Chapter 1
Managing Terrestrial Carbon in a Changing Climate

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Abstract The threat of abrupt climate change by increase in atmospheric concentration of CO_2 and other greenhouse gases has enhanced the interest and urgency of identifying strategies for reducing and sequestering anthropogenic emissions. The latter are caused by land use conversion that began with the dawn of settled agriculture several millennia ago, and by fossil fuel combustion that began with the onset of the industrial revolution in about 1750. Emissions from land use conversion during the pre-industrial era until about 1850 are estimated at $\sim$320 Pg. Since 1850, emissions from fossil fuel combustion are estimated at $\sim$350 Pg and those from land use conversion at $\sim$150 Pg. These and other anthropogenic activities have caused drastic perturbation of the global carbon cycle with increase in the atmospheric C pool and an attendant decrease in the pedologic, biotic, and geologic (fossil fuel) pools. Together, the pedologic pool (4,000 Pg to 3 m depth) and the biotic pool (620 Pg), called the terrestrial pool, is the third largest pool, after the oceanic (38,000 Pg) and the geologic ($\sim$5,000 Pg). The depletion of the terrestrial C pool has created a C sink capacity which can be filled by conversion to a restorative land use and adoption of recommended soil, plant, and animal management practices. The process of transfer of atmospheric CO_2 into the pedologic and biotic pools is called carbon sequestration. This natural process contrasts with that of the geoengineering techniques of *carbon capture and storage* (CCS) involving geologic and oceanic storage and mineral carbonation of CO_2 into calcite etc. The strategy of biosequestration, in addition to being cost-effective, has numerous ancillary benefits. It is a truly win–win option. Specifically, it improves soil quality, enhances agronomic productivity, and advances food security. Improvement in soil quality by C sequestration is related to generation and stabilization of micro-aggregates created through formation of organo-mineral complexes. The strategies of biosequestration involve development of a positive ecosystems C budget in soil by mulch farming, conservation

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agriculture, no-till systems, integrated nutrient management including biological N fixation and mycorrhizae use of amendments including biochar, and adoption of complex farming systems such as agroforestry. There is no silver bullet or panacea, and the choice of a practice/strategy depends on site-specific conditions.

Keywords Carbon sequestration • Geoengineering • Soil quality • Ecosystem services • Carbon capture and storage • Conservation agriculture • Soil structure

1.1 Introduction

Enrichment of the atmospheric concentration of CO_2 from 280 ppmv in the pre-industrial era to 390 ppmv in 2010, and the attendant increase in risks of *abrupt climate change* (ACC), have created an urgency to identity strategies of managing the *global carbon cycle* (GCC), and to limiting the increase in global temperature to 2 °C (Ramanathan and Xu 2010; UNFCCC 2009). Thus, establishing the cause-effect relationships for enrichment of atmospheric CO_2 is important to systemically reducing emissions and mitigating ACC. The importance of fossil fuel combustion since the onset of the industrial revolution during the Anthropocene (Crutzen 2002; McNeill 2000) is widely recognized. Global emissions from fossil fuel combustions increased dramatically during the second half of the twentieth century (Sterman 2008). Yet the role of land use change in emitting CO_2 and other *greenhouse gases* (GHGs) into the atmosphere cannot be overemphasized (Foley et al. 2005). In 1700, about 50 % of the terrestrial biosphere was wild, and most of the remainder (45 %) was in a semi-natural state. By 2000, most of the biosphere had been converted into "anthromes" consisting of croplands, grazing lands, plantations, and urban ecosystems and rural communities (Ellis et al. 2010). About 39 % of the earth's ice-free surface had been converted into agricultural and urban ecosystems, and an additional 37 % is embedded within or in close proximity to anthromes and is drastically influenced by anthropogenic processes. Transformation of natural/wilds to anthromes leads to depletion of the terrestrial C pool and emissions of CO_2 and other GHGs into the atmosphere. Depletion of the terrestrial C pool causes degradation of ecosystem services and functions. Management and restoration of the terrestrial C pool is essential to restoring the ecosystem functions, improving the environment, and mitigating ACC.

The objective of this chapter is to describe the relative contributions of land use change and fossil fuel combustion to the emission of CO_2 and other GHGs into the atmosphere, to identify processes and practices of C sequestration in the biosphere, and to explain the importance of soil C sequestration to *adapting to and mitigating* (ADAM) ACC, improving the environment, and advancing food security. Furthermore, processes of soil C sequestration are discussed in the context of enhancing permanence or *mean residence time* (MRT) and improving ecosystem services.

1.2 Relative Contributions of Fossil Fuel Combustion Versus Land Use Change

From 1850 to 1998, approximately 270 ± 30 Pg C had been emitted as CO_2 into the atmosphere from fossil fuel burning and cement production. In comparison, about 136 ± 55 Pg had been emitted as a result of land use change (IPCC 2000), of which 78 ± 12 Pg was from world soils. Another estimate showed that between 1750 and 2002, 292 Pg CO_2–C was contributed by fossil fuel combustion, and an additional 200 Pg C was projected to be emitted between 2003 and 2030 (Holdren 2008). Houghton (2007) estimated the total magnitude of anthropogenic emissions at 500 Pg since 1850, comprising 375 Pg from fossil fuel combustion, 100 Pg from land use change, and 25 Pg from cement production. Of these emissions, 150 Pg have been adsorbed by the oceans, 125 Pg by the terrestrial biosphere, and the remainder (225 Pg) by the atmosphere (Houghton 2007). The data in Table 1.1 show a progressive increase in CO_2–C emissions from fossil fuel combustion, beginning with merely 3 Tg (teragram = 10^{12} g = million metric tonnes) in 1750 to 8.7 Pg (petagram = 10^{15} g = billion metric tonnes) in 2008. According to these data, total emissions by fossil fuel combustion since 1750 are estimated at 350 Pg (Marland et al. 2007). At present, about 1.6 Pg C/year are contributed (~17 % of total) from land use change, involving primarily deforestation in the tropics. As late as the early 1950s, more CO_2–C emissions were contributed by land use (deforestation) than by fossil fuel combustion. Global average per capita CO_2 emissions have doubled from 0.65 Mg CO_2 in 1950 to 1.2 Mg in 1970, and have remained stable since then (Oelkers and Cole 2008).

