

Terrestrial Carbon Sequestration as a Climate Change Mitigation Activity

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Abstract

An unprecedented increase in the atmospheric concentration of carbon dioxide (CO₂) from fossil fuel combustion and land use change necessitates identification of strategies for mitigating the threat of the attendant global warming. However, the challenges of climate change can be effectively overcome by the storage of carbon in terrestrial carbon sinks viz. plants, plant products and soils for longer periods of time. Carbon sequestration in this regard is truly a win-win strategy. It restores degraded soils, enhances biomass production, purifies surface and ground waters, and reduces the rate of enrichment of atmospheric CO₂ by offsetting emissions due to fossil fuel. Carbon sequestration is a growing research topic that addresses one important aspect of an overall strategy for carbon management to help mitigate the increasing emissions of CO₂ into the atmosphere. Thus, terrestrial ecosystems being recognized as an important component of Carbon (C) cycle, have gained importance owing to its potential to sequester carbon. This paper aims at presenting an overview of estimates on carbon sequestration potential of varied terrestrial ecosystems.

Keywords: Carbon sequestration; Carbon dioxide; Biomass; Fossil fuel; Soil; Forest; Grassland

Introduction

There is a growing awareness all over the world about the adverse impact of greenhouse gas emission and the consequent climate change. At the dawn of third millennium, greenhouse gases are widely accepted by international scientific community as one of the potential threats to the existence of human kind coupled with extinction of other flora and fauna. The gases with special optical properties that are responsible for climate warming include carbon dioxide (CO₂), water vapors, Methane (CH₄), Nitrous oxide (N₂O), Nitrogen oxides (NO_x), stratospheric ozone (O₃), carbon monoxide (CO) and Chlorofluorocarbons (CFC's). Among all these greenhouse gases, CO₂ plays a lead role as it contributes to 50% of the total greenhouse effect [1]. Though fundamental to life on earth, concentration of atmospheric CO₂ has increased from a pre-industrial level of 280 ppm to 390 ppm and is increasing at a rate of 1.5 μL yr⁻¹ giving rise to an alarming situation [2]. However, the challenges of climate change can be effectively overcome by the storage of carbon in terrestrial carbon sinks viz. plants, plant products and soils for longer periods of time. In terrestrial system, in which carbon is retained in live biomass, decomposing organic matter and soil play an important role in the global carbon cycle. Carbon is exchanged between these systems and the atmosphere through photosynthesis, respiration, decomposition and combustion. Human activities are responsible for making changes in carbon stocks in these pools by changing the land use pattern of any area [3]. The land use/cover changes have caused a significant release of CO₂ to the atmosphere from the terrestrial biota and soils, soil being a major source of atmospheric CO₂. However, adoption of carbon sequestration measures in the soil can considerably reduce the rise in atmospheric CO₂ level [4]. In order to sustain the amount of carbon in the soil, the identified ecological factors should be enhanced through the application of good forest and land management practices, such as creation of vegetal buffer zones around farmlands, zero-tillage practice, mulching, retaining of forest slash and crop residues, fertilizer application, elongation of fallow periods, crop rotation and tree planting initiatives in degraded areas among others. Through these healthy practices, forest vegetation can be maintained; thereby increasing the carbon stock of forest soil by reducing direct loss to the atmosphere [5].

There are estimates that terrestrial ecosystems could sequester

significant quantities of carbon over the next 50 years [6]. The maximum amount of carbon is sequestered by the plantation based scenario and thus is the best land use pattern which fulfils the future demands in a sustainable manner [7]. Forests are the sites for long-term carbon storage on earth [8] and their sequestration can be enhanced by their proper management [9]. Biomass and carbon in India's forests have shown a marginal increase [10] and soil carbon sink in India's forest soils can be increased by bringing more and more waste land, degraded land and other unusable land under afforestation program [11].

