

Soil carbon sequestration

SOLAW Background Thematic Report - TR04B

R. Lal



Table of contents

Introduction	5
The global carbon cycle	5
Basic concepts of carbon sequestration	7
Challenges of enhancing soil carbon storage	9
Technical potential of soil carbon sequestration using recommended practices	14
Co-benefits of terrestrial sequestration	15
Achieving global food security	16
Farming soil carbon	18
Need for new tools to measure SOM dynamics	19
Biofuels and soil carbon pool	20
Yield gaps and best management practices	22
Reasons BMPs are not adopted by resource-poor farmers	24
Enhancing farm income	25
Policy implications	25
Conclusions	26
References	27

List of figures

1. Strategies of carbon sequestration based on natural processes, engineering techniques and chemical transformations
2. Interaction between the pedologic (soils) pool and the biotic pool as two distinct but related components of the terrestrial pool
3. Recommended management practices to sequester carbon in soils
4. Managing cycling of water, carbon, nitrogen, phosphorous and sulphur to enhance soil quality and accentuate ecosystem services
5. Growing biomass and cyanobacteria as biofuel feedstocks from industrial CO₂ and city wastewater
6. Yield gap between BMPs and traditional technologies
7. (a) World and (b) regional fertilizer consumption
8. Co-benefits and ecosystem services created by SOC sequestration

List of tables

1. Cost of carbon sequestration using different techniques
2. Fossil-fuel-based input for modern agriculture
3. Cumulative avoided emissions from land-use conversion
4. Cost of carbon sequestration by different techniques
5. Area under no-till farming in different countries
6. Changes in irrigated land area in countries of sub-Saharan Africa from 1960 to 2003

Introduction

This report describes the technical potential of C sequestration in soils, discusses technological options that are available for realizing the potential, and outlines the challenges of turning world soils into sinks for atmospheric CO₂. The goal is to collate, review and synthesize important information on soil C sequestration to enhance the credibility and integrity of the scientific information (Sills, 2010).

An increase in the atmospheric concentration of carbon dioxide (CO₂) (from 280 parts per million (ppm) in the pre-industrial era to 390 ppm in 2010, an enrichment of 39 percent) and other greenhouse gases (GHGs, such as nitrous oxide [N₂O] and methane [CH₄]), may accentuate radiative forcing and alter the Earth's mean temperature and precipitation (IPCC, 2007). The atmospheric concentration of CO₂ at 390 ppm as a volume is equivalent to ~590 ppm as a mass. The mass of the atmosphere is 5.14×10^{18} kg (Trenberth *et al.*, 1988). Therefore, the total mass of CO₂ is 3 030 Pectagrams+ (Pg), which is equivalent to 825 Pg of carbon. Because of this strong impact on radiative forcing, there is increasing emphasis on identifying strategies that will reduce the rate of enrichment of atmospheric CO₂ by offsetting anthropogenic emissions. The focus, therefore, is on sequestration of CO₂ from the atmosphere or point sources. Anthropogenic sources include the combustion of fossil fuel, cement manufacturing, deforestation and the burning of biomass, and land-use conversion including drainage of peatlands, soil tillage, animal husbandry, etc.

There is a strong interest in stabilizing the atmospheric abundance of CO₂ and other GHGs to mitigate the risks of global warming. The Conference of the Parties (COP)-15 arrived at the Copenhagen Accord, which suggests reducing net emissions to hold the increase in global temperature below 2 °C (UNFCCC, 2009). Although disappointing, the Accord provides opportunities for limiting warming (Ramanathan and Xu, 2010). Its acceptance implies that CO₂ concentration needs to be limited to below 441 ppm by 2100 by reducing CO₂, CH₄ and N₂O emissions and by offsetting emissions through sequestration of carbon in soils and other terrestrial and inland aquatic ecosystems.

Three strategies are available for lowering CO₂ emissions to mitigate climate change (Schrag, 2007): (i) reducing global energy use; (ii) developing low or no-C fuel; and (iii) sequestering CO₂ from point sources or atmosphere using natural and engineering techniques. Between 1750 and 2003, anthropogenic emissions were estimated at 292 Pg from the combustion of fossil fuels (Holdren, 2008), and at 136 ± 30 Pg from land-use change, deforestation and soil cultivation (IPCC, 2001). Currently, approximately 8.3 Pg C yr^{-1} is emitted by fossil fuel combustion (IPCC, 2007; WMO, 2010) and 1.6 Pg C yr^{-1} by deforestation, land-use change and soil cultivation. The total for anthropogenic emissions is 9.9 Pg C yr^{-1} , of which 4.2 Pg C yr^{-1} is absorbed by the atmosphere and 2.3 Pg C yr^{-1} by the ocean. The remainder may be absorbed by unidentified terrestrial sinks.

