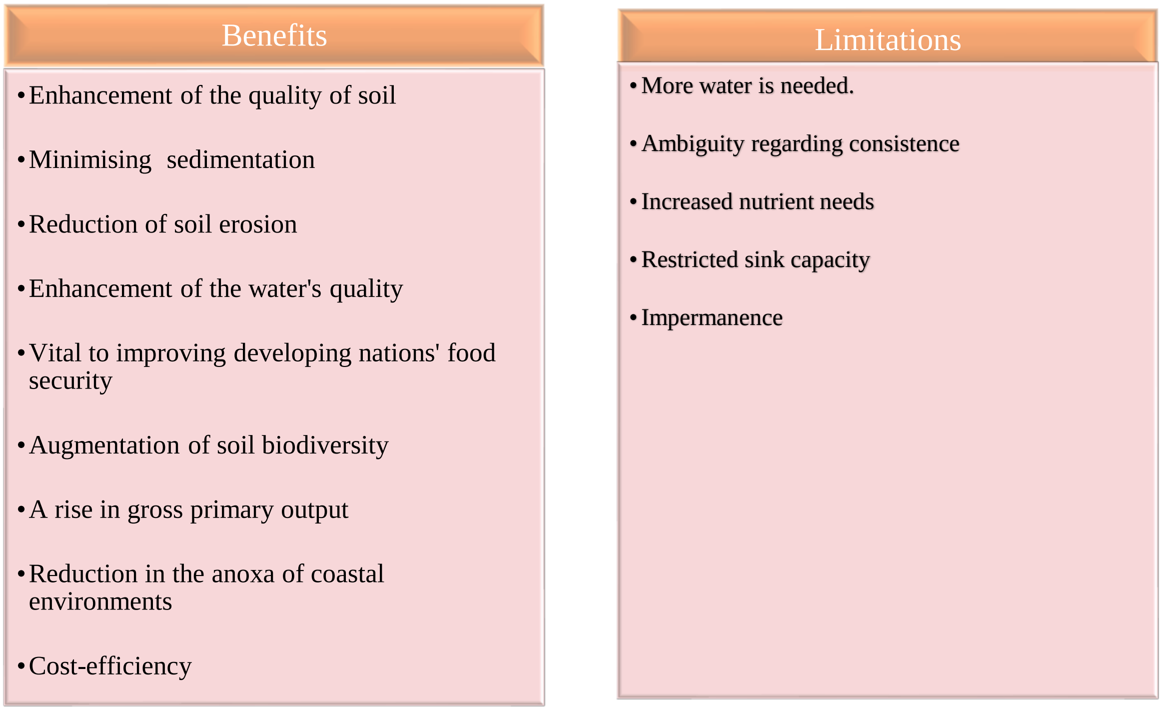
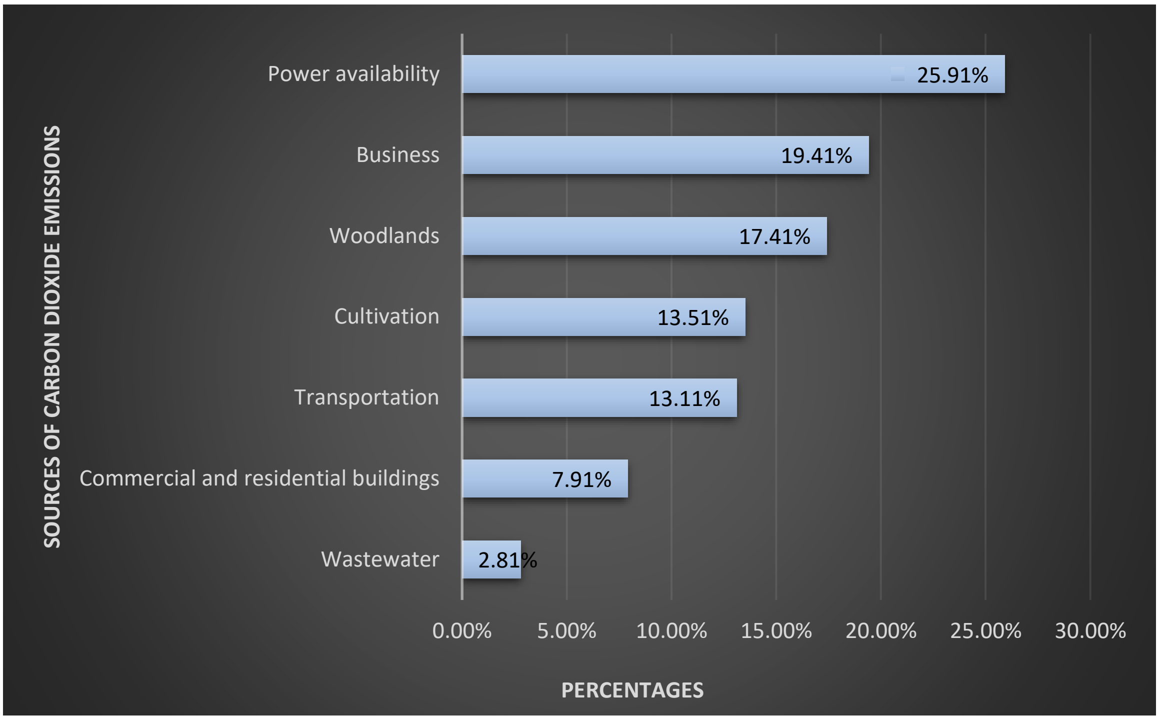


