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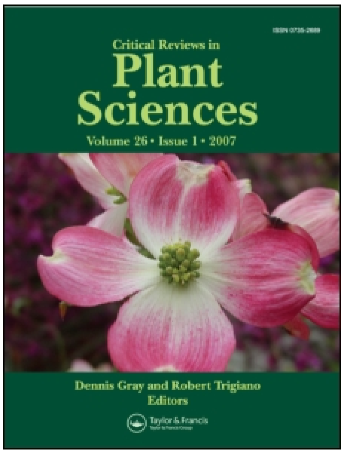

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Sequestering Atmospheric Carbon Dioxide

R. Lal [a]
[a] Carbon Management and Sequestration Center, The Ohio State University, Columbus, OH

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Sequestering Atmospheric Carbon Dioxide

R. Lal
Carbon Management and Sequestration Center
The Ohio State University, Columbus OH 43210

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The abrupt climate change, attributed to increase in atmospheric concentration of CO_2 and other greenhouse gases, has necessitated identification of technological options to sequester CO_2 into other long-lived pools. Other viable pools for C sequestration include geologic, oceanic, and the terrestrial. There is also a potential to convert CO_2 into stable minerals. There are geoengineering techniques of CO_2 capture and storage into old oil wells to enhance oil recovery (EOR) and access coalbed methane (CBM), store in saline aquifers and sedimentary rocks, and combine it with basalt where it goes through chemical transformations. Geoengineering techniques have relatively high sink capacity and also high costs. Further, geoengineering techniques require measurement, monitoring, and verification (MMV) protocols. In contrast, C sequestration in terrestrial ecosystems (soil and biota) is based on the natural process of photosynthesis, and humification of biosolids applied to the soil. Terrestrial pools have relatively lower sink capacity, but are cost-effective and have numerous ancillary benefits. Total CO_2 drawdown is estimated at reduction in 50 ppm of atmospheric concentration over 5 decades. Increasing C pool in agricultural soils is essential to advancing food security, and that in degraded/desertified soils to improve the environment. Rather than either/or scenarios, both strategies of C sequestration via geoengineering and terrestrial strategies have specific niches which need to be carefully and objectively identified and implemented. The terrestrial C sequestration is a win-win strategy because of its numerous benefits, especially its positive impact on food security while mitigating climate change and improving the environment.

Keywords greenhouse gases, global warming, soil carbon dynamics, geologic sequestration, oceanic sequestration, terrestrial sequestration

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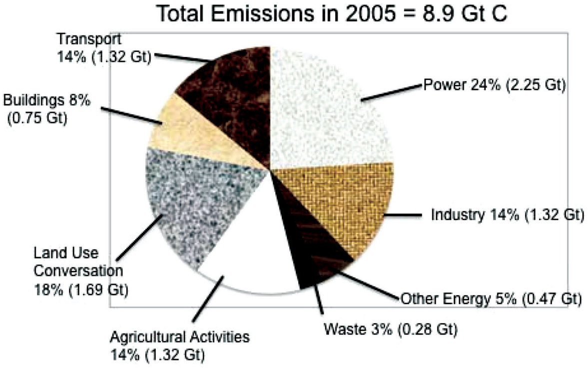
Address correspondence to R. Lal, Carbon Management and Sequestration Center, The Ohio State University, Columbus OH 43210. E-mail: Lal.1@osu.edu



Decade	Emissions (Gt C/yr)		
	Fossil Fuel	Land Use	Total
1980s	5.4 ± 0.3	1.4	6.8
1990s	6.4 ± 0.4	1.6	8.0
2000s	7.2 ± 0.3	11.7	8.9

FIG. 1. Estimates of global emissions from anthropogenic activities in 2005 (Redrawn from Koonin, 2008; IPCC, 2007).