Both fossil fuel combustion and land use change are driven by the increase in population (Table 1.2). The world population increased from merely 2 million in ~10,000 BCE to 188 million in 1 CE, 1 billion in about 1,800 CE, and 7 billion in 2011. The increase in human population resulted in an increase in cropland area from <5 Mha ~5,000 BCE to 300 Mha in 1,600 CE, 419 Mha in 1,800, 850 Mha

Table 1.1 Global estimates of fossil fuel emissions

Years	Total emissions (Tg C/year)
1750	3
1800	8
1850	54
1900	534
1950	1,630
1960	2,578
1970	4,075
1980	5,297
1990	6,096
2000	6,744
2008	8,700

Source Adapted from Marland and Rotty (1984), ORNL (2001), LeQuéré et al. (2010)

Table 1.2 Temporal changes in population, and total and per capita croplands and pastureland area

Time	Population 10^6	Cropland		Pastureland	
		Total (10^6 ha)	Per capita (ha)	Total (10^6 ha)	Per capita (ha)
10,000 BCE	2	0	0	0	0
5,000 BCE	18	4.8	0.24	0.4	0.02
1 CE	188	131	0.52	106	0.56
500	210	124	0.43	108	0.51
1,000	295	153	0.36	143	0.48
1,500	461	232	0.33	224	0.49
1,600	554	255	0.29	288	0.52
1,700	603	300	0.30	324	0.54
1,800	989	419	0.24	513	0.52
1,900	1,654	850	0.35	1,293	0.78
1,950	2,545	1,214	0.33	2,466	0.97
2,000	6,145	1,532	0.16	3,429	0.55

Source Adapted from Goldewijk et al. (2011)

in 1,900, and 1,500 Mha in 2,000. There was a similar increase in the area under grazing land/pasture land. The area under grazing/pasture land increased from 0.4 Mha ~5,000 BCE to 288 Mha in 1,600 CE, 513 Mha in 1,800, 1,293 Mha in 1900, and 3,429 Mha in 2,000 (Table 1.2).

Because of the drastic transformation of earth by humans since the transition of hunter/gatherer societies to a sedentary lifestyle and settled agriculture, some argue that the anthropogenic greenhouse era began thousands of years ago (Ruddiman 2003, 2006). Indeed, records show that the increase in CO_2 emissions began with the start of forest clearance 8,000 years ago and the increase in CH_4 with the onset of rice cultivation and the domestication of animals about 5,000 years ago. Ruddiman (2003) hypothesized that per annum rates of C release of CO_2 from land use in pre-industrial times may have been lower by an average factor of 10 or more. Even so, the cumulative emissions over millennia (for 8,000 years) could still be enormous. Total emissions by land use conversion of 480 Pg have been estimated as follows (Ruddiman 2003):

$$\text{(i) the pre-industrial era: } 7800\,\text{years} \times 0.04\,\text{Pg C/year} = 320\,\text{Pg} \qquad (1.1)$$

$$\text{(ii) the industrial era: } 200\,\text{years} \times 0.8\,\text{Pg C/year} = 160\,\text{Pg} \qquad (1.2)$$

Indeed, the greatest land clearance occurred during the last 200 years, with a total mean annual flux of 1.04 Pg C between 1850 and 2000, and as much as 2 Pg C between 1980 and 2000 (Table 1.3). Thus, cumulative C emitted from land use conversion has been estimated at 480 Pg over the last 8,000 years, equivalent to the enrichment of atmospheric concentration of CO_2 by ~120 ppm (4 Pg CO_2–C emission = 1 ppmv CO_2 concentration in the atmosphere) (Broecker 2007).

These statistics of CO_2–C emission from land use change (vs. fossil fuel emissions) for the last 8,000 years or more, tentative and crude as they may be, are

Table 1.3 Estimates of average annual flux of CO_2–C from land use change

Region	Annual emission (Pg C/year)		
	1850–2000	1980–1989	1990–1999
Tropics	0.65	1.93	2.20
Temperate	0.39	0.06	−0.02
Total	1.04	1.99	2.18

Source Adapted and recalculated from Houghten (2003)

important to the identification of strategies of C sequestration in the terrestrial biosphere. The fact that the terrestrial biosphere has lost as much as 480 Pg is a strong indication of its large C sink capacity. For this reason, recarbonization of the biosphere, enhancing the C pool in both soils and vegetation, is an important option to mitigating ACC.