Carbon Sequestration By Terrestrial Ecosystems

A study was carried out to estimate the creation of carbon sinks and sequestration achieved in community projected forests of Sambalpur forest division, Orissa, India [12]. Their results have shown that 1.53 to 3.01 tonnes of carbon is being sequestered per ha per year, with only protection, which can be enhanced through proper implementation of the management prescriptions. The study suggests that Joint Forest Management in India could be effectively utilized for carbon sequestration so as to mitigate climate change. Forestry can play a major role towards increasing the global carbon sequestration if the world's forest could be managed properly with due importance to afforestation and reforestation and carbon management in existing forests [13,14]. Forest transition also contributes to carbon sequestration besides conserving biodiversity and improving local and regional environment [15]. Woodbury et al. [16] worked on the estimation of carbon stocks and sequestration rates in U.S. forests, including effects of land use change and used the data on the production of wood products and emission from decomposition to estimate carbon stocks and sequestration rates in wood products and landfills. The result revealed that the pools with largest carbon stocks were not the same as those

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with the largest sequestration rates, except for the tree pool. The study recommends that in the near future, the U.S. forests will continue to sequester carbon at a rate similar to that in recent years. However, this carbon assimilation is altered by environmental disturbances like wild fires and hurricanes by decreasing carbon uptake or increasing carbon release into the atmosphere [17].

Agriculture is one of the high priority sectors where the impacts of climate change exceed tolerance limits with implications for the livelihoods of millions of smallholder farmers dependent on this sector. Agroforestry interventions, because of their ability to provide economic and environmental benefits, are considered to be the best “no regrets” measures in making communities adapt and become resilient to the impacts of climate change. Agroforestry practices like alley cropping and silvopastures have the greatest potential for conserving and sequestering carbon because of the close interaction between crops, pasture, trees and soil [18]. Therefore, agroforestry systems have a direct near-term carbon storage capability in trees and soils, and have the potential to offset immediate greenhouse gas emissions associated with deforestation and shifting cultivation [19,20]. The important elements of agroforestry systems that can play a significant role in the adaptation to climate change include changes in the microclimate, protection through provision of permanent cover, opportunities for diversification of the agricultural systems, improving efficiency of use of soil, water and climatic resources, contribution to soil fertility improvement, reducing carbon emissions and increasing sequestration, and promoting gender equity [21,22]. The International Panel on Climate Change (IPCC) estimates that the current worldwide area under agroforestry is 400 million ha, which results in a carbon gain of $0.72 \text{ Mgha}^{-1} \text{ year}^{-1}$. It is estimated that the potential carbon gain could increase to $26 \times 10^6 \text{ Mgha}^{-1} \text{ year}^{-1}$ by 2010 and to $45 \times 10^6 \text{ Mgha}^{-1} \text{ year}^{-1}$ by 2040 [23]. The use of agroforestry crops is a promising tool for reducing atmospheric CO_2 concentration through fossil fuel substitution. In particular, plantations characterized by high yields such as short rotation forestry are becoming popular worldwide for biomass production and their role acknowledged in the Kyoto Protocol [24]. Oelbermann et al. [25] reviewed carbon sequestration in tropical and temperate agroforestry systems. Their study revealed that despite two crop rotations and greater organic matter input in tropical agro forests, does not necessarily increase the soil organic carbon (SOC) pool significantly when compared to a temperate system of similar age. A study of carbon storage and nitrogen cycling in silvopastoral systems on sodic soils was carried out by Kaur et al. [26]. They observed that compared to ‘grass-only’ systems, soil organic matter, biological productivity and carbon storage were greater in the silvopastoral systems. Of the total nitrogen uptake by the plants, 4 to 21 per cent was retained in the perennial tree components and nitrogen cycling in the soil-plant system was found to be efficient. Thus, they suggested that the silvopastoral systems, integrating trees and grasses, hold promise as a strategy for improving highly sodic soils.