I. INTRODUCTION

Anthropogenic activities with drastic impacts on the global carbon (C) cycle include deforestation and land use conversion, biomass burning, soil cultivation, animal husbandry, draining wetlands, and fossil fuel combustion. Conversion of natural to agricultural ecosystems has been a major source of emission of greenhouse gases (GHGs) since the dawn of settled agriculture about 10,000 years ago, and of the domestication of livestock and cultivation of rice paddies about 5,000 years ago (Ruddiman, 2003; 2005). Until the 1940s and 1950s, more CO_2 emissions came from land use conversion and soil cultivation than from fossil fuel combustion. During the first decade of the 21st century, as much as 15% of the annual CO_2 emission (∼1.69 Gt/yr) is contributed by land use conversion and an additional 14% by agricultural activities (1.32 Gt/yr) (Fig. 1; Koonin, 2008; IPCC, 2007). Total C emissions from terrestrial ecosystems have been estimated at 320 Gt from the prehistoric times to the industrial revolution, and an additional 136 Gt since ∼1850 (Ruddiman, 2003). In comparison, total emissions from fossil fuel combustion are estimated at ∼300 Gt (IPCC, 2007). The atmospheric C pool is now estimated at ∼800 Gt (Oelkers and Cole, 2008), and increasing at the rate of ∼3.5 Gt/yr (IPCC, 2007). In comparison, the terrestrial C pool consists of 2500 Gt to 1-m depth in soils or the pedologic pool (Batjes, 1996), and 620 Gt in the biotic pool (Lal, 2004). There is a direct link between the soil C pool and the atmospheric pool. Also, 4 Gt of C emitted equals 1 ppm of CO_2 in the atmosphere (Broecker, 2007).

Atmospheric enrichment of CO_2 and other GHGs (e.g., CH_4, N_2O) is increasing global temperature (IPCC, 2007), with attendant impact on ecosystems (Cole and Monger, 1994), and on biota, especially plant species (Parmesan, 2006; McKenny *et al.*, 2007). Global warming is driving species ranges poleward and toward higher elevation at temperate latitudes (Colwell *et al.*, 2008). Decline in availability of water for crop production and increase in risks of soil degradation with the projected climate change may adversely impact the net primary production (NPP) and exacerbate food insecurity (Borlaug, 2007; FAO, 2007; Brown and Funk, 2008), especially in developing countries. Food prices in June 2008 were at an all-time high, and caused riots in many countries, including Egypt, Haiti, and Mexico. The food crisis may be compounded with increase in population from 6.7 billion in 2008 to 9.2 billion in 2050, and to change in diet. The adverse impact of climate change on NPP and agronomic production (Lobell *et al.*, 2008) are likely to be more severe in developing countries, where almost all future increase in human population may occur, and the resource-poor farmers and land managers are unable to apply adaptive/mitigation strategies through implementation of recommended management practices (RMPs). Higher temperatures with projected warming may decrease global harvests (Holden, 2009). In addition to adverse effects on agricultural ecosystems, climate change may lead to sea level rise, inundation of coastal regions, spread of pests and pathogens, etc. (IPCC, 2007). Mitigating the climate change due to enrichment of atmospheric concentration of CO_2 and other GHGs is among the principal challenges of the 21st century (Pacala and Socolow, 2004; Schrag, 2007; Koonin, 2008). Thus, there is a strong interest in identification and implementation of technological options to reduce atmospheric concentration of CO_2 and mitigate the climate change, which is the focus of this special issue of *Critical Reviews in Plant Sciences*.

II. CARBON SEQUESTRATION

Transfer of atmospheric CO_2 into other long-lived pools so that it is not re-emitted into the atmosphere is called C sequestration (Lal, 2008). Other global pools are geologic, oceanic, and terrestrial. Depending upon the intended pool into which the atmospheric CO_2 is being transferred, there are numerous strategies of C sequestration (Fig. 2), some of which are briefly outlined below.

