Chapter 1
Terrestrial Biosphere as a Source and Sink of Atmospheric Carbon Dioxide

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Abstract The terrestrial biosphere has lost a considerable amount of its antecedent carbon (C) pool because of anthropogenic activities since the dawn of settled agriculture about 12–14 millennia ago. Deforestation and land use conversion has presumably caused cumulative emission of 476 Pg C (1 Pg = 10^{15} g). Of this, 78 ± 12 Pg C may have been depleted from world's soils. Globally, about 2,300 Pg C are stored to 3-m depth in the soil organic carbon (SOC) pool, 1,700 Pg C in permafrost, 600 Pg C in peatlands, and up to 1,700 Pg C in the soil inorganic carbon (SIC) pool. While a large fraction of C emissions may have been absorbed by the ocean and land-based sinks, the knowledge about the historic loss provides a reference point about the technical C sink capacity of the terrestrial biosphere. The later may be as much as a draw-down of 50 ppm of atmospheric carbon dioxide (CO_2) over century or more, which in view of the already accumulated levels of atmospheric CO_2 of 390 ppm is significant. Priority soils and ecosystems for recarbonization of the

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R. Lal et al. (eds.), *Recarbonization of the Biosphere: Ecosystems and the Global Carbon Cycle*, DOI 10.1007/978-94-007-4159-1_1,

biosphere include degraded soils (eroded, salinized, depleted, polluted and drained peatland soils), and desertified ecosystems. Whereas the generic technologies for sustainable intensification exist for croplands, grazing lands, forest lands and restoration of degraded soils, these technologies must be validated and fine-tuned for soil-and-site specific conditions. The adverse externalities of land use change for both, climate and soils requires policy actions for corrective incentives. However, there is no panacea, and a wide range of technological options need to be carefully and prudently evaluated under site-specific situations. Policy interventions must incentivize land managers for implementing sustainable land use-, soil- and crop management practices that are avoiding the adverse effects for climate and soils. Incentives that foster the natural process of recarbonization of the biosphere can be a cost-effective strategy, and would have numerous co-benefits.

Keywords Abrupt climate change • Terrestrial biosphere • Land use • Land cover change • Urbanization • Fossil fuel combustion • Ecosystem C pool • Anthromes • Afforestation • Deforestation • Soil restoration • Soil erosion • Carbon transported by erosion • Mineral-associated carbon • Rubisco • C_4 plants • C_3 plants • Policy implications • Ecosystem services • Payments for ecosystem services • Zero emission technology • Aerosols • Co-benefits • Payments for ecosystem services

Abbreviations

ACC	Abrupt climate change
C	Carbon
CCS	Carbon capture and storage
CDM	Clean Development Mechanism
Gha	Gigahectare
GCC	Global carbon cycle
GHGs	Greenhouse gases
LULCC	Land use land cover change
Mha	Million hectare
NPP	Net primary productivity
ppm	Parts per million
Pg	Petagram
SIC	Soil inorganic carbon
SOC	Soil organic carbon

1.1 Introduction

The terrestrial biosphere impacts and is impacted by the climate. The abrupt climate change (ACC) can affect the ecosystem carbon (C) pools through losses by erosion and mineralization, and decline in biodiversity along with the attendant changes and

