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Carbon sequestration to mitigate the climatic changes and their adverse effects

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Abstract- Atmospheric carbon dioxide plays an important role in climate change on the geological time scale. To combate the climatic change and risk of global warming, and to save the planet, it is urgent to reduce and stabilize the concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHGs) in the earth's atmosphere. This review has mainly studied the possible strategies of carbon sequestration by natural and engineering techniques, and off-setting the GHGs emissions, especially focusing on the long-term storage of carbon in oceans, soils, vegetation, geologic formations, industrial materials, and engineered construction works. Carbon can be sequestrated by absorption of carbon dioxide via physicochemical process and biological pump by phytoplankton, by application of iron nutrients in oceans, and engineering techniques for direct injection in oceans by enhanced dilution by CO_2 hydrate particles from the moving ship hydrate discharge. The photosynthesis by terrestrial plants, largest carbon sinks, can augment the carbon sequestration by (1) the increase of forest growth on existing and unmanaged all available lands in the tropical and other regions, (2) the increase of forest or grassland in arid and semiarid regions, desert, semi desert and savanna areas, (3) afforestation of marginal agricultural land, (4) development of forestry or grassland in degraded mining areas, (5) cultivating urban and residential turf grass, (6) preserving forestry in polar region, (7) soil restoration and soil management practices for regenerative agriculture, grassland and pastureland, (8) agroforestry practices and growing energy crops on spare lands. The artificial engineered techniques can be used for carbon sequestration by energy-efficient and energy-capturing building construction, geopolymer cement, capture and storage of industrial carbon emissions, engineered underground geological sequestration along with mineral carbonation of CO_2 (e.g., in deep ocean, geological strata, declining oil field, saline aquifer, and unminable coal seam), and construction of landfills and safe-guard wetlands. Engineering techniques are expensive and have leakage risks. In comparison, natural biotic techniques are cost-effective processes and have numerous ancillary benefits. Although all the possible strategies for the carbon sequestration are implemented, it would be difficult to reduce the concentrations of GHGs from atmosphere and mitigate the effects of climatic change, unless the viable strategies are adopted in anthropogenic activities for (1) the lowering of CO_2 emissions from energy, fossil fuel combustion, process industry, degrading soil cultivation, land-use change, deforestation, biomass burning, draining of wetlands etc, (2) reducing the global energy use, (3) off-setting CO_2 emissions and (4) developing low or no-carbon fuel from bio-diesel and renewable energies of solar, wind and hydraulic power.

Keywords — Carbon sequestration, Climate change, Biological and natural sinks, Low or no-carbon fuel development

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Contents

1 INTRODUCTION

The carbon reservoir in the tropical, continental and desert biosphere and in the atmosphere is still poorly known and knowledge of its variability over long geological periods is important for several reasons: for identifying the sources and sinks that control the atmospheric carbon dioxide (CO_2) concentration, for the realistic assessment of atmospheric CO_2 increases due to human activities, and for estimating the associated trends of change in greenhouse forcing due to natural and anthropogenic factors. The importance of atmospheric concentration of CO_2 on global temperature was recognized by Arrhenius [1] towards the end of the nineteenth century, whereas anthropogenic perturbation of the global C cycle during the twentieth century has been a historically unprecedented phenomenon [2]. Atmospheric CO_2 plays an important role in climate change on the geological time scale (s106 yr scale), based not only on geological records but also on computational models [3]. Atmospheric CO_2 level on the geological timescale is regulated by the global carbon cycle which involves silicate weathering, carbonate weathering, carbonate precipitation, organic carbon burial, carbonate metamorphism, mantle degassing and so on [4]. The present annual increase of atmospheric CO_2 is 0.5% [5]. The atmospheric abundance of CO_2 has increased by 36% from 280 ppm in ~1750 to 381 ppm in 2006 with an annual rate of increase during the 2000s at 1.93 ppm [6]. Global surface temperatures have increased by 0.8°C since the late nineteenth century, and 11 out of the 12 warmest years on record have occurred since 1995 [7]. Earth's mean temperature is projected to increase by 1.5–5.8°C during the twenty-first century [8]. The rate of increase in global temperature has been 0.15°C per decade since 1975. There is a direct relationship between increased levels of carbon dioxide in the atmosphere and rising global temperatures. In addition to the sea-level rise of 15–23 cm during the twentieth century [7], there have been notable shifts in ecosystems [9] and frequency and intensity of occurrence of wild fires [10], [11]. These and other observed climate changes are reportedly caused by emission of GHGs through anthropogenic activities including land-use change, deforestation, biomass burning, draining of wetlands, soil cultivation and fossil fuel combustion. Consequently, the concentration of atmospheric GHGs and their radiative forcing have progressively increased with increase in human population, but especially so since the onset of industrial revolution around 1850 [2].

Principal sources of CO_2 since 1850 have been fossil fuel combustion contributing ~330 Pg C and land use change contributing 158 Pg C [12]. The most important soil borne and land use related greenhouse gases are CO_2, methane (CH_4) and nitrous oxide (N_2O). The land use change, attributed to deforestation and the attendant biomass burning, soil tillage along with erosion and other degradation processes, includes an estimated emission of 78±12 Pg C from world soils. From a global standpoint, N_2O from unmanaged soils and CH_4 from peatlands and other wetlands make soils naturally net greenhouse gas emitters [7], [8], [13], [14].

Of the total annual emission of approximately 9.4 Pg C y^{-1} during the 2000s (including 7.5 Pg C y^{-1} from fossil fuel combustion and 1.9 Pg C y^{-1} from land use conversion), 4.1 Pg C (44%) is absorbed annually by the atmosphere, 2.2 Pg C (23%) by the ocean, and 2.7 Pg C (33%) by land-based sinks [6]. The rate of future increase in atmospheric CO_2 concentration will depend on the anthropogenic activities, the interaction of biogeochemical and climate processes on the global C cycle and interaction among principal C pools [2]. There are five global C pools, of which the largest oceanic pool is estimated at 38 000 Pg and is increasing at the rate of 2.3 Pg C yr^{-1}. The geological C pool, comprising fossil fuels, is estimated at 4130 Pg, of which 85% is coal, 5.5% is oil and 3.3% is gas. Proven reserves of fossil fuel include 678 Pg of coal (3.2 Pg yr^{-1} production), 146 Pg of oil (3.6 Pg yr^{-1} of production) and 98 Pg of natural gas (1.5 Pg yr^{-1} of production; [15]). Presently, coal and oil each account for approximately 40% of global CO_2 emissions [15]. Thus, the geological pool is depleting, through fossil fuel combustion, at the rate of 7.0 Pg C yr^{-1}. The third largest pool is pedologic, estimated at 2500 Pg to 1 m depth. It consists of two distinct components: soil organic carbon (SOC) pool estimated at 1550 Pg and soil inorganic carbon (SIC) pool at 950 Pg, about twice the quantity in atmospheric CO_2 and three times that in vegetation [16].