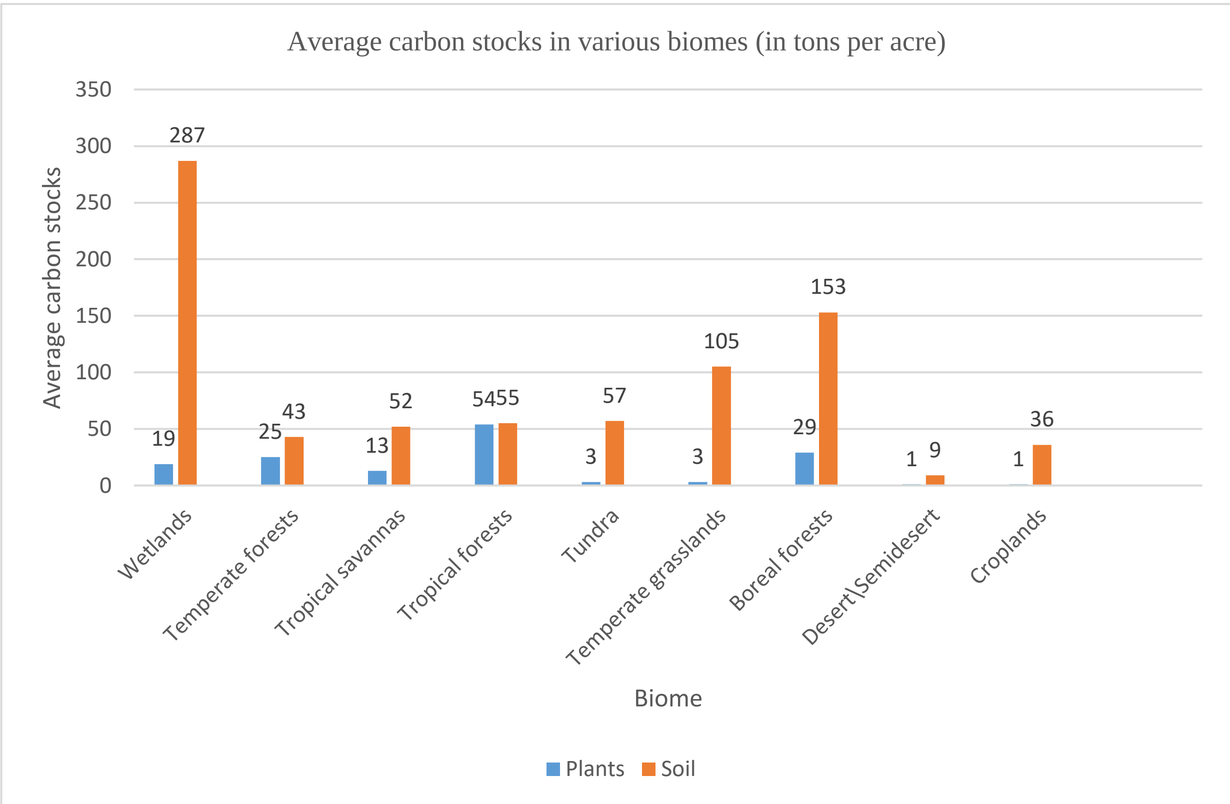
Figure 10. Pros and cons of carbon farming