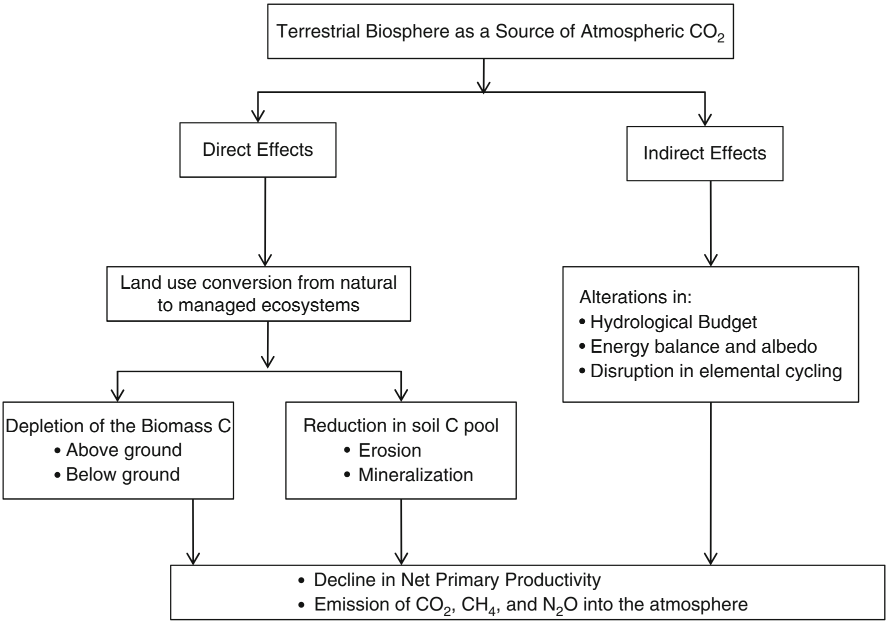

Fig. 1.1 Human-induced alterations in the terrestrial biosphere

spatial shifts in major biomes (Fig. 1.1). Land use change, including conversion from natural to managed ecosystems and specific management practices to raise plants and animals, has strong influence on the C pools in the above and below-ground biomass and in the soil profile. Humans have drastically transformed the terrestrial biosphere ever since the dawn of settled agriculture about 12–14 millennia ago (Ruddiman 2003, 2005). Principal biomes of the world (Table 1.1) are major reservoirs of C, stored in biomass and soil. Anthropogenic perturbations have disturbed the ecosystem C pools of the natural biomes through conversion and land use change to cropland, grazing/pasture land, forest plantations, urban settlements and rural communities, and industrial and infra-structure development. In addition, drainage of wetlands has also reduced the C pool in these ecosystems through oxidation of peat. It has been estimated that prior to the industrial revolution in 1700, nearly half of the terrestrial biosphere was wild, and most of the remainder (~45%) was in a semi-natural state (Ellis et al. 2010). By 2000, only 25% was wild, <20% in semi-natural state, and the remainder had been converted to agricultural and settled anthropogenic biomes (anthromes) or biomes drastically altered by human. Majority of the natural biomes have been completely transformed into croplands, rangelands, plantations, and urban/rural settlements. Agricultural expansion and intensification, in particular, are the main driver of global land use/land cover change (LULCC, Pielke et al. 2011). The global area of cropland dramatically increased to about 11% of earth's total ice-free land surface as did the global area used for grazing livestock to about 25% of earth's total ice-free land surface. Further, about 0.5% of the total global land area is urban (Schneider et al. 2009). At the

Table 1.1 Principal global biomes and climates

Climates	Biome
I. Low latitude climates	
1. Tropical rainforest (Af)	Annual precipitation >250 cm, temperature 27°C, humidity 77–88%, 10° N and S of equator
2. Wet-dry tropical Savanna (Aw)	Annual precipitation 75–150 cm, temperature range of 15°
3. Dry tropical climate (Bw)	Annual precipitation 25–50 cm, temperature range 15°C, latitude 15–25°N and S
II. Mid latitude climates	
4. Temperate Savanna/Steppe (Bs)	Annual precipitation of <10 cm, temperature range 24°C, latitude 35–55°N
5. Mediterranean climate/Chaparral (Cs)	Wet winter/dry summer, annual precipitation of 25–45 cm, temperature range 7°C, latitude 30–50°N and S
6. Dry middle climates (grasslands (Bs))	Annual precipitation of 75–80 cm, temperature range 30°C, latitude range of 30–55°N and S
7. Moist deciduous forest (Cf)	Annual precipitation 80 cm, temperature range 30°C, latitude 30–55°N and S
III. High latitude climates	
8. Boreal forest/Taiga (Dfc)	Annual precipitation 30 cm, temperature range 40°C, latitude 50–70°N and S
9. Tundra (E)	Annual precipitation 20 cm, temperature range −22°C to 6°C, latitude 60–75°N
10. Alpine/highland (H)	Annual precipitation of 20–25 cm, temperature range −18°C to 10°C, Latitude (depends on altitude)

beginning of the twenty-first century, 39% of the earth's total ice-free surface had been converted into agricultural land and settlements, and an additional 37% has been embedded within managed biomes (Ellis et al. 2010), and was vulnerable to human activities. Consequently, these anthromes have been drastically decarbonized, leading to increase in atmospheric concentration of CO_2 and other greenhouse gases (GHGs), and increased risks of ACC.