A comparison of carbon sequestration rates and total carbon stock pile in degraded and non-degraded sites of Oak and Pine forest of Kumaun Central Himalaya was made by Jina et al. [27]. The study confirms that the sequestration of CO_2 in non-degraded forests is significantly greater than the degraded forests. The study further suggests that community forests should be encouraged because of their significance of becoming the sink for increased CO_2 worldwide. Schafer et al. [28] studied the effect of elevated levels of CO_2 on the carbon assimilation and allocation of pine forests. Their study confirms that under elevated levels of CO_2 , net ecosystem production increased by $272 \text{ g C m}^{-2} \text{ a}^{-1}$; 44% greater than under ambient levels of CO_2 . The

majority (87%) of this carbon was sequestered in a moderately long-term carbon pool in wood, with the remainder in the forest floor–soil subsystem. Plant species which are less vulnerable to climate change have a greater potential of carbon sequestration. This view is supported by Negi and Chauhan [3], who studied the greenhouse gas mitigation potential by Sal (*Shorea robusta Gaertn F.*) forests in Doon valley, Uttarakhand, India. Sal, a less vulnerable species to climate change provides a positive response to climate change shown by its increased productivity and thus has the capability to sequester greater amounts of carbon. Davey et al. [29] conducted a study on poplar trees and came to the conclusion that these trees are well suited to elevated levels of CO_2 and can be grown for long term storage of carbon in wood. Land carbon budget and sequestration potential of the natural forests of Madhya Pradesh, India was estimated by Pande [8] with the aim to prepare a stand and state level carbon budget for the state and to describe the temporal carbon dynamics of these forests. Besides, an attempt has also been made to explore the possible potential of open canopy forests as potential sites for future carbon sequestration. The study reveals that open canopy forests have a great potential for sequestering more and more carbon. Ramachandran et al. [30] estimated carbon stock in a natural forest area of Kolli hills, part of the Eastern Ghats of Tamil Nadu, India. The total biomass, both above and below ground, was calculated and the total carbon stock estimated. Likewise, they estimated the sequestered soil organic carbon. The study reveals that the lesser soil organic carbon indicates that the forest area is severely affected by degradation due to various need based forestry practices and anthropogenic disturbances. The study further suggests that at national level, carbon data bank is envisaged for all types of forests in India to study the temporal change and carbon sequestration potential for better management of forests. Urban forests are very important as far as carbon sequestration is concerned. They have a great potential of carbon sequestration which can be further increased by their proper management [31,32]. An attempt was made by Singh et al. [33] to collect and analyze data to present the state of carbon stocks in Common Access Resources (CAR's) of some selected areas in the states of Rajasthan and Gujarat, India and also their potential of carbon sequestration. The study confirms that carbon sequestration potential of CAR's is at par with the demand of the local needs for fuel and fodder. It has been found that carbon sequestration potential in these CAR's is $6.13 \text{ Mg ha}^{-1} \text{ yr}^{-1}$.

In addition to CAR's, community projected forests, rubber plantations, home gardens, boundary plantings and roadside trees, which are created to meet industrial and social needs, also help to sequester substantial quantities of carbon in their biomass, long-lasting wood products and soil at any given point of time [12,21, 34-37]. Bamboo forests play an important role as far as carbon sequestration is concerned. The bamboo forests are also included in the list of eligible afforestation and reforestation projects under the Clean Development Mechanism [38]. As a major non-wood forest product and wood substitute, bamboo is of increasing interest to ecologists owing to its rapid growth and correspondingly high potential for mitigating climate change. Compared with other types of forests, the bamboo forests generate different ecosystem services, such as carbon storage, and water and soil conservation because of their special root reporting regeneration strategy and selective cutting utilization system [39]. Besides, bamboo forests also aid in cleaning air, reducing noise pollution and maintaining wildlife biodiversity. Their carbon sequestration potential and other services can be enhanced by their proper management [40]. Land areas set aside to be preserved in their natural habitat and designated as national parks play a significant

role in sequestering carbon [41]. Perks et al. [42] studied the carbon sequestration benefits of new native woodland expansion in Scotland and observed that expansion of woodlands by planting more and more trees contributes to climate change mitigation by increasing the overall carbon sequestration rate. Fallow vegetation provides a significant carbon sink as the carbon stocks of vegetation and the underlying solum increase with advancement in age of the vegetation and hence improving carbon sequestration with advancement in the age of the fallow cycle [43]. Trees Outside Forest (TOF) play an important role in global carbon cycling, since they are large pools of carbon as well as potential carbon sinks in the places which have less forested areas [44]. Bouchard et al. [45] studied the potential of roadside vegetated filter strips and swales for their carbon sequestration potential. They observed that the carbon density of roadside vegetated filter strips and swales was comparable to literature values for grasslands, and accumulation rates from this study were similar to grassland and turf values. They suggested that grasslands could be surrogate land use for roadway vegetated filter strips and swales.