1.3 The Global Carbon Cycle

The GCC involves principal C reservoirs and fluxes among them. The contemporary GCC involves five principal pools (Fig. 1.1). The largest pool is carbonate rocks (65 × 106 Pg), followed by ocean comprising 38,000 Pg C, mostly as inorganic C. The second largest pool is geologic, comprising fossil fuels, coal, oil, gas, shale, and peat, together estimated at ~5,000 Pg. The third largest pool is soil, containing ~4,000 Pg of *soil organic carbon* (SOC) and *soil inorganic carbon* (SIC) to 3 m depth. The fourth largest pool is the atmosphere containing ~800 Pg C. Thus, atmosphere merely contains 0.001 % of the C contained in the atmosphere–ocean–upper crust system (Oelkers and Cole 2008). The mass of the Earth's atmosphere is 5.14 × 1,018 kg (Trenbath et al. 1988); with a CO_2 concentration of 390 ppmv, total mass of CO_2 is about 3,000 Pg or equivalent to about 800 Pg C (Oelkers and Cole 2008). The smallest pool is biotic, estimated to contain 620 Pg C, comprising 560 Pg of live material and 60 Pg of detritus material. Combined together, the soil (4,000 Pg) and the biotic (620 Pg) pools, or the terrestrial pool, is estimated at 4,620 Pg, containing about 4.8 times more C than the atmospheric pool.

The GCC on a decadal scale from 1960 to 2008 is shown in Table 1.4. The cumulative annual sources of CO_2 were 4.6 Pg during the 1960s, 6.0 Pg during the 1970s, 7.0 Pg during the 1980s, 8.0 Pg during the 1990s, and 9.1 Pg during the 2000s (2000–2008), with total annual emissions of 9.9 Pg (8.7 from fossil fuel combustion and 1.2 Pg from land use change) in 2008. Of the total annual emissions, land use change contributed 32.6 % in the 1960s, 21.7 % during the 1970s, 21.4 % during the 1980s, 20.0 % during the 1990s, and 15.4 % during the 2000s (2000–2008), with a contribution of 12.1 % during 2008 (Table 1.4). Whereas the emissions from fossil fuel combustion have increased between 1960 and 2008 at the mean annual rate of 0.117 Pg C/year, those from land use

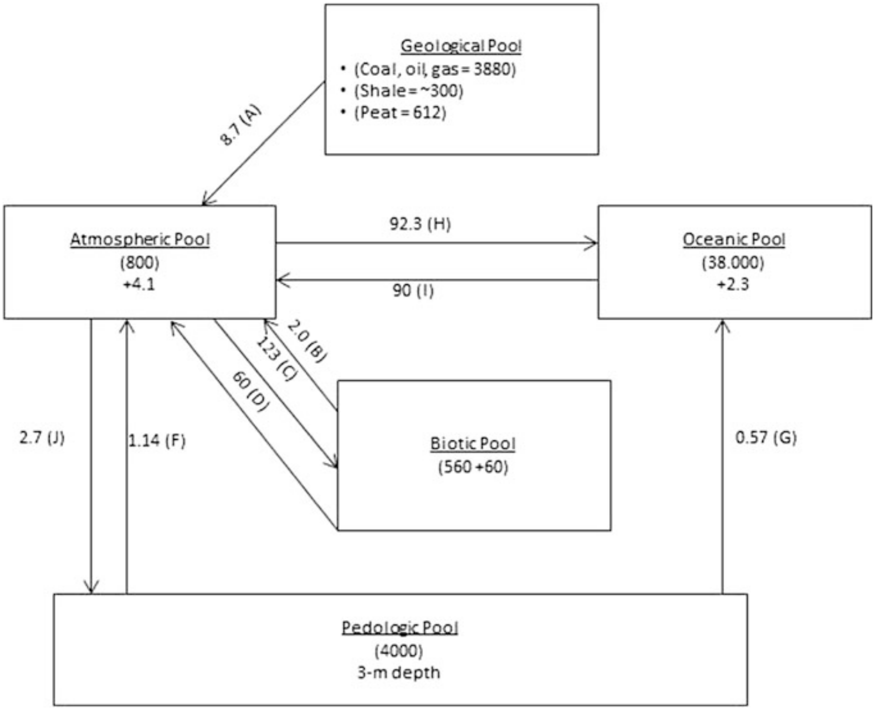

Fig. 1.1 The global carbon cycle. *Source* This author

Table 1.4 Global carbon budget on a decadal scale

Parameter	1960s	1970s	1980s	1990s	2000–2008	2008
1. Sources (Pg C/year)						
Fossil fuel + cement	3.1	4.7	5.5	6.4	7.7	8.7
Land use	1.5	1.3	1.5	1.6	1.4	1.2
Total	4.6	6.0	7.0	8.0	9.1	9.9
2. Sinks (Pg C/year)						
Atmosphere	1.8	2.7	3.4	3.1	4.1	3.9
Ocean	1.5	1.7	2.0	2.2	2.3	2.3
Land	1.2	2.6	1.8	2.6	3.0	4.7
Total known sinks	4.5	7.0	7.2	7.9	9.4	10.9
3. Residual sink	0.1	−1.0	−0.2	0.1	−0.3	−1.0
Total ocean + land sinks	2.8	3.3	3.6	4.7	5.0	5.0
4. Natural sinks as % of sources	60.9	55.0	51.4	58.8	54.9	50.5

Source Adapted and recalculated from LeQuéré et al. (2010)

conversions have decreased at the mean annual rate of 6.25 Tg C/year. Combined, the anthropogenic emissions have increased at the mean annual rate of 0.110 Pg C/year between 1960 and 2008 (Table 1.4).