Land use conversion and creation of anthromes have drastically influenced the global C cycle (GCC). It is estimated that since 1850 about 35% of anthropogenic emission resulted from land use conversion (Foley et al. 2005). Perhaps as late as 1950s relatively more anthropogenic emissions were generated from LULCC than from fossil fuel combustion. In addition to perturbing the GCC, creation of anthromes also affects energy and hydrologic balance, elemental cycling, biodiversity and natural habitat, and the attendant degradation of the quality of soil and water resources (Fig. 1.1). There has been a large-scale deforestation, including that in North America and Europe, since the middle of seventeenth century (Table 1.2). The rate of deforestation accelerated in the humid tropics (e.g., Amazon Basin, Congo Basin, West Africa and Sumatra) during the middle of twentieth century. By 1990, global forest cover decreased by about 1,100 Mha, and only a few desert regions, parts of

Table 1.2 Estimates of global deforestation between 1650 and 1978 (Adapted from Williams 1994)

	Land area deforested (10^6 ha)	
Year	High estimate	Low estimate
Pre-1650	152.2	98.6
1650–1749	75.8	59.8
1750–1849	159.2	168.0
1850–1978	418.5	418.5
Total area	805.7	744.9

Table 1.3 Increase in population, industrial output, energy, use of irrigation, fertilizers and pesticides between 1900 and 2000 (Ponting 2007)

Parameter	Increase factor between 1900 and 2000
Population	3.8
Urban population	12.8
Industrial output	35
Energy use	12.5
Oil production	300
Water use	9
Irrigated area	6.8
Fertilizer use	342
Organic chemicals	1,000
Urban water use	20

Table 1.4 Agricultural intensification, and energy-related emissions between 1890 and 1990 (Adapted from Crutzen 2002)

Parameter	Increased factor between 1980 and 1990
I. Agriculture	
Cattle population	4
Pig population	9
Cropland area	2
Forest area	0.8
Use and fish catch	35
II. Energy related emissions	
Coal production	4
CO_2 emissions	17
SO_2 emissions	13
Lead emissions	8

the central Amazon and Congo Basins, and the Arctic and Antarctic had not been affected by LULCC by 2000 (Pielke et al. 2011). In recent decades, the global deforestation rate decreased but is still at about 13 Mha year^{-1} for the period 2000–2007, with deforestation rate for tropical forests alone of 12 Mha year^{-1} (Pan et al. 2011). Further, agricultural lands are being used intensively to increase agronomic/food production through input of water for irrigation, chemical fertilizers as plant nutrients, and pesticides to control pests and pathogens. Increase in population during the twentieth century by a factor of four accentuated the demand for production of food and other basic necessities. Consequently, there has been a drastic increase in the area under cropland and especially irrigated croplands, fertilizers and pesticide use, and the cattle population (Tables 1.3 and 1.4). The era since the industrial revolution is appropriately termed the "Anthropocene" (Crutzen 2002). Over the 40 year period ending in 2006, agricultural intensification doubled crop production even though the area under arable land use increased by only 12%, fertilizer use increased by 700%, and mechanization increased drastically (Foley et al. 2007). As much as 24% of the Earth's net primary productivity (NPP) is appropriated by humans (Haberl et al. 2007). Thus, the objective of this chapter is to describe the principles, practices and policies for recarbonization of the biosphere to mitigate and adapt to ACC.