A. Geoengineering

These engineering techniques are based on capture, transport, and injection of CO_2 into geologic strata and oceanic ecosystems (Broecker, 2008). Different types of geoengineering options are briefly described below:

1. *Geologic Sequestration*

Capture and storage of atmospheric CO_2 into geologic formations is potentially a useful strategy, because of its large sink capacity (Broecker, 2008; Topp and Gale, 2004; Friedman, 2007). The technique, also called geoengineering (Wigley, 2006), involves capture and transport (Rubin, 2008), and injection of liquefied CO_2 into deep geological formations. The technique of CO_2 injection was originally developed to enhance oil recovery or EOR (Lake, 1989) and is being successfully used in Norway,

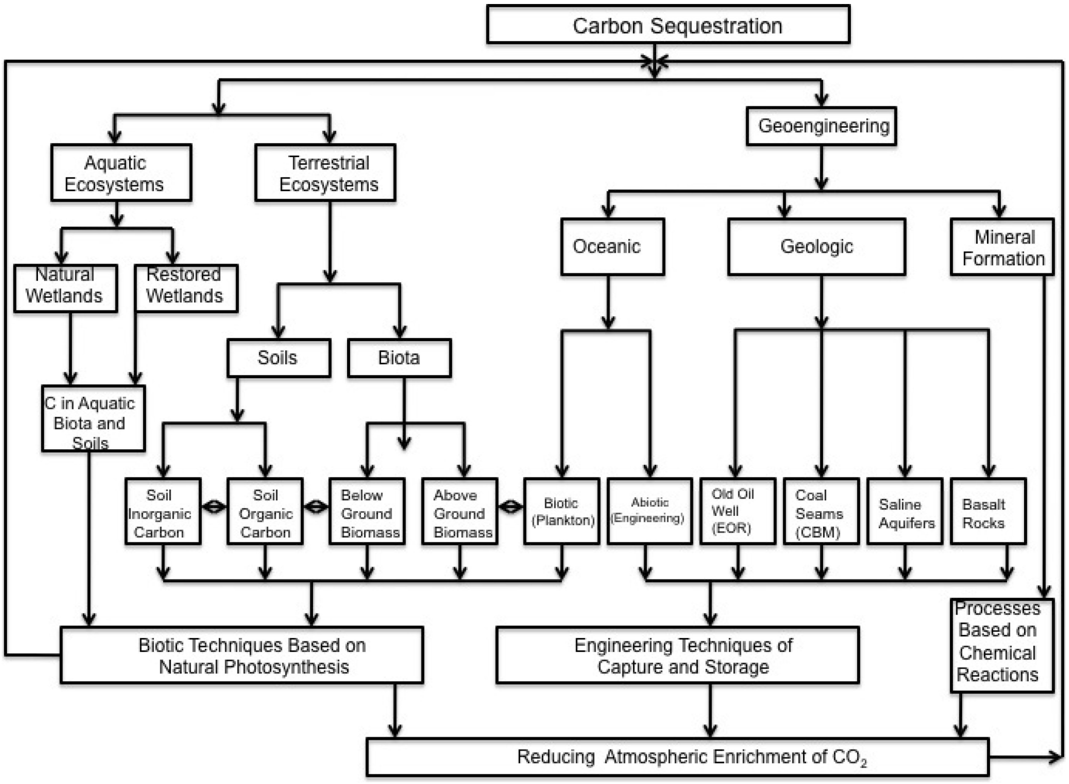


FIG. 2. Biotic, engineering and chemical techniques of sequestration of atmospheric CO_2.

Texas, and elsewhere. The same process is used to recover coal-bed methane (CBM) from unmineable coal seams (Benson and Cole, 2008; Lal, 2008). Rather than EOR and CBM, CO_2 can also be injected into saline aquifers and porous rocks capped by stable geologic formations. Those in support of geoengineering consider it to be a solution to the global problem of climate change caused by atmospheric enrichment of CO_2 (Oelkers and Cole, 2008). However, the technique is expansive and in need of a precise protocol for measurement, monitoring, and verification (MMV) in view of the risks of leakage.

2. *Sequestration into Basalt*

A special type of geologic sequestration is injection of CO_2 into basalt (Matter *et al.*, 2007; McGill *et al.*, 2006). These formations occur widely in the United States, Russia, Southern India, Iceland, etc. The process leads to formation of stable $MgCO_3$ (magnesite), and $CaCO_3$(calcite) (Oelkers *et al.*, 2008).