The capacity of the land-based sink is progressively decreasing in proportion to total emissions [6], probably due to gradual increase in extent and severity of soil degradation. The carbon sink capacity of the world's agricultural and degraded soils is 50 to 66% of the historic carbon loss of 42 to 78 Gt C [17]. The rate of soil organic carbon sequestration with adoption of recommended technologies depends on soil texture and structure, rainfall, temperature, farming system, and soil management. Strategies to increase the soil carbon pool include soil restoration and woodland regeneration, no-till farming, cover crops, nutrient management, manuring and sludge application, improved grazing, water conservation and harvesting, efficient irrigation, agroforestry practices, and growing energy crops on spare lands. An increase of 1 ton of soil carbon pool of degraded cropland soils may increase crop yield by 20 to 40 kilograms per hectare (kg/ha) for wheat, 10 to 20 kg/ha for maize, and 0.5 to 1 kg/ha for cowpeas. As well as enhancing food security, carbon sequestration has the potential to offset fossil fuel emissions by 0.4 to 1.2 gigatons of carbon per year, or 5 to 15% of the global fossil-fuel emission [12].

Reducing concentrations of CO_2 and other GHGs in Earth's atmosphere is identified as one of the most pressing modern-day environmental issues [7]. Agriculture, in addition to being affected by the climate, contributes to climate change through its exchanges of GHGs with the atmosphere [18]. Thus, the management of agricultural systems to sequester atmospheric CO_2 as SOC and to minimize GHG emissions has been proposed as a partial solution to the climate change problem. Therefore, in this review we have strived to analyze the changes in terrestrial organic carbon storage and vegetation with variations of climatic conditions over geologic period and assess their role in global carbon cycle variations. We also identify critical knowledge gaps where further research is needed. Understanding the global C cycle and its perturbation by anthropogenic activities is important for developing viable strategies for mitigating climate change.

2 CARBON SEQUESTRATION

It is urgently needed to reduce and stabilize the atmospheric abundance of CO_2 and other GHGs to mitigate the risks of global warming [19], [20], [21], [22]. Developing technologies to reduce the rate of increase of atmospheric concentration of CO_2 from annual emissions of 8.6 Pg C yr^{-1} from energy, process industry, land-use conversion and soil cultivation are the important issues of the twenty-first century [2]. There are four strategies of lowering CO_2 emissions to mitigate climate change [15]: (1) reducing the global energy use; (2) developing low or no-carbon fuel; (3) off-setting GHGs emissions; and (4) sequestering CO_2 from point sources or atmosphere through natural and engineering techniques [2]. This review has mainly studied the possible strategies of (4) carbon sequestration by natural and engineering techniques (Fig. 1) and very slightly focused on (1) reducing the global energy use and (3) off-setting GHGs emissions (Fig. 2).

Carbon sequestration is the longterm storage of carbon in oceans, soils, vegetation (especially forests, grassland and agriculture), geologic formations, industrial materials, and engineered construction works. In oceans carbon can be sequestrated by absorption of carbon dioxide via physicochemical and biological processes, aided natural process, and engineering techniques. The largest carbon sinks are photosynthesis by terrestrial plants that can augment the carbon sequestration by the following natural and aided processes: (1) increase of forest growth on existing and unmanaged land; (2) increase of forest or grassland in arid and semi arid regions, desert, semi desert and savanna areas; (3) afforestation of marginal agricultural land; (4) development of forestry or grassland in degraded mining areas; (5) cultivating urban and residential turf grass; (6) preserving forestry in polar region and litter addition in the subarctic heath ecosystem; (7) carbon sequestration in plant and soil at high CO_2; (8) soil management practices for agriculture, grassland and pastureland (increase of clay in soil structure, regenerative agriculture, and straw incorporation in soils). Mineral sequestration is a natural process of carbon sequestration. The artificial engineered techniques can be used for carbon sequestration by energy-efficient and energy-capturing building construction, capture and storage of industrial carbon emissions, engineered geological sequestration, and construction of safe-guard wetlands.

Natural sinks are typically much larger than artificial sinks. The main artificial sinks are: landfills, carbon capture and storage proposals. Although engineering techniques of CO_2 injection have a large potential of thousands of Pg, those are expensive, have leakage risks and may be available for routine use by 2025 and beyond. In comparison, biotic techniques are natural and cost-effective processes, have numerous ancillary benefits, are immediately applicable but have finite sink capacity. Biotic and abiotic C sequestration options have specific nitches, are complementary, and have potential to mitigate the climate change risks. Management for carbon sequestration affects other gases that influence climate such as atmospheric concentrations of nitrous oxide and methane. Changes in these gases must also be factored into management strategies for carbon storage.

3 CARBON SEQUESTRATION IN OCEANS

Oceans represent the largest active carbon sink on Earth, absorbing more than a quarter of the carbon dioxide that humans put into the air. On longer timescales they may be both sources and sinks – during ice ages CO_2 levels decrease to ~180 ppmv, that is believed to be stored in the oceans and later released from the oceans providing CO_2 levels during previous interglacials at around ~280 ppmv.

3.1 Natural process

The CO_2 is driven by two processes in seawater such as solubility pump, the primary mechanism (i.e., differential CO_2 solubility and thermohaline circulation) and biological pump by phytoplankton. However, some studies reported that phytoplankton photosynthesis mechanism can sequester approximately 45 Pg C/yr [23], [24]. Some of the particulate organic material formed by phytoplankton is deposited at the ocean floor and is thus sequestered [25].

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3.2 Aided natural process

The application of iron nutrients (e,g., hematite, iron oxide or melanterite, iron sulfate) in select parts of the oceans, at appropriate scales, could have the combined effect of restoring ocean productivity, while at the same time mitigating the effects of human caused emissions of carbon dioxide to the atmosphere by increasing phytoplankton production [26], [27], [28], [29].