1.2 Loss of Carbon from the Terrestrial Biosphere

Anthropogenic CO_2-C emission from fossil fuel combustion and cement production increased from about 0.5 Pg C year^{-1} in 1900 to 6.6 Pg C year^{-1} in 2000 (Sterman 2008), 8.7 Pg C year^{-1} in 2008 (Canadell et al. 2007a,b; Le Quéré et al. 2009), and 9.1 Pg C year^{-1} in 2010 (Peters et al. 2011). The emissions from land-use change in 2010 were about 0.9 Pg C year^{-1}, and ~40% of the total emission of 10 Pg C year^{-1} remained in the atmosphere (Peters et al. 2011). Thus, in conjunction with emission from land use conversion, total anthropogenic emissions have increased atmospheric concentration of CO_2 from 280 ppm during the pre-industrial era to 390 ppm in 2010 (WMO 2010). Increase in atmospheric CO_2-C is influenced both by land use conversion, and fossil fuel combustion and cement production. In contrast to the onset of Anthropocene around 1,800 (Crutzen and Stoermer 2002), Ruddiman (2003) hypothesized that the Anthropocene began thousands of years ago with the dawn of settled agriculture. Increase in atmospheric CO_2 concentration may have begun about 8,000 years ago and that of methane (CH_4) about 5,000 years ago corresponding with start of forest clearance and cultivation of irrigated rice paddies, respectively (Ruddiman 2003). Emissions of CO_2-C over 8,000 years are estimated by Ruddiman (2003) as follows:

(a) Pre-industrial Era (7,800 years) @ 0.04 Pg C year^{-1} = 312 Pg C
(b) Industrial Era (200 years) @ 0.8 Pg C year^{-1} = 160 Pg C

Thus, total emission from the terrestrial biosphere equal 472 Pg. While most of these emissions may have been absorbed by ocean and by the forest and land sinks, the cumulative emission equals ~120 ppm (~4 Pg = 1 ppm) (Broecker 2007). Of this cumulative emission, 78 ± 12 Pg C may have been depleted from the pedosphere, especially from the soils of agroecosystems and those which have been degraded or desertified (Lal 1999). Crude and tentative as these estimates may be, these data provide a reference point or base line towards judging the technical C sink capacity of the terrestrial biosphere.

1.3 Recarbonization of the Terrestrial Biosphere

There is a strong need to identify a wide range of feasible options to reduce and sequester anthropogenic CO_2 emissions. The cost of not acting may be much higher than that of an appropriate and timely action by the world community. It is precisely in this context that the importance of the strategy of recarbonization of the biosphere cannot be over-emphasized. The philosophy of recarbonization through restoration and rehabilitation of degraded soils and desertified ecosystems and judicious/prudent management of the biosphere is also in accord with numerous cultural believes and societal values such as the one expressed by Voltaire "Il faut cultivar notre jardin" (Read 2006).

There has been a drastic reduction in the land area under biomes with a high ecosystem C pool. The data in Table 1.5 show the decrease in the land area under forest and savanna biomes between 1700 and 2000. In contrast, there has been a strong increase in anthromes, especially the cropland and grazing land. However, even before 1500 humans had immense impacts on forests in the northern, temperate and the tropical regions (Williams 2000). Also, the distribution of historical LULCC over time is highly regionalized (Pielke et al. 2011). For example, by 1500 large areas of Western Europe had been partially cleared, and LULCC intensified, in particular, in this region through 1800 while significant LULCC also occurred over much of Asia including India and China. By 1750, only Western Europe and perhaps parts of Northern China were strongly affected by LULCC. However, by 1990 intensive LULCC had impacted parts of the United States, much of Western Europe, India, Northern China, and elsewhere. Further, large areas of the Southern Hemisphere underwent LULCC throughout the nineteenth century (Pielke et al. 2011). Globally, up to 800 Mha of closed canopy forest and up to 300 Mha of open woodland and shrubland were cleared (Williams 2000). Such LULCC and, in particular, deforestation have depleted the ecosystem C pool, and created C sink capacity which can potentially be refilled to some extent through conversion to a restorative land use, and adaption of recommended practices of soil and vegetation management.

Technical options for restoration of croplands, forest lands, wetlands and degraded/desertified lands are outlined in Fig. 1.2. These are generic technologies, but there is no single solution that is universally applicable. These technologies must be validated and adapted under soil/site-specific situation, with due consideration to social, cultural, economic and political factors which involve the human dimensions of land use and management.