The atmospheric uptake has progressively increased (Pg C/year) by 1.8 in the 1960s, 2.7 in the 1970s, 3.4 in the 1980s, 3.1 in the 1900s, and 4.1 in the 2000s (2000–2008). The oceanic uptake also increased (Pg C/year) by 1.5 in the 1960s, 1.7 in the 1970s, 2.0 in the 1980s, 2.2 in the 1990s, and 2.3 in the 2000s (2000–2008). The uptake by land-based sinks (Pg C/year) also increased between the 1960s and the 2000s by 1.2 in the 1960s, 2.6 in the 1970s, 1.8 in the 1980s, 2.6 in the 1990s, and 3.0 in the 2000s (2000–2008). The natural sinks (land and ocean combined) absorbed anthropogenic emissions (Pg C/year) by 2.8 in the 1960s, 3.3 in the 1970s, 3.6 in the 1980s, 4.7 in the 1990s and 5.0 in the 2000s. Relative uptake by natural sinks (land plus oceans) as a percentage of the total anthropogenic emission was 61 in the 1960s, 55 in the 1970s, 51 in the 1980s, 59 in the 1990s, and 55 in the 2000s. Some have argued that the C absorption by natural sinks has declined between the 1960s and the 2000s, probably because of the acidification of oceans and degradation and desertification of lands and soils.

Phytosequestration of land plants, and transfer of some *net primary productivity* (NPP) into humus, is a viable option for recarbonizing the biosphere. The annual *gross primary productivity* (GPP) is estimated at 123 Pg (arrow C, Fig. 1.1), of which 60 Pg is returned to the atmosphere through plant respiration (arrow D, Fig. 1.1). Of the remaining 63 Pg, called NPP, around 53 Pg (arrow E, Fig. 1.1) is transferred to roots and allocated to plant metabolism, and the remaining 10 Pg is called the *net ecosystem productivity* (NEP) (Jansson et al. 2010). Most of the NEP is lost to the atmosphere by land use change (arrow B, Fig. 1.1), biotic stresses, fires, and erosion (arrow F, Fig. 1.1). The remainder (0.3–0.5 Pg/year) is called the *net biome productivity* (NBP) (Jansson et al. 2010). The NBP can be enhanced to about 10 Pg C/year through land use and prudent management, and has the potential to persist in the terrestrial biosphere for from centuries to millennia depending on the specific land use in soils and biomass. Thus, C sequestration in the terrestrial biosphere has the potential to offset anthropogenic emissions and mitigate ACC. Here in lies the basic principle of managing the terrestrial C pool to mitigate climate change and also improve the environment.

1.4 The Terrestrial Carbon Pool

The total land area under all biomes, including deserts and ice cover, is 14.3 Bha (Bha = 10^9 ha) (Table 1.5). Of this, 4.85 Bha (33.9 %) is under forest, 2.4 Bha (16.7 %) under savanna, 2.65 Bha (18.5 %) under deserts, 1.88 Bha (13.1 %) under permafrost, 0.8 Bha (5.6 %) under tundra, 0.35 Bha (2.4 %) under peatlands, and 1.4 Bha (9.8 %) under cropland (Table 1.5). The total C pool in vegetation is $\sim$560 Pg, and an additional 60 Pg is contained in the detritus material (see box marked Biotic Pool in Fig. 1.1). Of this, 447 Pg (78.8 %) is contained in forests, 88 Pg (15.5 %) in savanna/grasslands/steppe, and the remaining 32 Pg (5.7 %) in other biomass. The total C pool in the world's soils is estimated at 4,000 Pg to 3 m depth (Table 1.5, see box marked Pedologic Pool in Fig. 1.1).

Of this, 1,104 Pg (27.6 %) is contained in soils under forest, 517 Pg (12.9 %) under savanna, 1,024 Pg (28.6 %) under permafrost, 450 Pg (11.2 %) under peatlands, 332 Pg (8.3 %) under deserts, 144 Pg (3.6 %) under tundra, and 248 Pg (6.2 %) under cropland.

The data in Table 1.5 and the analyses presented above indicate the following:

1. Vulnerability of the pedologic pools to climate change: the projected ACC and the attendant warming may thaw some areas under permafrost and tundra, and also accentuate decomposition of peat lands (through drainage and land use conversion). Thus, 1,618 Pg (40 %) of the pedologic pool is vulnerable to decomposition and emission to the atmosphere with the projected ACC. It is important to identify technological options and policy interventions to minimize the risks of positive feedback from these pools, which comprise 40 % of the total pedologic pools.
2. The last column in Table 1.5 shows the ratio of C density (Mg C/ha) for soil: vegetation. The ratio is 59 in croplands, 36 in tundra, 30 in peatlands, 11 in temperate grasslands, 5 in tropical grasslands and 2.5 in tropical forests. This high ratio implies the high risks of degradation of soils of these ecosystems (by thaw, erosion, fire, deforestation, conversion to other land uses, or drainage) to natural and anthropogenic perturbations. Therefore, the soils of these ecosystems must be managed with extreme caution. An understanding of soil properties and processes is extremely important to the sustainable management of soils of these ecologically-sensitive biomes.
3. Major soils of the world are listed in Table 1.6. In terms of the land area, principal soil Orders include Entisols (16.2 %), Aridisols (12.0 %), Inceptisols (9.8 %), Alfisols (9.6 %), Gelisols (8.6 %), Ultisols (8.4 %), Oxisols (7.5 %), Mollisols (6.9 %), Spodosols (2.6 %), Vertisols (2.4 %), Histosols (1.2 %), and Andisols (0.7 %). Rocky land (10 %) and shifting sands (4.1 %) also cover large areas, but have no or little vegetation cover.

In the context of the SOC pool, the fraction most vulnerable to decomposition or erosion by land misuse and soil mismanagement is that in Gelisols, containing 316 Pg (21 %) of the pedological pools to 1 m depth (Table 1.6). The soils supporting tropical rainforest or Oxisols contain 126 Pg (8.3 %). Molliosols and Histosols together contain 300 Pg or ~20 % of the pedological C pool to 1 m depth. Thus, a total of ~50 % of the terrestrial C pool is vulnerable to decomposition, and may also create positive feedback to ACC.