An additional method of long-term ocean-based sequestration is to deposit crop residue such as corn stalks or excess hay in the alluvial fan areas of the deep ocean basin that will be quickly buried in silt on the sea floor, sequestering the biomass for very long time spans.

3.3 Engineering techniques

Another proposed form of carbon sequestration in the ocean is direct injection. To be stable and minimize outgassing, CO_2 must be injected at great depths in this method, and expected to form "lakes" of liquid CO_2 at the bottom. The liquefied CO_2 separated from industrial sources can be injected into the ocean by one of the following four techniques: (i) it is injected below 1000 m from a manifold lying at the ocean floor, and being lighter than water, it rises to approximately 1000 m depth forming a droplet plume; (ii) it is also injected as a denser CO_2–seawater mixture at 500–1000 m depth, and the mixture sinks into the deeper ocean; (iii) it is discharged from a large pipe towed behind a ship; and (iv) it is pumped into a depression at the bottom of the ocean floor forming a CO_2 lake. Liquefied CO_2 injected at approximately 3000 m depth is believed to remain stable [30]. The oceanic sink capacity for CO_2 sequestration is estimated at 5000–10000 Pg C, exceeding the estimated fossil fuel reserves [31], [32]. However, this method, too, has potentially dangerous environmental consequences. Ocean acidification by injecting CO_2 and climate change may affect the biological pump by negatively impacting calcifying organisms such as coccolithophores, foraminiferans and pteropods and in future by warming and stratifying the the ocean water column, thus reducing the supply of limiting nutrients to surface waters biota [33], [34], [35]. Similar to deep injection, ocean fertilization may also change the ecology of the ocean [36]. However, with the current state of knowledge, the topic of ocean fertilization remains a debatable issue. Israelsson et al. [37] evaluated the expected environmental impact of several promising schemes for ocean carbon sequestration by direct injection of CO_2, and suggested the following schemes. Three discharge approaches are considered, each designed to maximize dilution over the water column: a point release of negatively buoyant CO_2 hydrate particles from a moving ship; a stationary point release of CO_2 hydrate particles forming a sinking plume; and a long, bottom-mounted diffuser discharging buoyant liquid CO_2 droplets. Two of these scenarios take advantage of the enhanced dilution offered by CO_2 hydrate particles, and are based on recent laboratory and field studies on the formation and behavior of such particles. Overall, results suggest that it is possible with present or near present technology to engineer discharge configurations that achieve sufficient dilution to largely avoid acute impacts. In particular, the moving ship hydrate discharge is identified as the most promising due to its operational flexibility. They concluded that ocean carbon sequestration by direct injection should not be dismissed as a climate change mitigation strategy on the basis of environmental impact alone. Rather, it can be considered as a viable option for further study, especially in regions where geologic sequestration proves impractical.

4 ARTIFICIAL ENGINEERED SEQUESTRATION

Carbon can be passively stored or remain productively utilized over time in a variety of ways.

4.1 Building construction

After harvesting, wood (as a carbon-rich material) can be incorporated into construction or a range of other durable products, thus sequestering its carbon over years or even centuries. Building construction and operation (electricity usage, heating, etc.) are estimated to contribute nearly half of the annual human-caused carbon additions to the atmosphere. A very carefully designed and durable, energy-efficient and energy-capturing building has the potential to sequester, as much as or more carbon than was released by the acquisition and incorporation of all its materials.

4.2 Capture and storage of industrial carbon emissions

Zeolitic imidazolate framework is a metal-organic framework carbon dioxide sink which could be used to keep industrial emissions of carbon dioxide out of the atmosphere. Calcium rich, industrial solid wastes and residues provide a potential source of highly reactive oxides, without the need for pre-processing. Huntzinger et al. [38] examined the feasibility of carbon sequestration in cement kiln dust (CKD), a byproduct generated during the manufacturing of cement. Based on stoichiometry and measured consumption of CO_2 during the experiments, degrees of carbonation greater than 70% of the material's potential theoretical extent were achieved under ambient temperature and pressure conditions. The major sequestration product appears to be calcite; however, more detailed material characterization is needed on pre and postcarbonated samples to better elucidate carbonation pathways and products.

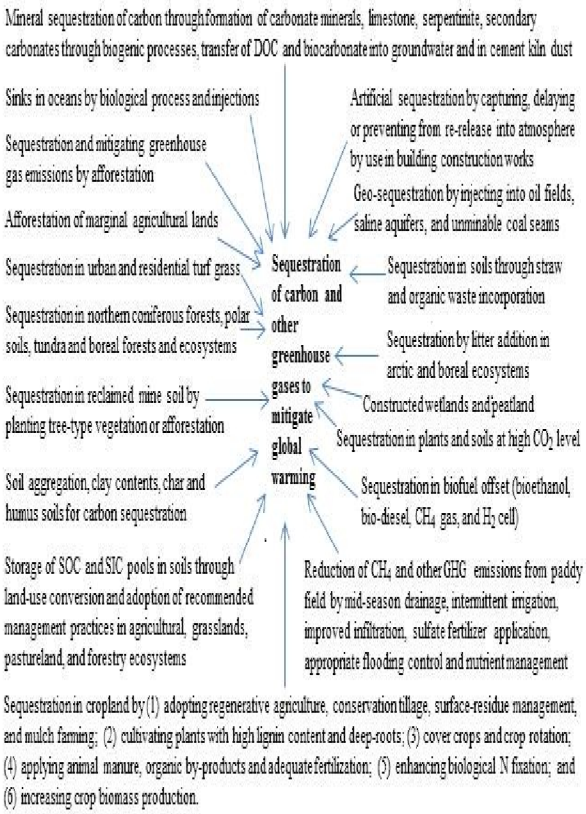

Fig. 1. Artificial and natural measures and technological options for carbon sequestration.