Table 1. Percentages of carbon dioxide emissions from different sources

Sources	Percentage
Transportation and preservation	10.70%
Farming	8%
Energy Production	13.60%
Electrical power	14.80%
Development	11.40%
Research	7.1%
Water utilization	18.3%
Domestic	4.4%
Services sectors	11.7%



Graph 1. Percentages of different sources of CO_2 emission



Graph 2. Comparing average carbon stocks across biomes.

This learning process benefited both experts and farmers, fostering new knowledge and collaboration. Once approved by the committee of experts, the plans were put into action by farmers on their own. At this point, knowledgeable farm advisors are brought to help the learning groups carry out the modifications and carry on with the learning process. Farmers implemented the strategies, tracking progress through their notes and annual soil health testing by researchers [108].

11.3. Soil sampling, nutrient analysis, and estimated carbon balance

To initiate the experiment, the landowners obtained samples from designated spots within each test and control plot, utilizing three geographically referenced points per area. Ten land samples were taken at 10-meter intervals around a 10-meter circle. Samples were frozen for future carbon analysis, and a pooled sample was utilized to establish the initial parameters of the study. Pooled samples were analyzed using the Finnish method [ammonium acetate and Ethylenediamine tetraacetic acid (EDTA)] for key elements, organic matter, plant nutrients, pH, and soil quality. The objective was to determine potential nutrient constraints that might hinder efficiency and soil organic matter buildup and identify the fields' initial state [109]. Farmers were given the results of the soil tests, as well as calculated lime and fertilizer recommendations. Fig 9 below highlights the collaboration between farmers and experts in adopting carbon farming practices [110].

12. Carbon farming projects

12.1. Colorado Carbon Sequestration Pilot Project

Organic matter plays a major role in Colorado, where county-level carbon farming research is growing. To find out if applying carbon to rangeland can sequester carbon, Boulder County, Colorado's Carbon Sequestration Pilot Project is testing different carbon farming techniques [24]. Additionally, the research aims to determine which practices—composting cover crops, no-till farming, or building windbreaks—should be implemented first to effectively incorporate carbon farming practices into cropping systems in the Northern Front Range. The Be a Carbon Farmer Project in Boulder County is searching for volunteer families to plant a particular list of plants, donate $50, and monitor carbon sequestration in their vegetable gardens for three years [24].

12.2. Saguna Rice Technique Project (SRTP)

Agriculture is the main contributor to climate change in developing countries, accounting for 28% of their GHG emission. It is the third-biggest greenhouse gas emitter in the globe. In two districts of Maharashtra, Shekar Bhadsavale and Emmanuel D'Sliva launched a new carbon farming initiative in India, starting with 20 farmers in 2019. The peasants that were selected were usually small-scale farmers who farmed rice, string beans, and other cover crops using no-till methods on plots of land that weighed one hectare or less. Several farmers have reported that growing rice without tilling the soil has increased their income and yield. By preserving more organic carbon in the soil, the Saguna Rice Technique, a type of zero till agriculture, boosts soil quality in addition to increasing farm productivity and income. Bhadsavale Shekar. The Saguna Rice Technique, developed by Shekar Bhadsavale, has been embraced by over a thousand farmers across multiple states of developing countries. Ten years prior, Emmanuel D'Sliva established the first carbon credit programs by planting trees in forty-four native villages.