The strategy of managing C in the terrestrial biosphere is therefore, the following:

1. preserve the existing C pool by minimizing the risks of decomposition and erosion, and
2. enhance the biotic and pedologic pools by carbon sequestration in ecosystems which have been depleted through degradation (erosion, deforestation) and desertification.

Table 1.5 Global distribution of soil and biotic pools in different biomes

Vegetation	Ecoregion	Area (10^6 ha)	Soil carbon (3 m)		Vegetation carbon		Soil C: Veg. C density
			Pool (Pg)	Density (Mg/ha)	Pool (Pg)	Density (Mg/ha)	
I. Forest							
	(1) Tropical	2,450	692	282	276	112	2.5
	(2) Temperate	1,200	262	218	99	82	2.6
	(3) Boreal	1,200	150	91	72	60	1.5
	Subtotal	4,850	1,104	–	447	–	–
II. Savanna/grassland/steppe							
	(1) Tropical	1,500	345	230	72	48	4.8
	(2) Temperate	900	172	191	16	18	10.6
	Subtotal	2,400	517	–	88	–	–
III. Deserts		2,650	332	125	9	3.4	36.8
IV. Peatlands		350	450	1,285	15	43	29.9
V. Permafrost		1,878	1,024	545	–	0	–
VI. Tundra		800	144	180	4	5	36
VII. Cropland		1,400	248	177	4	3	59
Grand total		14,328	4,004	–	567	–	–

Source Adapted from Eglin et al. (2010)

Table 1.6 Estimates of carbon pool in world soils (1 m depth)

Soil order	Area		Soil C pool (Pg)		Total (Pg)
	(10^6 ha)	%	Soil organic carbon	Soil inorganic carbon	
Alfisols	1,262	9.6	158	43	201
Andisols	91	0.7	20	0	20
Aridisols	1,570	12.0	59	456	515
Entisols	2,114	16.2	90	263	353
Gelisols	1,126	8.6	316	7	323
Histosols	153	1.2	179	0	179
Inceptisols	1,286	9.8	190	34	224
Mollisols	901	6.9	121	116	237
Oxisols	981	7.5	126	0	126
Spodosols	335	2.6	64	0	64
Ultisols	1,105	8.4	137	0	137
Vertisols	316	2.4	42	21	63
Rocky land	1,308	10.0	22	0	22
Shifting sand	532	4.1	2	5	7
Total	13,080	100	1,526	940	2,466

Source Adapted from Eswaran et al. (2000)

1.5 Carbon Storage Versus Sequestration

There are two terms commonly used in expressing processes and techniques used in transferring atmospheric CO_2 into other pools with a long MRT. One is *CO_2 Capture and Storage* (CCS) by geoengineering techniques. There are three types of CCS technique: geologic, oceanic, and mineral carbonation (Fig. 1.2). The potential and constraints of these techniques are described by Broecker (2008), Oelkers and Cole (2008), Adams and Caldeina (2008), Benson and Cole (2008), and Schneider (2008) among others.

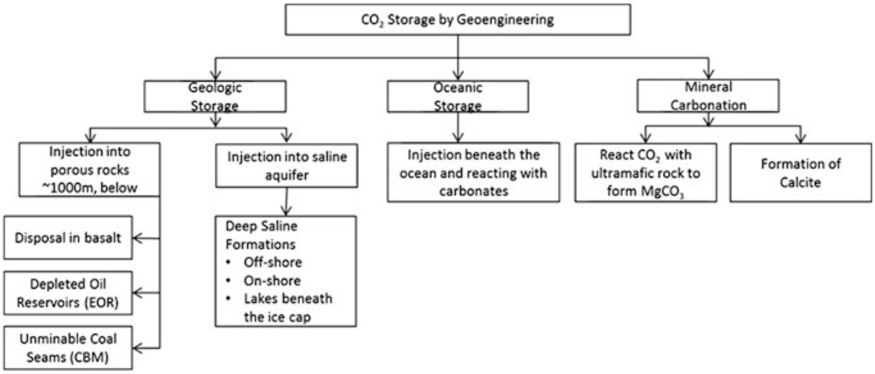

Fig. 1.2 Storage of CO_2 by several geoengineering and geochemical techniques. *Source* This author

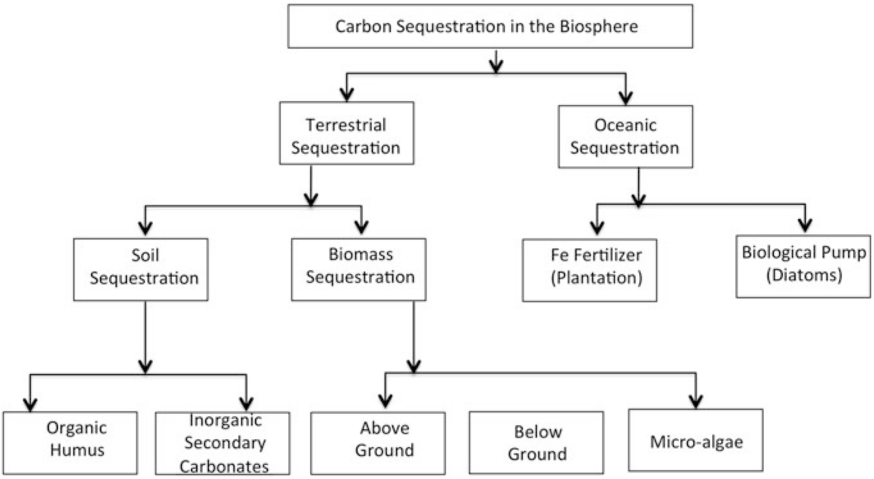

Fig. 1.3 Types of CO_2 sequestration in the biosphere to mitigate climate change. *Source* This author