The global carbon cycle

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 4 130 Pg, of which 85 percent is coal, 5.5 percent is oil and 3.3 percent is gas. Proven reserves of fossil fuel include 678 Pg of coal (3.2 Pg yr^{-1} of 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) (Schrag, 2007). Currently, coal and oil each account for approximately 40 percent of global CO₂ emissions (Schrag, 2007). Thus, the fossil fuel pool is depleting as a result of fossil fuel combustion, at the rate of 8.3 Pg C yr^{-1} .

The third largest pool is in the soil, pedologic and is estimated at 2 500 Pg to 1 m depth. This pool has two distinct components: soil organic C (SOC) pool estimated at 1 550 Pg and soil inorganic C (SIC) pool at 950 Pg (Batjes, 1996). The SOC pool includes highly active humus and relatively inert charcoal C. It comprises a mixture of: (i) plant and animal residues at various stages of decomposition; (ii) substances synthesized microbiologically and/or chemically from the breakdown products; and (iii) the bodies of live micro-organisms and small animals and their decomposing products (Schnitzer, 1991). On the basis of the mean residence time (MRT) or ease of decomposition, the SOC pool can be grouped into three categories: labile with an MRT of days to years, intermediate with MRT of years to decades and centuries and passive with MRT of centuries to millennia.

The SIC pool includes elemental C and carbonate minerals such as calcite, and dolomite, and comprises primary and secondary carbonates. The primary carbonates are derived from the weathering of parent material. In contrast, the secondary carbonates are formed by dissolution of CO₂ in soil air into dilute carbonic acid and its interaction with calcium (Ca⁺²) and magnesium (Mg⁺²) brought in from outside the local ecosystem (e.g. calcareous dust, irrigation water, fertilizers, manures). The SIC is an important constituent of soils in arid and semi-arid regions.

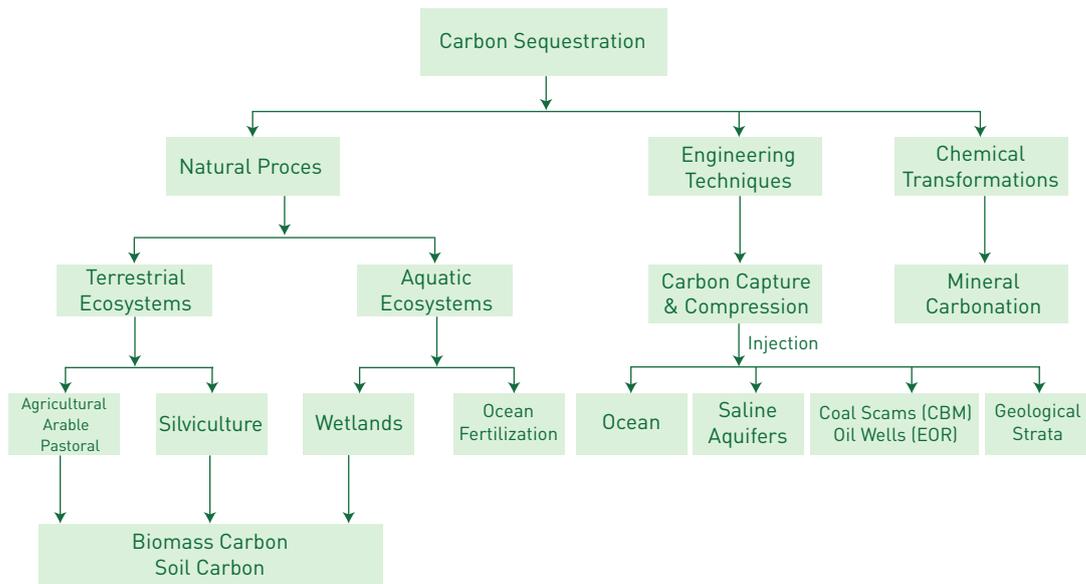
The fourth largest pool is the atmospheric pool comprising ~800 Pg of CO₂-C, and is increasing at the rate of 4.2 Pg C yr⁻¹ or 0.54 percent yr⁻¹. The smallest among the global C pools is the biotic pool, which is estimated at 620 Pg, comprising 560 Pg of live biomass and 60 Pg of detritus material. The pedologic and biotic C pools together are called the terrestrial C pool estimated at approximately 3 120 Pg.