Maintaining/preserving natural ecosystems is essential to enhancing/sustaining ecosystem services and functions. Assuming that 2.4 Gha of land can be used for enhancing the biosphere C pool, it has a technical potential of sequestering at least 3.5 Pg C year^{-1}, even at a modest rate of 1.5 Mg C ha^{-1} year^{-1}.

Table 1.5 Global area (10^9 ha) under different biomes between 1700 and 2000

Year	Forests/ Woodland	Savanna/Grass /Steppe	Abandoned forests/Woodland	Abandoned Savanna/ Grass/Steppe	Cropland	Pasture land
1700	5.28	3.23	0	0	0.41	0.32
1750	5.19	3.20	0	0	0.54	–
1800	5.09	3.17	0	0	0.68	0.51
1850	4.99	3.14	0	0	0.82	–
1900	4.80	3.02	0.01	0.002	1.14	1.29
1950	4.60	2.83	0.05	0.02	1.53	2.47
1990	4.40	2.67	0.15	0.06	1.79	3.34
2000	4.09	2.03	–	–	1.53	3.43

Loveland et al. (2000), Ramankutty and Foley (1999), FAOSTAT (2010), and Ruddiman and Ellis (2009)

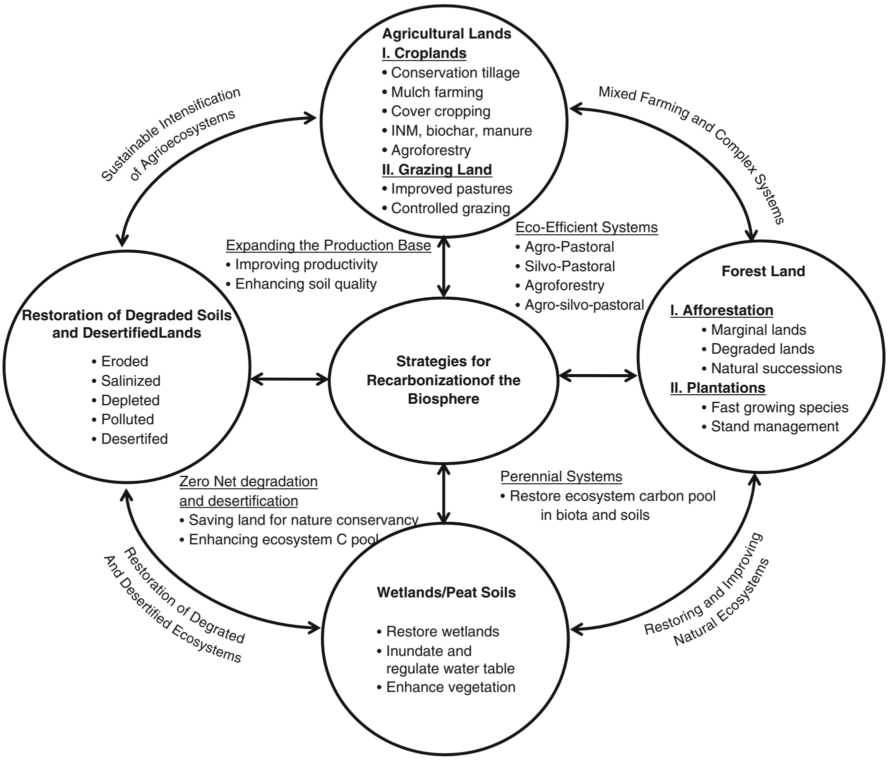

Fig. 1.2 Strategies towards recarbonization of the biosphere

Management of the terrestrial C pool may also imply leaving the natural ecosystem intact to the extent possible. Strategies to manage the C pool in these lands have been proposed by Read (2007) Read and Parshotam (2007), Fischer and Schrattenholzer (2001) among others. These strategies include the following:

1. Afforestation on marginal lands and degraded soils to enhance the NPP and increase the input of C into the soil,
2. Restoration and enhancement of soil quality and biomass productivity of degraded/depleted agricultural soils,
3. Restoration of wetlands and peatlands, and
4. Adoption of sustainable-intensive land use in soil/crop management systems.