Forests being renowned as an important component of Carbon (C) cycle and have gained importance owing to its potential to sequester Carbon. As a result large-scale forest conservation and land developmental programmes have come up at regional, national and world level [46]. Carbon sequestration in forests occurs in living above ground biomass and living biomass of soil (roots and microbes) and recalcitrant organic and inorganic Carbon in surface soil. Worldwide forests contain 54% of the total global Carbon pool (2200 Gt) of the terrestrial ecosystems [47], while as the total Carbon content of forests has been estimated at 638 Gt intended for 2005, which is more than the amount of carbon in the total atmosphere [48,49]. But, the forestry sector is one of the important sources of CO₂ emissions that accounts for 1.6 ± 0.8 Gt of Carbon annually. This constitutes 20% of the global CO₂ emissions [50]. It is noteworthy to mention here that Carbon sequestration in agricultural soils has a potential to significantly contribute to climate change mitigation as there is a potential to sequester up to 60-70 Mt CO₂ y⁻¹ in agricultural soils of European countries (EU-15), which is equivalent to 1.5-1.7% of the EU's anthropogenic CO₂ emissions [51].

About 80% of the world's potential for increasing Carbon storage in forests (estimated at 60-87 Pg Carbon from now up to 2050) lies in developing countries [52]. The forest woodland contained more Carbon than all other categories collectively, but the proportion of total Carbon in this class progressively declined throughout the century from 73% in 1880 to 63% in 1980 [53]. While as, in India, a national level estimate of carbon storage was conducted by [54]. They conducted a study to estimate role of India's forests from 1995 to 2005 towards carbon (C) sink using secondary data of growing stock from different sources and estimated that from 1995 to 2005, Carbon in biomass of Indian forests have increased from 2692.474 to 2865.739 mt registering an annual increment of 173.265 mt of Carbon during a decade. Sathaye and Ravindranath [55] reported in 2001 on Climate Change, about 36.9 million hectare degraded forestland with carbon mitigation potential of 74.75 t Carbon/ha is available for regeneration in India with Carbon abatement cost in the forestry sector in India can be the basis of attracting Global Environment Facility (GEF) funded projects.

Rawat and Rawat [56] reported that the potential yield of natural forests in India as 6 m³/ha/yr and emphasized that plantation crops like Eucalyptus are fast growing species can contribute and enhance the carbon sequestration potential of Indian forests. In a study [8] to assess

sequestration potential of natural forests of Madhya Pradesh, the total carbon pool in standing crop was reported to be 363.01 mt for open forest. The scrubland contributed 2.74 mt of carbon in the pool. The contribution of litter was 9.425 mt. As far as bole biomass is concerned, dense and open forests contributed 247.40 mt and 56.58 mt, respectively, in the total bole Carbon in standing crop (304.013 mt). Gera et al. [57] carried out a study on Carbon sequestration potential of agroforestry in Rupnagar district of Punjab and found that the total carbon that can be sequestered over the period of analysis varies between 59361 t for Eucalyptus bund plantation to 330510 t for Poplar block plantation. The block plantation also gave maximum sequestration potential of 115 t/ha that was higher by 79.69% and 105.34% with respect to Poplar bund plantation and Eucalyptus bund planting respectively. Borah and Chandra [58] in a study to estimate Carbon sequestration potential of selected bamboo species of Northeast India reported highest total above ground carbon in *Bambusa balcooa* (234.17 t ha⁻¹) followed by *Bambusa tulda* (86.99 t ha⁻¹) and *Bambusa nutans* (63.25 t ha⁻¹). Sexana et al. [10] in another study estimated Forest cover, 1083.81 mt of carbon for the year 1994 with Maharashtra topping the list with 198.43 mt of carbon. growing stock and biomass for the year 1984 statewide for the whole country reported a total of Carbon storage in wood products [14] may be one of the potential ways, which can be achieved by prolonging the life of wood and wood products by adopting wood preservation [9,59] and also wood burial is an economic process which greatly contributes to carbon sequestration [60].