4.3 Engineered geological sequestration

The declining oil fields, saline aquifers, and unminable coal seams have been suggested as storage sites for geo-sequestration of carbon dioxide by injecting directly into underground geological formations. Caverns and old mines that are commonly used to store natural gas are not considered, because of a lack of storage safety. Xie and Economides [39] studied the technical risks, regulatory issues, and economic burden of CO_2 geological sequestration on the U.S. by using the Kyoto Protocol emission requirement as the base line. The financial burden for CO_2 injection to geological formations (oil and gas reservoirs, saline aquifers, and coalbeds) is tremendous. There are too many uncertainties and risks for long term CO_2 sequestration. The contradiction between the regulatory framework for CO_2 sequestration and social and economic development is hard to be disentangled. A Kyoto Protocol scale carbon sequestration program will not have detectable effect on global temperature. On the contrary, it may cause serious immediate environmental problems. The Kyoto Protocol will not be able to prevent the global from warming even the temperature is solely caused by anthropogenic carbon emission. Instead, it will cause enormous social hardships and greatly hamper the economic development and energy efficiency of all the countries that abide by it. The work shows that the potential technical and legal risks and financial costs for sequestering CO_2 underground make it impossible to promulgate any regulatory framework without causing detrimental effects on economic development and energy utilization.

4.4 Constructed wetlands: ecological engineering process

The constructed wetlands that are used in ameliorating water quality, can be affected by lowering water table height from future climate change and releasing many solutes including dissolved organic carbon, CO_2, nitrate, sulphate, sodium, chloride, iron and magnesium from the peat-soils of a riparian wetland [40] unless suitable design safeguard is used. From the viewpoint of climate change and taking into consideration the mean fluxes of CO_2, CH_4 and N_2O, peatland protection is more favourable than peatland cultivation in the long term. The most important gaps in our understanding appear to be with regard to estimating fluxes along with soil erosion, the role of black carbon formation, natural 'background' sequestration rates of undisturbed soils and the net response of soils, particularly in cold regions, to global warming.

5 MINERAL SEQUESTRATION BY NATURAL PROCESS

Carbon sequestration through the formation of solid carbonate minerals is a potential means to reduce CO_2 emissions. This process occurs slowly in nature and is responsible for the deposition and accumulation of limestone (calcium carbonate) over geologic time. One proposed reaction is that of the olivine-rich rock dunite, or its hydrated equivalent serpentinite with carbon dioxide to form the carbonate mineral magnesite, plus silica and iron oxide (magnetite). Serpentinite sequestration is favored because of the non-toxic and stable nature of magnesium carbonate. The ideal reactions involve the magnesium endmember components of the olivine (reaction 1) or serpentine (reaction 2), the latter derived from earlier olivine by hydration and silicification (reaction 3). The presence of iron in the olivine or serpentine reduces the efficiency of sequestration, since the iron components of these minerals break down to iron oxide and silica (reaction 4).

Serpentinite reactions
Reaction 1
Mg-Olivine + Carbon dioxide → Magnesite + Silica
$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2 + H_2O$

Reaction 2
Serpentine + carbon dioxide → Magnesite + silica + water

$Mg_3[Si_2O_5(OH)_4] + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O$

Reaction 3
Mg-Olivine + Water + Silica → Serpentine
$3Mg_2SiO_4 + 2SiO_2 + 4H_2O \rightarrow 2Mg_3[Si_2O_5(OH)_4$

Reaction 4
Fe-Olivine + Water → Magnetite + Silica + Hydrogen
$3Fe_2SiO_4 + 2H_2O \rightarrow 2Fe_3O_4 + 3SiO_2 + 2H_2$

6 CARBON SEQUESTRATION BY FOREST AND GRASSLAND

Forestry activities and landuse change are widely recognized as a part of strategies to mitigate GHGs emissions [41], [42], [43], [44], [45]. Afforestation not only possesses great potential [41], [42], [46], [47], [48], [49] but also is a cost-effective and environmentally beneficial strategy for carbon sequestration in woody tissues and soil organic matter [41], [45], [50], [51], [52], [53]. Forests can store and sink more and more carbon and carbon dioxide by increasing in density or area globally.

6.1 Increase of forest growth on existing and unmanaged land

Under the Kyoto Protocol Article 3, carbon sequestered through afforestation (establishment of trees on land that has not previously been managed for forests) is allowed to be used by Annex I Parties (i.e. industrialized counties) as carbon credit in meeting their GHG emission reduction commitments [44]. In Canada's boreal forest as much as 80% of the total carbon is stored in the soils as dead organic matter [54]. A 40-year study of African, Asian, and South American tropical forests shows tropical forests absorb about 18% of all carbon dioxide added by fossil fuels. Tropical reforestation can mitigate global warming until all available land has been reforested with mature forests.

The net rate of carbon uptake is greatest when forests are young, and slows with time. Old forests can sequester carbon for a long time but provide essentially no net uptake. The old-growth forests have traditionally been considered negligible as carbon sinks because carbon uptake has been thought to be balanced by respiration. However, Zhou et al. [55] showed that the top 20-centimeter soil layer in preserved old-growth forests in southern China accumulated atmospheric carbon at an unexpectedly high average rate of 0.61 Mg C /hectare/y from 1979 to 2003 suggesting that the carbon cycle processes in the belowground system of the old forests are changing in response to the changing climate environment and supports the establishment of a new, nonequilibrium conceptual framework to study soil carbon dynamics. The forests can be source by burning the woody tissue or converted those to short-lived products, such as paper; and sinks by using the wood for long-lived construction or furniture. A post harvest approach that reduces waste and puts most of the wood into long-lived products is an effective strategy to help reduce global atmospheric carbon. However, the net sink for carbon in long-lived wood products is still relatively small, so forest cutting ultimately acts to reduce the storage of carbon on land.

Lelyakin et al. [56] reported that Russian forests sink can be estimated as 160 MtC/yr in the year 1993 and the net-sink of CO_2 has a tendency to increase in future, up to 200-240 MtC/yr by the year 2010. The main sinks are connected with the South Siberia and European-Ural part of the country. There is an increasing trend of reforestation and afforestation of longleaf pine forests (*Pinus palustris* Mill.) in the southeastern United States that will increase terrestrial carbon storage and provide many simultaneous ecological and economic benefits [57]. Longleaf pine is a long-lived species with a low mortality rate, tolerant to fire and many insects and diseases, has high specific gravity, sustain growth at older ages (over 150 years), can tolerate a very wide variety of habitats and might better adapt to future climate scenarios with higher temperatures and higher atmospheric CO_2 levels. Moreover, the higher-value, longer-lasting wood products derived from longleaf pine forests will continue to store carbon over long time periods. The Intergovernmental Panel on Climate Change concluded that "a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber fibre or energy from the forest, will generate the largest sustained mitigation benefit".