The terrestrial and atmospheric C pools strongly interact with one another through photosynthesis and respiration. The annual rate of photosynthesis is 120 Pg C, most of which is returned to the atmosphere by plant and soil respiration. Conversion from natural to managed ecosystems, extractive farming practices based on low external input, and soil degrading land use tend to deplete terrestrial C pools. The pedologic pool loses 1.1 Pg C into the atmosphere as a result of soil erosion and another 0.3-0.8 Pg C yr⁻¹ to the ocean through erosion-induced transportation to aquatic ecosystems. Yet, the terrestrial sink is currently increasing at a net rate of 1.4 ± 0.7 Pg C yr⁻¹. Thus, the terrestrial sink absorbs approximately 2-4 Pg C yr⁻¹ and its sink capacity may increase to approximately 5 Pg C yr⁻¹ by 2050 (Cramer *et al.*, 2001; Scholes and Noble, 2001). Increase in the terrestrial sink capacity may be the result of the CO₂ fertilization effect and changes in land use and management. The biotic pool also contributes to an increase in atmospheric CO₂ concentration through deforestation and land-use conversion at the rate of ~1.6 Pg C/yr.

The strong interactions between the atmospheric, pedologic and the biotic C pools comprise important components of the global carbon cycle (GCC). Understanding and managing these interactions form the basis of any strategy to sequester atmospheric CO₂ in the biotic and pedologic pools. This report describes the underlying processes and outlines land use and management options that would transfer atmospheric CO₂ into the pedologic pool on a long-term basis.

The atmospheric pool is connected to the oceanic pool, which absorbs 92.3 Pg yr⁻¹ and releases 90 Pg yr⁻¹ with a net positive balance of 2.3 Pg C yr⁻¹. The oceanic pool will absorb approximately 5 Pg C yr⁻¹ by 2100 (Orr *et al.*, 2001). The total dissolved inorganic C in the oceans is approximately 59 times that of the atmospheric pool. On the scales of millennia, the oceans determine the atmospheric CO₂ concentration, not vice versa (Falkowski *et al.*, 2000).

FIGURE 1: STRATEGIES OF CARBON SEQUESTRATION BASED ON NATURAL PROCESSES, ENGINEERING TECHNIQUES AND CHEMICAL TRANSFORMATIONS



Basic concepts of carbon sequestration

Atmospheric enrichment of GHGs can be moderated by either reducing anthropogenic emissions, or sequestering C in plant biomass or the soil. Transfer of atmospheric CO₂ into other pools with a longer MRT, in such a manner that it is not re-emitted into the atmosphere in the near future, is called sequestration. Depending on the processes and technological innovations, there are three main types of C sequestration (Figure 1): (i) those based on the natural process of photosynthesis and conversion of atmospheric CO₂ into biomass, soil organic matter or humus and other components of the terrestrial biosphere; (ii) those involving engineering techniques; and (iii) those involving chemical transformations (Lal, 2008).

The rate of enrichment of atmospheric CO₂ concentration can be reduced and moderated by its transfer to other pools by mitigative and adaptive options. Mitigative strategies involve those options that either reduce emissions or sequester C. Emission reduction includes those technologies that enhance energy-use efficiency, and involve low-C or no-C fuel sources. In general, natural processes of sequestering C into terrestrial and aquatic ecosystems are more cost-effective and have numerous co-benefits, such as enhancement of ecosystem services, as compared with engineering techniques and conversion of CO₂ into carbonates (Table 1; McKinsey and Company, 2009).

TABLE 1: COST OF CARBON SEQUESTRATION USING DIFFERENT TECHNIQUES

Technique/Strategy	Cost of abatement C / Đ [Mg C eq.] ⁻¹
Tillage and residue management	-183.3
Waste recycling	-55.0
Degraded-land restoration	36.7
Second-generation biofuels	18.3
Pastureland afforestation	36.7