Carbon storage of terrestrial ecosystems in China and its spatial pattern are controlled by temperature and precipitation. About 97.95–118.93 Pg carbon is stored in soil, forest and grassland in China [61]. China's forest ecosystems store a significant amount of carbon in non-biomass forms such as litter and soil organic carbon [62]. Williams et al. [63] worked to determine how slash and burn agriculture affected vegetation and soil carbon stocks and biodiversity on an area of miombo woodland in Mozambique, and how carbon stocks and biodiversity responded once agriculture was abandoned. Their work revealed that there were significant relationships between periods of re-growth and basal area stem numbers and stem biomass. No significant difference was observed in stem carbon stocks on woodlands and on abandoned farmland 20-30 years old. Also, no discernible increase in soil carbon stocks was observed with period of re-growth, suggesting that the rate of accumulation of organic matter in the soils was very slow. The regrowing plots did not contain the defining miombo species, and total stem numbers were significantly greater than in woodland plots, but species richness and diversity were similar in older abandonments and miombo woodlands. The study confirms that wood carbon stocks on abandoned farmland were capable of recovery within 2-3 decades, but soil carbon stocks did not change on this timescale. The study suggests the management to focus on identifying carbon rich soils, conserving remaining woodlands to protect soil carbon and preserve defining miombo species and on investigating whether fire control recovering woodland can stimulate accumulation of soil carbon and greater tree biomass, and restore defining miombo species. Conversion of tropical forests to agricultural management has important implications for carbon storage in soils and global climate change as it increases the C/N ratio causing an increase in the stock of organic carbon in the top layers of soil [64]. However, according to [65] the largest fluxes of carbon result from the clearing of forests for croplands, in part because a hectare of trees holds so much more carbon than a hectare of crops, and in part because 25–30% of the carbon in the top meter of soil in a natural ecosystem is lost with cultivation. Carbon sequestration following afforestation is associated with increased nitrogen use

efficiency as is reflected by an overall increase in C/N ratio, which often results in increased ecosystem-scale carbon stocks, mainly as a consequence of the build-up of aboveground tree biomass [66]. This potential could be used by proper management for increased C sequestration in dry regions of the world. Resh et al. [67] compared the soil carbon pools under nitrogen fixing trees with non-nitrogen fixers (*Eucalyptus*) at four tropical sites in Hawaii and Puerto Rico, USA. Using stable carbon isotope techniques, they tracked the loss of old soil organic carbon from nitrogen fixer and non-nitrogen fixer plantations. They concluded that the greater retention of older soil carbon under nitrogen fixing trees is a novel finding and indicates that forests with nitrogen fixing trees typically accumulate more carbon in soils than similar forests without nitrogen fixing trees as nitrogen concentration varies directly with carbon assimilation [68].