6.2 Increase of forestry or grassland in arid and semiarid, semi desert and savanna areas

The Sahara–Gobi desert belt, sometimes called as the Afro-Asian desert area, stretching for more than 15,000 km from the Atlantic coast to northern China [58] includes extra-arid, arid and semi-arid zones of the African and Asian continents and forms the most extensive arid area in the world (about 18×10^6 km^2). The investigations on the age, origin and history of the Sahara–Gobi deserts, climatic change and vegetation or organic carbon storage therein indicate the changes and shifts of vegetation zones in response to global climatic fluctuations. The results show that the origin and evolution of the present desert landscapes are the role of precipitation distribution and biomass variations during the Late Pleistocene and Holocene [59] not only in the Sahara–Gobi desert belt but also maybe in other parts of the world. According to various estimates [60], [61], [62] carbon density in tropical deserts does not exceed 0.01 kg /m^2, is about 0.6 kg /m^2 in extreme temperate deserts, while in temperate semi-deserts it may amount to 0.9–1 kg /m^2. The arid and semi arid regions, desert, semi desert and savanna areas can accumulate significant quantities of organic matter in soils or source of carbon in response to climatic and vegetation change. This can vary based on rainfall, the length of the winter season, and the frequency of naturally occurring lightning-induced grass-fires. However, the fossil fuel costs of irrigating these lands may exceed any net gain in carbon sequestration.

6.3 Afforestation of marginal agricultural land

Niu and Duiker [63] assessed the carbon sequestration potential by afforestation of marginal agricultural land and to identify hotspots for potential afforestation activities in the U.S. Midwest region (Michigan, Indiana, Ohio, Kentucky, West Virginia, Pennsylvania and Maryland). They estimated that there was a total of 6.5 million hectares (Mha) marginal agricultural land available in the U.S. Midwest region, which accounts for approximately 24% of the regional total agricultural land. The carbon sequestration potential capacity was predicted to be 508–540 Tg C (1 Tg = 1012 g) over 20 years and 1018–1080 Tg C over 50 years. The results indicate that afforestation of marginal agricultural land could offset 6–8% of current CO_2 emissions by combustion of fossil fuel in the region. This analysis showed only slight differences in carbon sequestration between forest types (coniferous and deciduous) or between short-rotation and permanent forest scenarios. Therefore, all suitable marginal agricultural lands in the world offer great potential for carbon sequestration and can be converted to forest for the best carbon management. The actual carbon sequestration potential could be less if the economical and social factors are taken into account. Future studies are needed to evaluate its economic feasibility, social acceptability, and operation capability.

6.4 Development of forestry in degraded mine soil

The drastic perturbations of soil by mining activities can accentuate CO_2 emission through mineralization, erosion, leaching, changes in soil moisture and temperature regimes, and reduction in biomass returned to the soil. The reclamation of drastically disturbed mined soil by planting tree-type vegetation or afforestation offers the possible mitigation strategies of terrestrial carbon sequestration and has a high potential to sequester SOC for a long enough time to off-set C emissions by mining activities in the region [64]. The SOC sequestration potential in reclaimed mine soil depends on amount of biomass production and return to soil, and mechanisms of C protection. The rate of SOC sequestration ranges from 0.1 to 3.1 Mg/ha/yr and 0.7 to 4 Mg/ha/yr in grass and forest reclaimed mine soil ecosystem, respectively. However, the factors affecting C sequestration and protection in reclaimed mine soil leading to increase in microbial activity, nutrient availability, soil aggregation, C build up, and soil profile development must be better understood in order to formulate guidelines for development of an holistic approach to sustainable management of these ecosystems. The ecosystem C budget of reclaimed mine soil ecosystems are not well understood that need to be evaluated.

6.5 Carbon sequestration in urban and residential turf grass

In urbanized landscapes anthropogenic drivers will dominate natural drivers in the control of SOC storage [65]. Cropland systems can lose substantial amounts of SOC due to a greater magnitude and frequency of soil disturbances and lack of the standing crop [66], whereas turf grass ecosystems can accumulate SOC at rates similar to or greater than those for grasslands and forests because of the absence of annual soil disturbances and the addition of supplements such as water and fertilizer. Therefore, an important characteristic of urban land-use conversion with respect to SOC storage is the introduction of turf grass cover and management [67]. Approximately 41% of the total urban area in the conterminous United States is in residential use, most of which is dominated by turf grass [68]. With approximately 3.5% to 4.9% of the nation's land base in urban use [68], the total estimated areal amount of turf grass for the conterminous United States is 163,800±35,850 km^2, which exceeds by three times the area of irrigated corn [67]. Pouyat et al. [69] reported that the turf grass systems will be similar in SOC densities across regional variations in climate, parent material, and topography; and introducing turf grass and management will lead to higher SOC densities in the arid Denver area of the USA and lower densities in the mesic Baltimore area relative to native cover types.

6.6 Link of climate, carbon sequestration and forestry in polar region

The fate of global soil carbon stores in response to predicted climate change is a 'hotly' debated topic. Changes in soil carbon, the largest terrestrial carbon pool, are critical for the global carbon cycle, atmospheric CO_2 levels and climate. The mineralization rate of SOM is regulated by SOM quality, climatic conditions, the amount and activity of microbes and by the composition and amount of suitable substrates for the microbes, but irrespective of differences in microbial community structure and behavior [70]. Northern coniferous forests are an important terrestrial carbon sink, and 24% of global terrestrial carbon is stored in the cool soils of tundra and boreal forests alone [71]. If soil carbon is lost due to global warming, that carbon will add to the CO_2 already in the atmosphere, thus further accelerating warming [72]. Different studies show that the temperature sensitivity of decomposition decreases with increasing temperatures [70], [72], [73] but increases with decreasing temperature [70]. A similar increase in temperature causes a larger proportional increase in the decomposition rate of soil carbons at a low temperature regions like northern latitudes compared to high temperature areas [70]. For this reason, northern polar soils are especially temperature sensitive, and there is a particular risk of carbon losses from these soils even if the average temperature increase is the same over all of Europe and other parts of the world [74]. The level of overall soil respiration rate was higher in spruce forest sites than in pine forest sites irrespective of climate conditions [70]. Carbon mineralization rate and carbon utilization potential was higher in summer than that in winter but microbial and fungal biomass was low [75]. Considerable uncertainties remain as to the temperature sensitivity of decomposition of both young, labile, rapidly turned over and older, non-labile, longer standing soil carbon pools [76], [77] that is recognized as an important determinant of carbon driven climate change. Furthermore, ^{14}C measurement of SOM fractions have led to the conclusion that most respired carbon dioxide is derived from recently deposited plant matter [78].