3. *Oceanic Sequestration*

Injection of captured and liquefied CO_2 beneath the ocean surface (∼1000 m) is another geoengineering option of CO_2 sequestration (Adams, 2008; House *et al.*, 2006; Lal, 2008). Similar to geologic sequestration, however, the cost effectiveness and environmental considerations are major challenges. Oceanic sequestration is also achieved through Fe fertilization by the process called "biological pump" (see section on Terrestrial Sequestration).

4. *Mineral Formation*

Conversion of CO_2 into stable chemical minerals ($CaCO_3$, $MgCO_3$) is another option. The process involves reacting industrial CO_2 with *ultramafic* rock to form stable minerals (Lackner *et al.*, 1995; Broecker, 2008). CO_2 disposed by means of silicates is another option involving reactions with minerals (Seifritz, 1990).

B. Terrestrial Sequestration

In contrast to geoengineering, the process of CO_2 sequestration into terrestrial ecosystems is based on the natural process of photosynthesis. It involves adoption of land use and soil/vegetation management systems which enhance NPP, and transfer some of the photosynthates (through return of biomass) into soil organic carbon (SOC) as stable humic substances with long residence time. In arid and semi-arid climates, soil carbon sequestration also involves conversion of CO_2 from soil air into secondary carbonates (Lal, 2004; 2008). There are two distinct but related components of terrestrial sequestration: vegetation (especially trees) and soils.

1. *Vegetation*

Afforestation of degraded/desertified soils and conversion of marginal and degraded agricultural soils (e.g., cropland, grazing lands, rangelands) is important to increase the terrestrial C pool. Pacala and Socolow (2004) estimated that 1 Gt C/yr can be sequestered through afforestation and establishment of tree plantations in tropics and temperate climates. In addition to C sequestration in the biomass, establishment of a perennial vegetation cover has a cooling effect by alternating both micro- and mescoclimates, changing albedo, and accentuating recycling of water vapor. Increase in plant and animal biodiversity is another ecosystem service that perennial vegetation cover provides. Fertilization of ocean with Fe is also being considered as a biotic sequestration. The process involves increase in growth of plankton through fertilization of warm water with iron. The settlement of dead plankton to the ocean floor, called "biological pump" of transferring atmospheric CO_2 to the ocean floor, is being assessed as an option. However, dumping large quantities of iron and nitrogen on large swaths of the world's oceans has severe environmental implications (Kintisch, 2008).

2. *Soil*

Carbon sequestration in soil, through increase in SOC and soil inorganic carbon (SIC) components, has a strong impact on the global C cycle. World soils have lost 50 to 100 Gt C through decomposition of soil organic matter (SOM), accelerated erosion, and leaching. The depletion of SOM, through conversion of natural to agricultural ecosystems along with drainage of wetlands and soil tillage or crop residues removal and burning, has created a soil C sink capacity. It implies that most agricultural soils contain lower SOC/SOM pools than their counterparts under natural ecosystems. Thus conversion to a restorative land use and adoption of RMPs can enhance the SOC pool. In general, the rate of SOC sequestration is 500 to 1500 kg/ha/yr in cool and humid climates compared with 50 to 500 kg/ha/yr in warm and arid regions (Lal, 2004). The strategy is to adopt those soil and crop management practices, which create positive C and N budgets. Important among these strategies are no-till farming with crop residue mulch and cover cropping (conservation agriculture), integrated nutrient management (INM) including use of compost and manure, and liberal use of biosolids (Lal, 2004; 2008). Similar to SOM, there is a potential of increasing SIC pool through formation of secondary carbonates in arid regions. In addition, there is also the potential of leaching biocarbonates, especially in soils irrigated with good quality water. However, the rate of formation of secondary carbonates is low (e.g., 5–10 kg/ha/yr) (Lal, 2004; 2008). Total sink capacity of C sequestration in soils and forest is equivalent to reduction of about 50 ppm of atmospheric CO_2 over 50 years.