Table 1.7 Pros and cons of biospheric processes versus engineering techniques of carbon sequestration. *Source* This author

Biotic sequestration	Geoengineering techniques of CCS
1. Pros	**1. Pros**
Natural process	High rate, and large total sink capacity
Cost effective and economical	Rapid process
Numerous co-benefits	Amenable to C trading
Improvement in environment	
No health hazard	
No legal issues	
Amenable to trading C credits	
2. Cons	**2. Cons**
Low sink capacity	Expensive
Dependent on land use	High risks and health hazard
Risks of leakage through decomposition	Few co-benefits (*enhanced oil recovery* (EOR), *coal-bed methane* (CBM))
	Legal issue regarding *measurement, monitoring and verification* (MMV)

In contrast to the geoengineering techniques of CCS, CO_2 sequestration involves the natural processes of photosynthesis and conversion of photosynthate into stable materials (i.e., wood, bio char, humus, recalcitrant organic compounds) so that its MRT within the biosphere is drastically increased from decades to centuries to millennia. Sequestration of CO_2 in the biosphere has two related but distinct components: terrestrial sequestration and oceanic sequestration (Fig. 1.3).

The goal is to retain in the biosphere a large fraction of the NBP and NEP. Details of the CO_2 sequestration techniques in the biosphere are described by Jansson et al. (2010), Jackson and Baker (2010), Lal (2010a), Sayre (2010), Read (2007), and Ogle et al. (2005) among others.

Pros and cons of CCS and biosequestration are outlined in Table 1.7. The natural process of biosequestration is cost-effective, and has numerous ancillary benefits in terms of several ecosystem services. However, CCS techniques are expensive and have high risks, though they are characterized by a large sink capacity. There is no one solution to addressing the complex issue of mitigating ACC by anthropogenic emissions. Niches for each technology must be identified and assessed under site-specific conditions.

1.6 Processes and Techniques of Carbon Sequestration in Soils

The strategy of C sequestration in soil is to increase C gains and reduce C losses. Gains of C in soil are due to addition of biomass from crop residues, animal waste, detritus material from timber and food industry, municipal waste, deposition etc. The loss of C in soil occurs through mineralization or decomposition, erosion, and leaching. The objective is to create a positive C budget in soil, especially by reducing losses through erosion and decomposition. Important techniques of C management on croplands are conservation agriculture or no-till farming, mulching, *integrated nutrient management* (INM) through nutrient cycling and use of bio and synthetic fertilizers, use of complex crop rotations including agroforestry, and application of amendments such as biochar and nano-enhanced materials (zeolites). The importance of soil and water conservation cannot be overemphasized (Lal 2004).

The goal is to produce more from less through sustainable intensification (Lal 2011). The latter implies less but efficient use of energy-based input, especially those with high *hidden C costs* (HCC) such as fertilizers, pesticides, and use of machinery. Conservation and an efficient use of water are also important, especially through replacement of wasteful flood irrigation by micro-irrigation techniques. There are also techniques of management of pasture lands and forest lands (Lal 2010a). Sustainable intensification of a managed ecosystem is needed to meet all the basic necessities of a growing population, regardless of climate change. These basic necessities of the world's population, seven billion in 2011 and projected to reach 9.2 billion by 2050, include an adequate supply of food, feed, fibre, and (bio-)fuel (4 Fs). Increasing the SOC pool to above the threshold level (1.5–2.0 %) in the root zone is essential to improving agronomic production and advancing global food security.

Principal processes of C sequestration in the pedosphere are outlined in Fig. 1.4. There are four basic techniques, two each for the sequestration of SOC

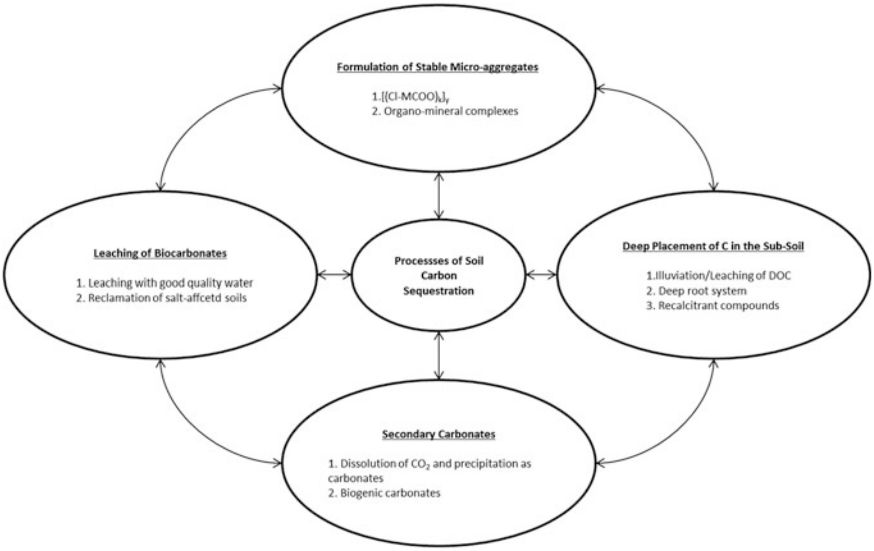

Fig. 1.4 Pedospheric processes leading to sequestration and stabilization of carbon in soil. *Source* This author

and SIC. Enhancing and increasing the stability of structural aggregates (especially micro-aggregates) is a principal mechanism of stabilizing the SOC pool and increasing its MRT. Structural aggregates are created and stabilized through the formation of organo-mineral complexes, especially those involving complexation of organic/humic substances with clay colloids and polyvalent cations (Ca^{2+}, Mg^{2+}, Fe^{3+}, Al^{3+}).