6.7 Effects of litter addition and warming on soil carbon in a subarctic heath ecosystem

Arctic and boreal ecosystems harbor more than one-third of the total global soil carbon pool [79] and are currently exposed to strong changes in climate [80]. Within the next 100 years, the annual mean temperature in the arctic region is predicted to be 3–5°C higher than today, although the increase will depend on political measures taken to limit the anthropogenic emissions and to manage the natural emissions of greenhouse gases [80], [81]. The increase in deciduous plants in the arctic region results in a higher litter input and altered litter quality [82]. Litter is not only the major source of soil organic matter, but it also affects the microclimate by buffering the soil against fluctuations in soil moisture and temperature [83]. The combined warming plus litter addition treatment altered the composition of soil organic matter; however, the reduced moisture content in the combined warming and litter addition treatment may have limited microbial processes.

7 CARBON SEQUESTRATION IN PLANT AND SOIL AT HIGH CO_2

Many laboratory experiments showed that plants grown in e[CO_2] (elevated CO_2) generally fix up to 300% more C than those grown in c[CO_2] (controlled CO_2) [84], [85]. Combined with increased allocation of C below ground of around 50 % due to shifts in whole plant partitioning [84], [86], this should result in greater potential sequestration of C [87]. Elevated CO_2 can influence the plant photosynthesis and productivity [88] resulting in increased dry matter yield [86], [88] that in the absence of limiting factors such as availability of nitrogen, cause the stimulation of net CO_2 assimilation [89]. However, the consequences of the patterns of belowground C allocation under field conditions are controversial. More amounts of root fragments and exudates and perhaps increased crop root turnover rate may result in increase in soil organic C inputs under CO_2 enrichment. In low-nutrient conditions, some plants allocate a greater proportion of fixed C below ground, which would also lead to greater sequestration of C. Some free-air CO_2 enrichment (FACE) experiments found a >50 % decrease in the proportion of fixed C to be respired below ground in e[CO2] than in c[CO_2] [84]. However, some laboratory measurements have found a >60 % increase, whilst still reporting increases in total C remaining below ground [90]. The effects of elevated pCO_2 on root respiration were not consistent at different wheat growth stages and were small for the cumulative root respiration of the entire season. Elevated atmospheric pCO_2 increases soil respiration mainly due to an increase in microbial respiration. Elevated pCO_2 enhances the carbon exchange between the soil and atmosphere [87]. The current ability to predict the fate of the additional C input from plant to soil is limited by our poor understanding of underlying processes, so that good models can not be created which would act as hypotheses for experiments conducted in the field or FACEl. Warmer climates in presence of N fertilization, as predicted for the next century, may have little potential to contribute to long-term soil C sequestration [91].

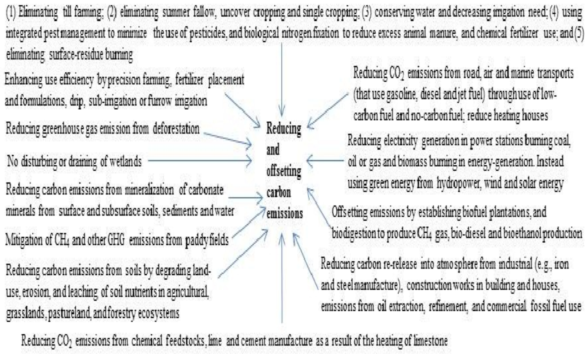

Fig. 2. Terrestrial carbon management options by reducing and offsetting emissions.

8 SOIL MANAGEMENT PRACTICES FOR AGRICULTURE AND CLIMATE CHANGE

The best way to reduce the atmospheric carbon dioxide is to increase the global storage of carbon or carbon sequestration in soils that has potential for mitigating global warming and increasing agricultural productivity. Soils can be a short to long-term storage medium of SOC and SIC pools through land-use conversion and adoption of recommended management practices in agricultural, grasslands, pastoral and forestry ecosystems and restoration of degraded and drastically disturbed soils. Carbon sink capacity of the world's agricultural and degraded soil is 50–66% of the historic carbon loss of 42–72 Pg (1 Pg=10^{15} g) of carbon; and cultivated soil can accumulate 0.4–0.8 Pg C year^{-1} if recommended farming practices are adopted [17]. Grasslands contribute to soil organic matter, stored mainly in their extensive fibrous root mats. Conversion to pastureland, particularly with good management of grazing, can sequester even more carbon in the soil. In Ohio, Akala and Lal [92] reported that pasture treatment increased SOC from 9.2 to 55.4 Mg ha^{-1} after 25 years, and forest treatment increased SOC from 14 to 48.4 Mg ha^{-1} after 21 years, suggesting that grassland and pasture treatments would increase SOC stock as much as forest management would. Controlled burns on far north Australian savannas can result in an overall carbon sink.

For the global environment, agriculture provides both a source and a sink of GHGs, which include CO_2, CH_4, and N_2O. The solution to sustaining food production is not to rely on new chemicals or fertilizers, but, rather, to develop new approaches to farming that improve local environmental quality, and adapting to climate change. Formation of charcoal and use of biochar as a fertilizer is another option [93]. The sustainable management of soil received strong support at the Rio Summit in 1992, as well as in Agenda 21 [94], the UN Framework Convention on Climate Change [95], Articles 3.3 and 3.4 of the Kyoto Protocol [96], and elsewhere. These conventions are indicative of recognition by the world community of the strong link between soil degradation and desertification on the one hand, and loss of biodiversity, threats to food security, increases in poverty, and risks of accelerated greenhouse effects and climate change on the other.