Most of the available land for recarbonization exists in developing countries where the future incremental demand for food, feed and fibers is also the highest. Thus, it is strategically important to involve all countries in the decision-making process, especially those where surplus land exists for the recarbonization process. Establishment of biofuel plantation by deforestation of tropical rainforest or clearance of peatlands (such as in Indonesia or Malaysia) is counter-productive because of a large C-debt created by this land use conversion (Righelato and Spracklen 2007; Fargione et al. 2008).

Recarbonization of biosphere C must particularly focus on restoring soil C pools, comprising the soil inorganic carbon (SIC) and soil organic carbon (SOC) pools, as recarbonized soils contribute to climate change adaptation and mitigation. Further, restoring the SOC pool enhances soil quality, ecosystem services and food security. LULCC has and continues to deplete soil C pools. For example, SOC pools to 100-cm depth decreased by 42% when native forest was converted to cropland but no significant changes occurred below 60-cm depth (Guo and Gifford 2002). However, the variability in subsoil C changes is high but not many studies report data on subsoil SOC (Prechtel et al. 2009; Poeplau et al. 2011). In temperate regions, in particular, deforestation and conversion to cropland caused a rapid SOC loss of $32 \pm 20\%$ to 29 ± 14 cm depth with a new SOC equilibrium being reached after 23 years (Poeplau et al. 2011). The change rate of SOC increased with temperature but decreased with increase in clay content and with decrease in soil texture. Further, changes in the subsoil (>20 cm depth) were not different from changes in the topsoil. However, studies on organic soils and wetlands soils were not included (Poeplau et al. 2011). When primary forests in the tropics are converted, SOC losses were $12 \pm 2\%$ to 36 ± 3 cm depth when converted to grassland, $25 \pm 3\%$ to 36 ± 4 cm depth when converted to cropland, and $30 \pm 3\%$ to 48 ± 8 cm when converted to perennial crops, respectively (Don et al. 2011). The relative SOC loss in the subsoil was similar on grassland but not significant for croplands. The SOC losses increased with increasing temperature, and for conversion into grassland also with increasing precipitation. However, current hot spots of LULCC in South East Asia and Africa, and those in C-rich tropical wetland forests were not taken into account (Don et al. 2011). In general, about 25–30% of the SOC stored in the top meter of soil is released by cultivation of native soils, whether under forest or prairie vegetation (Houghton 2010).

Improved vegetation and soil management practices can recarbonize the biosphere by recovering some of the SOC released in the past. For example, in temperate regions cropland conversion into forest increased SOC by 117 ± 54% to 28 ± 15 cm depth when the forest floor was included, and the SOC increase was negatively correlated with temperature and soil depth but positively with precipitation (Poeplau et al. 2011). When only the mineral soil was considered, SOC changed by 83 ± 39% to 40 ± 25 cm depth, and SOC increases decreased with higher precipitation. However, no SOC equilibrium may be reached more than 120 years after converting cropland into forest (Poeplau et al. 2011). When grassland was converted into forest and the forest floor included, SOC increased 28 ± 11% to 39 ± 12 cm depth and this increase was negatively correlated with precipitation but may probably not be in equilibrium after 200 years. However, when only the mineral soil was considered SOC did not change to 25 ± 16 cm depth. This may continue for at least 150 years after conversion and, in particular, not change with increase in temperature and soil depth, and decrease in clay content (Poeplau et al. 2011). Thus, experiments to recarbonize the soil must study changes in soil profile C and be accompanied by modeling as reaching a new equilibrium is a long-term process (Wutzler and Reichstein 2007). The persistence of SOC also depends on soil type as it determines reactive mineral surfaces, water availability, soil acidity and soil redox state (Schmidt et al. 2011).