The other mechanism is deep placement of C in the subsoil horizon, away from the climatic elements and the zone of drastic anthropogenic perturbations. In addition to illuviation and leaching, growing perennials/annuals with deep root systems and those containing recalcitrant compounds (e.g. phenols, suberin) can increase the MRT of the C added to the soil solum. Transfer of *dissolved organic C* (DOC) into subsoil and its eventual precipitation in the aquifer or other aquatic ecosystems is also an important mechanism which requires additional research.

Formation of secondary/pedologic carbonates and leaching of bicarbonates are two important mechanisms of the sequestration of SIC (Lal 2004). In general, the rate of C sequestration ranges from 10 to 1,000 kg/ha/year of SOC and from 1 to 10 kg/ha/year for SIC. Management-induced changes in the C pool are sensitive to climate with the following order from largest to smallest changes: tropical moist $>$ tropical dry $>$ temperate moist $>$ temperate dry (Ogle et al. 2005). Thus, management-induced sequestration of SOC is strongly influenced by the present and future climate.

1.7 Sequestration of SOC and Soil Quality

There exists a critical level of SOC below which soil quality is jeopardized (Aune and Lal 1998), it is prone to degradation, and it is less or not at all responsive to inputs. In view of the ever-increasing demands of the burgeoning population, there is a strong need to enhance the SOC pool in the soils of agro-ecosystems. The need is especially urgent for soils of the tropics and subtropics and those managed by resource-poor and small-size landholders who predominately carve out their meagre livings through the widespread use of extractive farming practices. Those soils which have been subject to land misuse and soil mismanagement for a long time, decades to centuries or even millennia, are in dire need of the restoration of their SOC pool. There is an urgent need to enhance agronomic productivity, and this has the additional benefits of offsetting some anthropogenic emissions and improving the environment. For these depleted and degraded soils, each additional 1 Mg C/ha of SOC improves the agronomic yields of crops from 20 to 300 kg/ha, depending on crop, soil type, climate, and management systems (Lal 2006a, 2010b, c). Food production in developing countries can be enhanced by an additional 30 to 50 millions Mg/year by increasing the SOC pool in the root zone of depleted and degraded soils by 1 Mg C/ha (Lal 2006b).

The increase in agronomic productivity by increasing the SOC pool occurs through improvement in soil physical, chemical, and biological quality (Fig. 1.5,

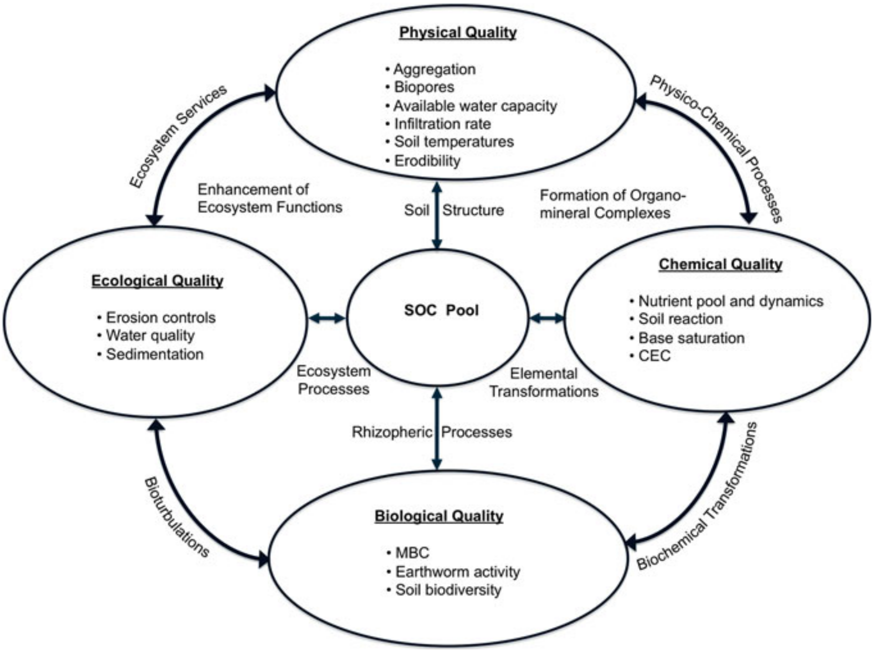

Fig. 1.5 Impacts of improving SOC pool in improvements in soil quality. *Source* This author

Table 1.8 Benefits of restoring organic carbon pool in depleted/degraded soils

Benefits
1. Improving soil structure and tilth
2. Enhancing activity and species diversity of soil fauna
3. Reducing risks of soil erosion and compaction etc.
4. Decreasing non-point source pollution
5. Improving water capacity available to plants
6. Strengthening nutrient cycling
7. Increasing *cation exchange capacity* (CEC) and nutrient retention capacity
8. Increasing agronomic productivity and food security
9. Offsetting anthropogenic emissions
10. Enhancing efficiency of use of agronomic inputs