8.1 Role of climate and clay on carbon sequestration in soils

When other factors are constant, soil clay content increases with precipitation and temperature rises, a consequence of rock weathering and clay neoformation [97]. Alvarez and Lavado [98] reported that the climatic factors play a key role in the genesis of local soils and clay neoformation that, in turn, is related to the soil organic carbon level under climatic change scenarios. The particle size distribution can regulate the level of organic carbon, irrespective of climate. Within an area climatically homogeneous, an increase in clay content means an increase in soil carbon concentration because of the protecting effect of clays on organic compounds [99] indicating that clay contents in soils play a role for carbon sequestration. In some locations a strong correlation between clay and organic carbon concentration has been reported; this being higher than between precipitation and organic carbon [100]. In other locations, precipitation [101] or temperature [102] were more closely associated with soil carbon than soil texture [98]. All data indicate that climate is the main factor in the regulation of the carbon content of these soils because of its influence on plant productivity, carbon mineralization and soil texture [98].

8.2 Regenerative agriculture

Current agricultural practices lead to carbon loss from soils. It has been suggested that improved farming practices could return the soils to being a carbon sink. The Rodale Institute says that the regenerative agriculture, if practiced on the planet's 3.5 billion tillable acres, could sequester up to 40% of current CO_2 emissions [103]. Improved soil and water quality, decreased nutrient loss, reduced soil erosion, increased water conservation, and greater crop production may result from increasing the amount of carbon stored in agricultural soils. Agricultural management practices that significantly enhance carbon sequestration in soils include conservation tillage or no-till farming, residue mulching, cover cropping, and crop rotation, all of which are more widely used in organic farming than in conventional farming.

Conservation tillage minimizes or eliminates manipulation of the soil for crop production by (1) the practice of mulch tillage that reduces soil erosion, improve water use efficiency, and increase carbon concentrations in the topsoil, and (2) reducing the amount of fossil fuel consumed by farm operations, whereas tillage causes a substantial decrease of SOM content and mineralization of carbon [104], [105], [106]. Results indicate, on average, that a change from conventional tillage (CT) to no-till (NT) can sequester 57 ± 14 g C m^{-2} yr^{-1}, excluding wheat (*Triticum aestivum* L.)-fallow systems which may not result in SOC accumulation with a change from CT to NT. The results suggest that paddy soils have greater potential to conserve SOM than in upland soils because the decomposition of organic matter occurs more slowly under flooded conditions due to different biogeochemical processes and mechanisms [107]. Carbon sequestration rates, with a change from CT to NT, can be expected to peak in 5-10 yr with SOC reaching a new equilibrium in 15-20 yr.

Crop rotation instead of intensive mono-cropping practices can increase the level of soil organic matter. Enhancing rotation complexity can sequester an average 14 ± 11 g C m^{-2} yr^{-1}, excluding a change from continuous corn (*Zea mays* L.) to corn-soybean (*Glycine max* L.) which may not result in a significant accumulation of SOC. Following initiation of an enhancement in rotation complexity, SOC may reach a new equilibrium in approximately 40-60 yr. Cover cropping improves carbon sequestration by enhancing soil structure, erosion control, organic N enrichment, scavenging soil residual N, nematode control and adding organic matter to the soil [108], [109], [110]. Because SOC is reactive to soil management practices, long-term studies have consistently shown the benefits of manuring, adequate fertilization, and crop rotation for maintaining agronomic productivity by increasing C input into the soil [111]. Crop residue burning in this agro-ecosystem caused a particularly serious decline of SOC that is practiced in commercial fields until recent years [111].

8.3 Soil carbon sequestrations in cropland

Cultivated soils (cropland) store great amounts of organic carbon; they are one of the sinks of atmospheric CO_2 [107], [112]. Wood et al. [113] reported that globally, agricultural soils account for less than one-fourth of the SOC pool; and soils in North America, Asia, and Europe are considerably richer in SOC (12.2, 12.6, and 14.6 $\mathrm{kg\,C\,m^{-2}}$, respectively) than in sub-Saharan Africa (7.7 $\mathrm{kg\,C\,m^{-2}}$). Part of the net crop carbon accumulation is removed through the harvesting process, while other types of crop residues, including litter and roots, remain in the cropland. These crop residues are decomposed to CO_2 (through mineralization) or transformed to SOM in the soil by microbial decomposition, with the mineralization strongly dependent on the C:N ratio [104]. Much remains to be learned about the leaching of organic carbon from cropland. However, there are some difficulties involved with increasing or decreasing SOC, and continuing on an indefinite basis by using the same soil management or land use practices. Bellamy et al. [114] concluded that the carbon loss was irrespective of land use but linked to climate change. However, after examining the data, Schulze and Freibauer [115] disputed this observation, concluding that the land-use factor played a primary role and climate variation was, apparently, only a secondary factor. The over 30 $\mathrm{Mg\,ha^{-1}}$ manure input per year is required for enhancing SOM accumulation [107]. Pathak et al. [116] showed that the NPK+FYM treatment (N, P and K plus farmyard manure) have good potential in C sequestration in Indian soils and mitigating GHGs emission without any additional cost. Rather it increased yield and net return in majority of the experiments. Compared to the control treatment the NPK+FYM treatment sequestered 0.33MgC/ha/yr whereas the NPK treatment sequestered 0.16MgC /ha/yr. In some of the locations, however, application of FYM for C sequestration involved additional expenditure and reduced the net income of the farmers. The technologies of SOC sequestration, therefore, need to be promoted by providing incentives, technological knowhow, required resources and policy support to the farmers. Furthermore, manure addition may not be entirely beneficial, as increased production of CH_4 and N_2O emission can occur [117]. Proper management, such as avoiding excess manure application and optimizing the application timing to synchronize with crop uptake, will ensure the most positive effects of manure addition on SOC storage and GHG emission [105].

8.4 Carbon sequestration in soils through straw incorporation

Organic wastes have been applied to soils for centuries, and probably millennia, as a means of supplying nutrients to crops and maintaining soil organic matter content, with the resulting benefits in soil structure and water retention. Powlson et al. [118] used the Rothamsted Carbon Model to estimate SOC accumulation using cereal straw in a silty clay loam soil under the climatic conditions of north-west Europe. The predominant justification for returning straw or other crop residues to soil should be the maintenance of soil organic matter, soil quality and functioning, not carbon sequestration for climate change mitigation. Using straw for electricity generation saved seven times more CO_2 than from SOC accumulation. The considerably greater climate change mitigation is achieved through saved CO_2 emissions by burning straw for electricity generation, replacing some use of fossil fuel. If straw is added to soil of higher clay content than other types of soils, SOC accumulation would be somewhat higher, because soils containing more clay tend to accumulate more SOC under comparable management practices [119].