The SOC losses after deforestation in tropical regions are also partly reversible. If cropland is afforested, SOC increased by 50 ± 12% to 44 ± 6 cm depth (Don et al. 2011). Further, afforestation of grassland increased the SOC pool by 18 ± 8% to 35 ± 6 cm depth. The average time period was only 33 years since afforestation but it is not known whether SOC equilibrium was already reached (Don et al. 2011). In summary, wherever land use change decreases soil C, the reverse process usually increases soil C (Guo and Gifford 2002). However, the simplifying assumption in many models that SOC pools can reach equilibrium has been challenged by the observation that some old forest soils do still accumulate C (Wutzler and Reichstein 2007). Similar, agricultural soils may never reach a theoretical equilibrium SOC level because of changing conditions and partial resets by disturbances such as erosion (Polyakov and Lal 2004). However, the chemically and biochemically protected SOC pools may be influenced by C-saturation behavior (Stewart et al. 2009). Once the chemically protected SOC pool is filled, added C may accumulate in the physically and in the non-protected fractions. Mineral-associated SOC pools, in particular, eventually saturate. In topsoils, reactive mineral surface area is a finite resource, and C-saturation may occur in SOC associated with the mineral phase in topsoils (Séquaris et al. 2010). Thus, arbitrarily defined soil fractions may have different C-saturation dynamics (Stewart et al. 2009).

Aside replacing SOC-depleting with SOC-accreting land use and management, recarbonization of the soil can be achieved by SOC sequestration implying an additional net transfer of C from the atmosphere to the soil via biomass (Powlson et al. 2011). Through enhancing the SOC pool the capacity of soil to produce food, feed, fiber and fuel can be restored for sustainable development. Thus, SOC-accreting soil and land use management practices must be implemented for the recarbonization of the soil.

Among management strategies to enhance SOC is phyto-engineering, i.e., the breeding and cultivating of plants for SOC sequestration. Strategies include improving the carboxylation efficiency of the enzyme Rubisco which catalyzes the first major step of C fixation during photosynthesis (Spreitzer and Salvucci 2002). Another approach includes increasing the proportion of C_4 plants in warmer climates as plants using the C_4 photosynthetic pathway are more efficient in converting solar radiation into biomass under these climatic conditions than those using the C_3 photosynthetic pathway (Zhu et al. 2010). However, as the overall efficiency of C_3 plants may be higher at lower temperatures (Jansson et al. 2010), the C_3/C_4 species mixture needs to be optimized for SOC sequestration in colder climates. As plant roots and associated microorganisms are the major soil C input (Lorenz and Lal 2005), breeding of plants with deeper and bushy root ecosystems and their cultivation may contribute to SOC sequestration (Kell 2011). Further, replacing annual crops with perennial crop relatives may contribute to the recarbonization of the soil by an additional net transfer of C from the atmosphere into soil (Glover et al. 2010). However, it must be evaluated whether (i) production of plants with deeper and bushy root ecosystems will be at the expense of aboveground biomass yields and (ii) whether soil resources (e.g., nutrients, water) are sufficient to support the cultivation of perennial crop relatives.

Engineering towards recarbonized soils can also be achieved through the construction of reclaimed mine soils and urban soils with high C contents in the stabilized SOC fraction (Hüttl and Gerwin 2005; Macías and Arbestain 2010). The soil addition of black C compounds (e.g., char, charcoal, biochar) may also contribute to a net transfer of C from the atmosphere but C sequestration strategies based on adding recalcitrant material to soil must be critically evaluated (Schmidt et al. 2011). For example, whether C can be sequestered by soil application of biochar together with organic wastes in land uses, soil types and climates other than those associated with Terra Preta (*do Indio*) in the Brazilian Amazon is not known (Glaser 2007; Liang et al. 2010; Sohi et al. 2010).

1.4 Policy Implications

There are important policy implications to implement programs effective in recarbonization of the biosphere. In view of the potentials in countries of all hemispheres, involvement of all countries is called for. Furthermore, adoption of 100% zero-emission technologies is relevant (Read 2006). This obligates the desired rate of technology adoption and facilitates positive approaches to market share and competitive edge (rather than setting one company/country against another as is the case in the zero emission caps) (Read 2006).