Source This author

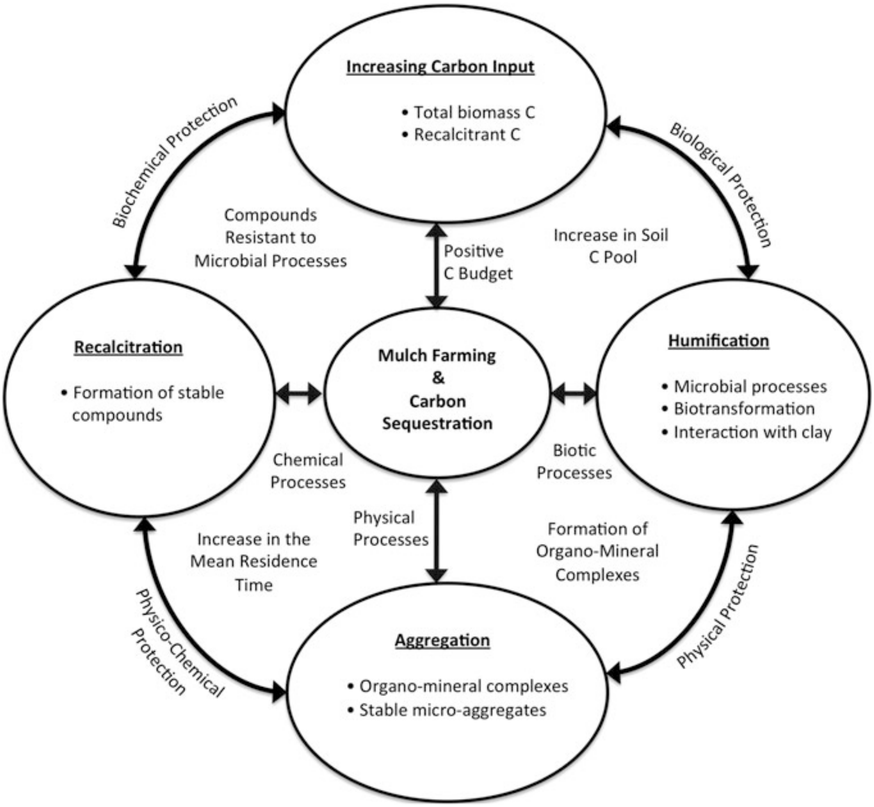

Fig. 1.6 Positive effects of mulch farming techniques on pedologic processes. *Source* This author

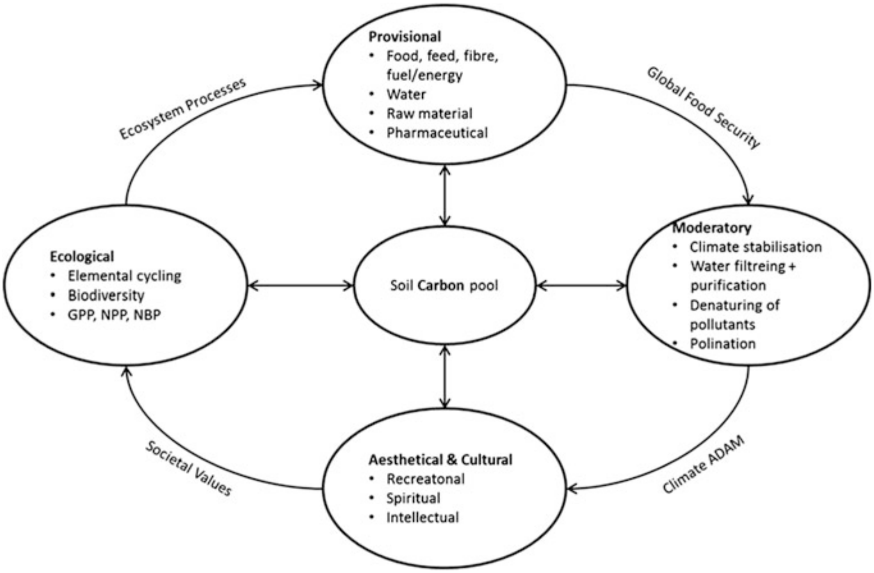

Fig. 1.7 Soil carbon pool and the ecosystem services (*ADAM* = adaptation and mitigation, *GPP* = gross primary productivity, *NPP* = net primary productivity, *NBP* = net biome productivity). *Source* This author

Table 1.8). Among numerous positive effects, improvement in soil structure and the *available water capacity* (AWC) are specifically relevant to physically degraded soils, increase in CEC and nutrient reserves for chemically degraded soils, and increase in biodiversity and *microbial biomass carbon* (MBC) and bioturbation for biologically degraded soils (Fig. 1.5). In addition to an increase in soil quality, long-term adoption of conservation-effective measures based on mulch farming also leads to improvement in biospheric processes (Fig. 1.6).

These processes enhance SOC sequestration, increase MRT, and lead to numerous benefits which improve soil quality (Table 1.8). Both the quality and quantity of SOC pool are drivers of numerous ecosystem services essential to the well-being of the Carbon Civilization and to other vital ecosystem functions (Fig. 1.7).

1.8 Conclusions

Sequestration of C in terrestrial ecosystems, soils, and vegetation is a win–win strategy. In addition to offsetting anthropogenic emissions from fossil fuel combustion and land use conversion, it also generates numerous ecosystem services. Important among these are an improvement in soil quality with an attendant increase in agronomic productivity and use efficiency of inputs, enhancement of the quantity and quality of water resources, and an increase in both above-ground and below-ground biodiversity. The strategy of bio-sequestration differs from that of CCS in being more cost-effective and economical, creating/strengthening numerous ecosystem services, and having low environmental and health-related risks. Improvement in soil quality by increasing the SOC pool is related to beneficial effects on soil physical, chemical, biological, and ecological quality. Common strategies of SOC sequestration are those which create a positive soil C budget by decreasing losses (erosion, mineralization, and leaching), and increasing gains (biomass C). The mean residence time of SOC can be increased by protection against microbial processes through physical, chemical, and biological mechanisms. There is no one silver bullet or panacea, and the choice of appropriate strategies depends on site-specific conditions involving the political parameters governing the issues pertaining to the human dimensions. Regardless of the debate on climate change, recarbonization of the biosphere is essential to the survival of the "Carbon Civilization".

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