13. Carbon Trading

Carbon trading is the exchange of units of reduced atmospheric carbon dioxide. Carbon Emission Reduction (CER) Certificates are awarded to nations that lower their carbon emissions; these certificates are traded and are known as carbon trading. Among the most significant GHGs and a key factor in global warming is carbon dioxide. Developed as well as developing nations view carbon dioxide as politically significant, and it now has a "market worth" for international trade. To address the problem of reducing emissions by destroying companies and countries to achieve regulatory goals, the Kyoto Protocol developed an international system for trading carbon units [111]. To exchange carbon units, it is necessary to show via carbon budgeting that either more carbon is fixed or emissions are reduced. The total of all carbon compound exchanges (inflows and outflows) that occur during the carbon cycle between the earth's carbon sinks—such as the atmosphere, land, and water bodies—is known as carbon budgeting. The exchange of certificates that represent different approaches to achieving carbon-related reduction goals is known as carbon trading, or more broadly, emissions trading. Countries can obtain Carbon Emission Reduction (CER) Certificates by completing Clean Development Mechanism (CDM) projects, or they can obtain ERUs (Emission Reduction Units) by completing Joint Implementation projects [112].

14. Carbon Farming Costs and Benefits

Healthy soil carbon boosts both crop yields and the environment by improving water and nutrient retention, and strengthening soil structure. Even with unpredictable weather patterns, carbon farming practices could still lead to higher crop yields. Regenerative farming practices result in financial savings for farmers. When contrasted with neighboring agricultural operations, farmers, for instance, estimate cost savings of up to 20%, decreased energy use, and millions of gallons of water saved [24]. When contrasted with other conservation techniques like farmland rehabilitation, conservation agriculture, and managed grazing, regenerative agriculture offers the most potential for sequestering carbon dioxide [113]. Carbon farming goes beyond production, boosting soil health with enhanced composition, reduced degradation, improved water access, and richer nutrients. Fig 10 below summarizes the positive and negative consequences of employing carbon farming techniques [114].

15. Limitations

The current methods for measuring and verifying carbon sequestration in soil present a significant barrier to wider adoption due to their high cost, time-consuming nature, and reliance on specialized equipment and trained personnel. Expensive checks block the path for wider carbon farming adoption. The stored carbon in soil can be released back into the atmosphere through disturbances like tillage, erosion, or land-use changes. This raises concerns about the permanence of carbon sequestration achieved through farming practices. Carbon farming mitigation ought to be supplementary and shouldn't impede other sectors' efforts to combat climate change [115]. The effectiveness of soil carbon sequestering techniques or biophysical limitations, in some cases, as well as financial constraints, cultural concerns, an unclear policy environment, and lack of knowledge or experience, are important obstacles. To find out what will encourage uptake if the policy context changes, more research will be necessary. Fig 8 below summarizes the positive and negative consequences of employing carbon farming techniques [116].

16. Conclusions

Innovative farming practices are being promoted due to the growing demands of humanity and the ensuing effects on the surroundings. Adopting less intensive and strategically planned agricultural practices can enhance the resilience of agricultural output in the face of climate change. Sustainable cultivation methods for a changing climate require a thorough understanding of the interactions between agricultural practices and the surrounding environment. In this scenario, carbon farming emerges as a holistic and sustainable solution for land management, offering a multitude of benefits for both society and the environment. Combining trees, crops, and animals in agroforestry boosts food production and security while lowering greenhouse gas emissions and storing carbon, though effectiveness varies with local context. Agroforestry ecosystems can be assessed using a range of environmental metrics, contingent on energy consumption, efficiency and yield, and production methods. Although agroforestry provides valuable environmental benefits, silvopastoral systems may offer a more potent solution for carbon storage and emission reduction based on current research findings. Furthermore, organic carbon stocks in the soil are effectively retained by carbon farming systems. Compared to single-crop farming, these systems accumulate significantly more soil organic carbon (SOC), which leads to improved soil quality and fertility. Nevertheless, for a variety of reasons, farmers do not value carbon farming despite its many benefits. Thus, to reduce the use of unsustainable farming practices and to urge ranchers to use carbon farming for agricultural production and soil management, knowledgeable advisory services are needed.

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