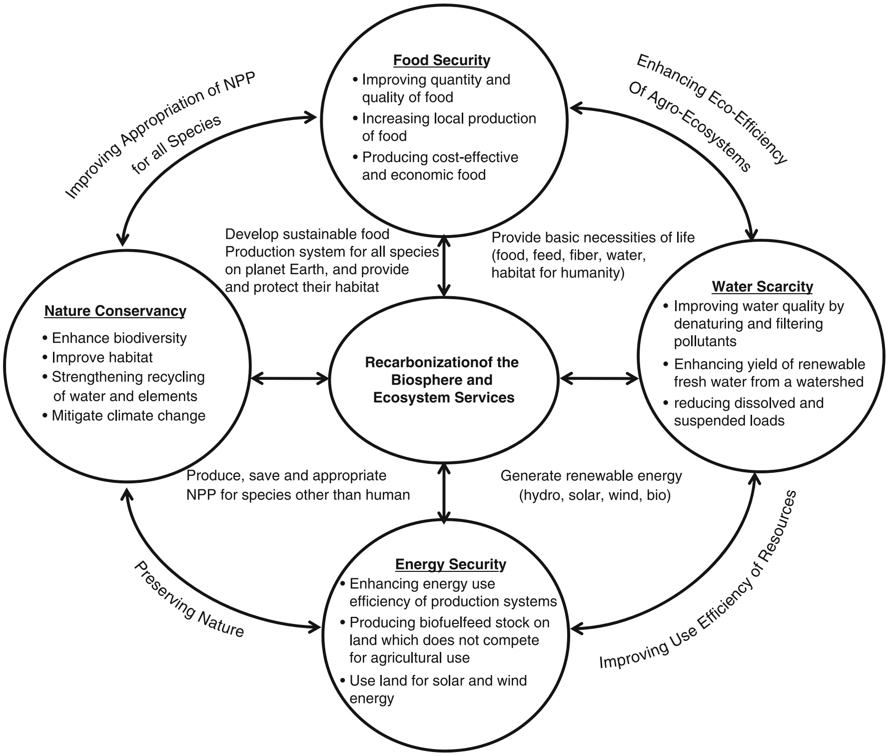

Fig. 1.3 Enhancement and provision of ecosystems services created by recarbonization of the terrestrial biosphere

While the ideas of carbon trade and of the Clean Development Mechanism (CDM) are not as attractive now as these were a decade ago, the concept of compensating land managers for generating/strengthening ecosystem services, and for buying and selling pollution (i.e., Australia's carbon tax, Petherick 2012) is valid and being vigorously pursued. The strategy of recarbonization of the biosphere would complement these new and emerging innovations being adopted by Australia, Japan, New Zealand, Switzerland and the European Union. The carbon trade could be linked with the concept of "zero emission technology". While the growth of C market is desirable, the price of C sequestered in the biosphere should be based on just, fair and transparent criteria.

Rather than subsidies, payment to farmers for enhancing ecosystem services is another positive strategy. Recarbonization of the biosphere strengthens numerous ecosystem services (Fig. 1.3). Important among these are increase in C sequestration, improvement in quantity and quality of water resources, and enhancement of biodiversity leading to food security, water security and energy security while also saving the land for nature conservancy. The adoption of technologies outlined in Fig. 1.2 can be vastly increased by incentivizing the land manager through payments for ecosystem services.

1.5 Conclusions

While the control of the elements has been in the prayers and thoughts of ancient civilizations for millennia (i.e., God Indra of the Indo-Aryans) and of the writers and philosophers (i.e., Homer's "Odyssey" and Shakespeare's "The Tempest") (Schneider 2008), recarbonization of the terrestrial (and aquatic) biosphere does provide some control of the runaway element of the ACC to the so called "Carbon Civilization" (Lal 2007). In strong contrast to the geoengineering techniques (CCS, sulfur aerosols, space reflectors), the strategy of recarbonization of the biosphere seems cost-effective (McKinsey & Co. 2009), and would have numerous co-benefits. Restoration of degraded soils and desertified ecosystems is a natural process, and is strongly linked to numerous ecosystem services including food security, water scarcity, and energy security.

There is no single technology for sustainable management of C pool in world's soils and biota. Most of the known/proven technologies must be validated, specified and adapted under soil-site specific conditions. Over and above the biophysical factors, the human dimensions involving social, cultural, ethnic, economic, and political factors must also be considered.

Incentivizing the land managers is important to adoption of the recommended soil/forest/land management options. Payments for ecosystems services, rather than subsidies, are positive approaches. It would promote innovation and stewardship of land resources, while adapting to and mitigating the ACC.

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