Organic carbon storage in the top 1m of soil was studied by Jespersen and Osher [69] from the Taunton Bay estuary in Hancock Country, Gulf of Maine. The results revealed that the organic carbon content in estuarine soil was greater than the carbon content in the top 1m of Maine's upland soils. The study suggests that systematically quantifying and dating the carbon in estuarine soils will provide valuable data for use in regional and global carbon budgets and climate models. Changes in soil carbon and nitrogen concentrations and contents on Walker Branch Watershed in Tennessee was studied by Johnson et al. [70] and compared with previously measured carbon and nitrogen fluxes and with changes in ecosystem carbon and nitrogen pools. The study revealed varying trends in carbon and nitrogen concentration in surface horizons as the concentration sometimes showed significant increase and sometimes decline. The study concludes that, although vegetation carbon and nitrogen pools increased steadily during the sampling period in most cases, changes in soil carbon and nitrogen pools on Walker Branch Watershed are highly variable in both space and time, and there has been no unidirectional trend during the time period of the study. Most agricultural soils contain soil carbon pool below their ecological potential, which can be enhanced by adoption of restoration measures adding a considerable amount of biomass to the soil [71]. Afforestation of a hot semi-arid shrub land results in significant carbon sequestration. Compared with carbon sequestration under a more humid climate, soils in semi-arid regions have a large potential for carbon storage [72]. A study of carbon sequestration in dry land ecosystems carried out by Lal [73] revealed that despite low soil organic carbon concentration because of desertification, total soil organic carbon pool of soils of the dry lands is 241 Pg. Desertification has caused historic carbon loss of 20 to 30 Pg. Assuming that two-thirds of the historic loss can be resequenced, the total potential of SOC sequestration is 12 to 20 Pg Carbon over a 50-year period. Land use and management practices to sequester soil organic carbon include afforestation with appropriate species, soil management on cropland, pasture management on grazing land, and restoration of degraded soils and ecosystems through afforestation and conversion to other restorative land uses.

Carbon sequestration by grasslands

Grasslands and savannas cover 20% of the earth's land surface [74] and store 30% of global soil organic carbon [75]. Grassland ecosystems managed for livestock production represent the largest land-use footprint globally, covering more than one-quarter of the world's land surface [76]. Global estimates of the relative amounts of carbon in different vegetation types suggest that grasslands probably contribute >10% of the total biosphere store [77,78]. Plant diversity greatly influences carbon accumulation rates in grasslands. Presence

of species with differing functional traits increases soil carbon and nitrogen accumulation. Carbon from plants enters the SOC pool in the form of either above-ground litter or root material. Greater carbon accumulation is associated with greater root biomass (i.e. greater carbon and nitrogen inputs in the soil) resulting from positive interactions among legumes and C4 grasses and the greater soil depths through which their roots are located at higher diversity [79]. Plant roots contribute to soil carbon not only through their death and decomposition, but also by rhizodeposition resulting from exudation, mucilage production and sloughing from living roots [80,81]. The annual Net Ecosystem Production (NEP) of temperate grassland is between 1 and 6 tC ha⁻¹ yr⁻¹ according to the radiation, temperature and water regimes, as well as to the nutrient status and the age of the sward [82]. Nutrient and water supplies limit the potential NEP. For grasslands, the nature, frequency and intensity of disturbance plays a key role in the carbon balance. Carbon accumulation in grassland ecosystems occurs mostly below ground [83]. In most temperate grassland ecosystems, 75–80% of the root biomass is in the top 30 cm of the soil but, because root growth, death and decomposition occur simultaneously and at different rates according to species and climatic conditions, accurate determination of carbon transfer from the various sources to the soil is difficult [81]. Also, in grasslands a significant but variable proportion of plant material is consumed by herbivores and then enters the SOC pool from animal excretion [84]. Rangeland soils hold considerable potential to store carbon and offset greenhouse gas emissions [85]. World rangelands contain 10–30% of the world's soil organic carbon. Carbon is added to soil from plant and animal materials deposited on the soil surface. It is known that approximately 50% of carbon assimilated by young plants can be transferred below ground [86]. Under existing management conditions, most temperate grasslands worldwide are considered to be carbon sinks implying that even modest changes in carbon storage in grassland ecosystems have the potential to modify the global carbon cycle and indirectly influence climate [87]. The changes in rangeland soil carbon can occur in response to a wide range of management and environmental factors like grazing, fire, converting marginal croplands into grasslands and fertilization. Carbon losses due to soil erosion can influence soil carbon storage on rangelands both by reducing soil productivity in source areas and potentially increasing it in depositional areas, and by redistributing the carbon to areas where soil organic matter mineralization rates are different [88]. However, carbon sequestration can be enhanced by improving management practices like fertilization, improved grazing management, conversion from cultivation and native vegetation, sowing of legumes and grasses, introduction of earthworms and irrigation [89]. Choosing species with large deep root systems is desirable for increasing carbon inputs and it has been argued that carbon deposited deep in the soil profile is less prone to oxidation and hence subsequent loss [90,91]. Kell [92] suggests that by planting deep rooted grasses, we can enhance the carbon retention capacity of soils as well as increase the carbon sequestration potential through better water and nutrient retention. Effective carbon sequestration can be achieved by restoring (reclaiming) herbaceous ecosystems on carbon-poor soils [93]. Vegetation restoration in the grasslands increases soil carbon sequestration by increasing the plant roots [94]. Jansson et al. [95] studied the aspect of genetic engineering in phyto-sequestration. Their study reveals that plant genetic engineering can increase phyto-sequestration by improving their tolerance to drought and salinity, which improves their NPP and, consequently, increase