8.5 Production of N_2O and CH_4 from farming practices

Nitrous oxide and methane account for about 6% and 19%, respectively, of the anthropologically derived greenhouse effect [120]. Global emissions of N_2O and CH_4 are directly related to land use and soil management practices [121], [122], because between one half and two thirds of all anthropogenic N_2O and one third of all anthropogenic CH_4 are thought to come from cropland soil [8]. The production of N_2O in soils is due mainly to nitrifying and denitrifying microorganisms [123]. To minimize N_2O emission from agricultural practices, soil managers may be able to adopt such methods as precision fertilizer application based on soil and plant testing [124], fertilizer application efficiency [125], minimizing the fallow period to avoid high rates of decomposition [125], and optimized split application using precision farming techniques [126], [127] .

In Japan, CH_4 emission from paddy fields accounts for 55% of the total Japanese CH_4 emissions, while that from paddy fields worldwide accounts for 16% of the total world CH_4 emissions. Methane flux shows a maximum from afternoon towards evening in a day, and at the late growth stage of rice in the year [117]. Methods of water management, timing and amounts of straw application, and types and rates of nitrogen fertilizer have important effects on CH_4 emission [117]. Among the management options for mitigating CH_4 emission in paddy fields, short-term drainage in mid-season, intermittent irrigation, improved infiltration, sulfate fertilizer application, and soil oxidation have the greatest potential [117]. Consequently, appropriate flooding control and nutrient management may mitigate CH_4 and other GHG emissions.

8.6 Soil management for adapting to climate change

Cox et al.'s [128] fully coupled, three-dimensional carbon–climate model indicated that the terrestrial biosphere acts as an overall carbon sink until about 2050, but turns into a source thereafter. Ciais et al. [129] reported that, while the United Kingdom accomplished its goal for reducing carbon dioxide emission from fossils fuels, this success has been wiped out by the acceleration of carbon emissions from the soil brought about by the heat and drought of 2003. The contribution of soil carbon pool enhancement to reducing the rate of enrichment of atmospheric concentration is debatable, and adopting agricultural soil as a carbon sink would reduce the obligation to cut emissions of carbon dioxide from fossil fuel combustion [130]. It would be risky to try to accumulate carbon dioxide emissions from fossil fuels into agricultural soil, because there is no guarantee that the soil carbon will remain there for centuries of farming. The importance of SOM in agricultural soil is, however, not controversial, as soil management is a principle for ensuring the sustainability of agriculture. Human-induced soil degradations, loss of productivity, inadequate replacement of nutrients in soils, water management, soil erosion, and shortened fallow periods cause SOM levels to decline more [66] and may intensify global warming. Over the short term, increasing CO_2 in the atmosphere could enhance plant growth through CO_2 fertilization, thus, removing some of the excess CO_2 [131]. However, current models predict that, in the longer term, rising temperatures will speed up the decomposition of organic carbon in soil, releasing CO_2 into the atmosphere in excess of any carbon sequestered in the soil, and adding to climate change [76].

9 CONCLUSIONS AND RECOMMENDATIONS

The management of natural (biotic) and engineered techniques (abiotic) can partially change the climate through sequestration of CO_2 and other GHGs in different long-term stable storages and minimizing GHGs emissions.

Engineering techniques of CO_2 storage in industrial materials, building construction, geopolymer cement, deep ocean, geological strata, old coal mines and oil wells, landfills, wetlands, and saline aquifers along with mineral carbonation of CO_2 are the possible carbon sequestration strategies, although those are not yet widely available and have leakage risks. In comparison, biotic techniques are immediately available and have numerous benefits. The recommended management practices for C sequestration in soils, croplands and terrestrial plants are as follows: (1) soil restoration and woodland regeneration; (2) adopting regenerative agriculture (e.g., conservation tillage or no-till farming, cover crops, crop rotation, surface-residue management, mulch farming, cereal straw and sludge application, nutrient management, appropriate manuring, efficient irrigation and water conservation, improved grazing etc); (3) cultivating crops with deep-root systems; (4) developing and cultivating plants with high lignin content, especially in residues and roots; (5) enhancing biological N fixation; (6) increasing crop biomass production; (7) agroforestry practices; (8) growing energy crops on spare lands; (9) increase of forest growth on existing and unmanaged all available land in the tropical and other areas; (10) increase of forest or grassland in arid and semi arid regions, desert, semi desert and savanna areas; (11) afforestation of marginal agricultural land; (12) conversion of urban and residential spare lands into turf grasslands; (13) planting trees in mining degraded lands; and (14) preserving forestry in polar region.

Before executing the policy of carbon sequestration by agricultural and non-agricultural soil management practices, the following issues should be investigated well: (1) impacts of land use and land management on soil carbon sequestration and ways to increase the storage time of carbon in the soil; (2) the underlying mechanisms controlling soil structure and the storage of carbon. These include various chemical, physical, biological, mineralogical, and ecological processes; (3) the relationships between biodiversity, atmospheric CO_2 levels, and increased nitrogen deposition in carbon storage.

After carbon sequestration by photosynthesis of terrestrial plants, oceans can be the second largest carbon sinks through the absorption of carbon dioxide via physicochemical process, biological pump by phytoplankton, and by application of iron nutrients in oceans.

In addition to carbon sequestration in biotic and abiotic systems, the GHGs emissions should be prevented and reduced through the different anthropogenic activities including land-use change, deforestation, biomass burning, draining of wetlands, degrading soil cultivation, fossil fuel combustion, GHGs emissions from energy and process industry etc.

The rate of increase in SOC stock, through land-use change and adopting recommended management practices, follows a sigmoid curve that attains the maximum 5–20 years after the adoption of recommended management practices, and continues until SOC attains another new equilibrium. As global warming progresses, the depletion of SOC stock from the root zone will strongly affect soil productivity and environmental quality. Farming practices which tend to accumulate carbon in the soil almost always engender other environmental benefits, including reduced erosion, improvements in soil and water quality, economies in fossil energy, and greater biodiversity. Soil organic carbon stock should be considered not only as a means to reduce atmospheric CO_2 levels, but also as a natural resource that can be managed to ensure global food security and promote environmental conservation. It would be risky to try to accumulate carbon dioxide emissions from fossil fuels into agricultural soil, because there is no guarantee that the soil carbon will remain there for centuries of farming.

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