carbon sequestration.

Biomass data is a basic requirement for the estimation of carbon density and storage and can be acquired in different ways but field-measured data is the most basic, direct and authentic [96,97]. Fan et al. [98] studied carbon storage in China's grasslands by measuring above and below ground biomass. They estimated that total carbon storage in the biomass of the grasslands of China was 3.32 Pg C, with 56.4% contained in the grasslands of the Tibet-Qinghai plateau and 17.9% in the northern temperate grasslands. Their study indicates that Chinese grasslands cover 6.4–9.5% of the world's grassland area and store 4.4–11.9% of the carbon contained in grassland vegetation. Sims and Bradford [99] studied the relationship of vegetation structure and dynamics to CO₂ fluxes for a grass and a sagebrush-dominated Southern Plains mixed-grass prairie and evaluated their potential for carbon sequestration. From their study, they concluded that these Southern Plains mixed-grass prairie communities have the potential to sequester carbon. The potential for carbon sequestration, however, appears to be greater for the grassland compared to the sagebrush site. Wolf et al. [100] compared the carbon sequestration potential of tropical pastures with afforestation in Panama and concluded that tropical afforestation is a more efficient carbon sink as compared to tropical pastures. Conversion of degraded agricultural soils to perennial crops can improve soil quality by increasing carbon sequestration due to their perennality, high biomass production, and deep root systems [101].

Bioenergy crops have the potential to sequester 317.5 Tg C yr⁻¹ based on biomass yields, the land area dedicated to crop production, the estimated carbon sequestration potential, and the conversion efficiency. The carbon mitigation per unit of land is very large with bioenergy crops specifically grown to decrease the carbon emission from fossil fuel. Converting cropland to bioenergy crops may increase carbon sequestration in soil organic matter and contribute to atmospheric CO₂ mitigation strategies [102]. Wulfschleger et al. [103] studied the potential of phosphate mine lands for carbon sequestration by planting short rotation bioenergy crops. They observed that in addition to providing a carbon-neutral option for mitigating rising CO₂ in the atmosphere, an important opportunity exists for promoting soil carbon sequestration as a result of restoration of these mined lands. Their analysis of soil carbon dynamics also indicates the potential for long-term increases in soil carbon under bioenergy crop plantations.

Soil organic carbon stocks in high-altitude grasslands are low at high altitudes, probably as a result of an overall temperature limitation of net primary productivity while the highest soil organic carbon stocks occur at the lowest altitudes [104]. The effect of land use conversion on the soil organic carbon sequestration was studied in the semiarid loess hilly areas by Chen et al. [105]. Their study reveals that land use conversion from cropland to shrub land or wild grassland (i.e. undisturbed land) was better for SOC sequestration than tree plantation in the semi-arid loess hilly area. The higher rates in grasslands compared with arable systems is explained partly by greater supply of carbon to the soil under grassland [106] and partly by the increased residence time of carbon resulting from the absence of disturbance by tilling. In grassland there is generally more soil organic carbon than under cropland as a result of several factors including lack of disturbance, greater return of plant residues, high root biomass, manure application and the return of dung during grazing [107]. Addition of nitrogen to prairie ecosystems increases the carbon accumulation in the soil. However, the increased nitrogen deposition is associated with decreased plant diversity as well as shifting of C4 species to C3 grasses [108]. West and Post [109]

found that increased diversity in crop rotation either through change from monoculture to rotation or by increasing the number of crops in rotation was associated with a change of 20±12 g C m⁻² year⁻¹, in an analysis of data from 67 experiments.

The substantial stocks of carbon sequestered in temperate grassland ecosystems are located largely below ground in roots and soil. Soil carbon sequestration on rangelands is influenced by biome, climate [89], management practices, and environmental factors [110]. Organic carbon in the soil is located in discrete pools, but the characteristics of these pools are still uncertain. Currently there is significant potential to increase carbon sequestration in temperate grassland systems by properly managing these ecosystems [111]. Changes in soil organic carbon stocks may result from land use changes (e.g. conversion of arable land to grassland) and grassland management. Soil is estimated to hold 25.8% of the total Carbon as compared to 74.2% sequestered by vegetation. In terms of biomass, the sequestration rate works out to be 6.13 Mg C ha⁻¹ yr⁻¹ [33]. Farm manures contribute to maintain or increase the soil carbon stocks of grassland [83].

Woody plant encroachment into grasslands and savannas is a significant global change phenomenon driven primarily by shifts in land use, that impacts biogeochemical cycling of SOC and nutrients in sometimes unpredictable ways [112]. Jackson et al. [113] investigated woody plant invasion along a precipitation gradient (200 to 1,100 mm yr⁻¹) by comparing carbon and nitrogen budgets and soil profiles between six pairs of adjacent grasslands in which one of each pair was invaded by woody species 30 to 100 years ago. They found a clear negative relationship between precipitation and changes in soil organic carbon and nitrogen content when grasslands were invaded by woody vegetation, with drier sites gaining, and wetter sites losing, soil organic carbon. Losses of soil organic carbon at the wetter sites were substantial enough to offset increases in plant biomass carbon, suggesting that current land-based assessments may overestimate carbon sinks. Since, woody plant encroachment into grasslands and savannas is a globally extensive land-cover change that alters biogeochemical processes and frequently results in soil organic carbon accrual. Creamer et al. [114] used soil physical fractionation, soil respiration kinetics, and the isotopic composition of soil respiration to investigate microbial degradation of accrued SOC in sandy loam soils along a chronosequence of C3 woody plant encroachment into a C4 dominated grassland in southern Texas. They found that the C3 derived carbon was rapidly respired from all landscape elements under the optimal conditions of the laboratory incubation which indicates that if environmental conditions were to change, resulting in a reduction of NPP or an increase in microbial activity in the woody clusters, the accrued C3 derived SOC could be lost through decomposition. They suggested that these results should be taken into consideration when making management decisions regarding woody plant control on rangelands or when treating woody plant encroachment as a carbon sink in modeling scenarios.

Reeder and Schuman [115] evaluated the effects of livestock grazing on carbon content of the plant–soil system of two semi-arid grasslands. They observed significantly higher soil carbon in grazed pastures compared to non-grazed enclosures, although for the short-grass steppe higher soil carbon was observed with the heavy grazing treatment only. Their data indicate that higher soil carbon with grazing was in part the result of more rapid annual shoot turnover, and redistribution of carbon within the plant–soil system as a result of changes in plant species composition. Grazing at light to moderate stocking rates resulted in stable, diverse plant communities dominated by forage grasses with dense, fibrous rooting systems conducive to soil

organic matter formation and thus carbon sequestration in the soil. This is because light to moderate levels of grazing generally result in a richer diversity of plant species with high above ground biomass than when livestock grazing is excluded [87,116-118]. However, Lone and Pandit [119] and Skinder and Pandit [120] opined that growing grazing pressures not only modify the natural ecosystems, but also reduce the rich biodiversity of plants and productivity of constituent species.

Conclusion

The challenges of climate change can be efficiently overcome by the storage of carbon in terrestrial carbon sinks viz. plants, plant products and soils for longer periods of time. Adoption of carbon sequestration measures can considerably reduce the rise in atmospheric CO₂ level. In order to sustain the amount of carbon in the terrestrial ecosystems the identified ecological factors should be enhanced through the application of good land and forest management practices. This will increase the carbon stock of terrestrial ecosystems thereby reducing direct loss to the atmosphere.

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