III. TERRESTRIAL CARBON SEQUESTRATION POTENTIAL

There are numerous options of sequestering atmospheric CO_2 into terrestrial ecosystems (Fig. 3). Pacala and Socolaw

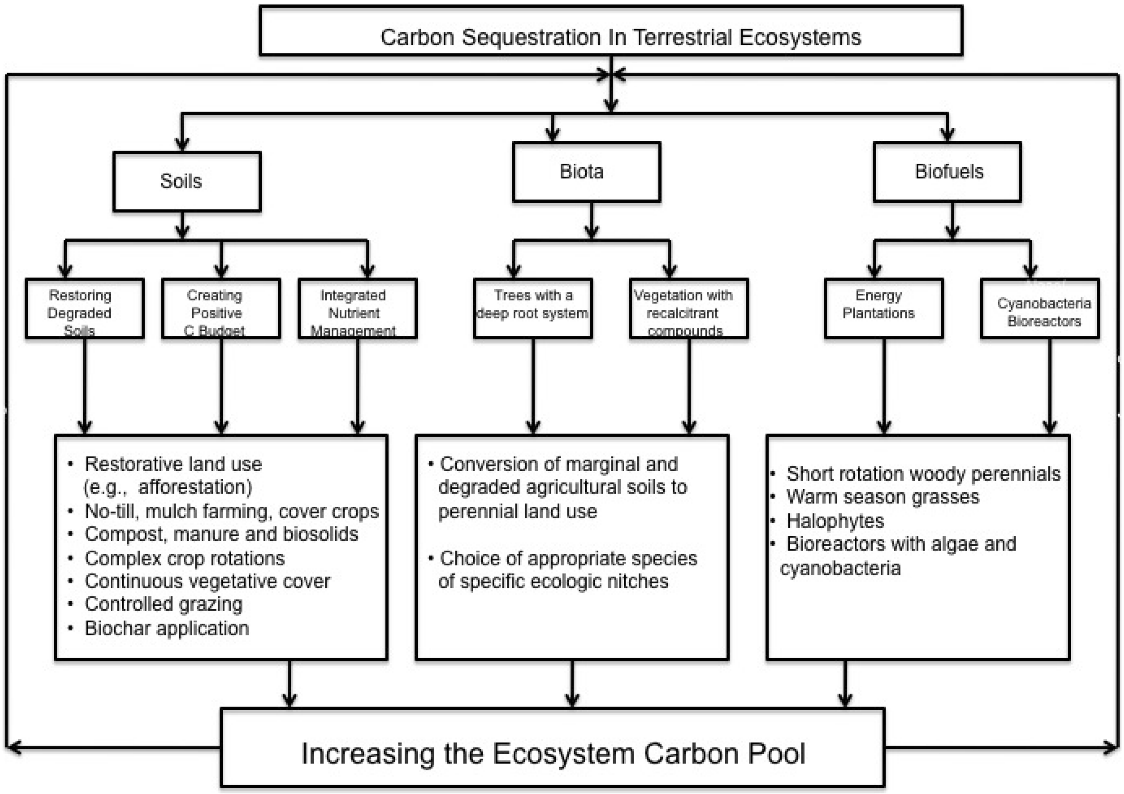


FIG. 3. Technical options for carbon sequestration in terrestrial ecosystems.

(2004) estimated the C sequestration potential of ∼3 Gt/yr through terrestrial ecosystems. Indeed, the potential of C sequestration in world soils alone may be ∼3 Gt/yr through restoration of degraded/desertified soils, adoption of RMPs on cropland (e.g., no-till farming in conjunction with crop residue mulch and cover crops), and improvement of rangeland/grazing land soils.

Since the discovery of the so-called "Terra Preta do Indio," by Wim Sombroek (Glaser, 2007), there has been a considerable interest in using biochar to enhance soil fertility and increase the C pool (Gaunt and Lehman, 2008; Lehman, 2007). Despite its apparent benefits to improving soil physical and nutritional properties, identifying appropriate sources of biomass to be converted into biochar remains a major challenge. Competing uses of crop residues include: soil amendment/mulch for erosion control and soil C sequestration, industrial raw material, feedstock for lignocellulosic ethanol, feedstock for biochar, etc. Thus, competing uses of crop residues and other agricultural/forestry byproducts must be objectively assessed.

There are merits and limitations of C sequestration in trees and soils (Table l). Being a natural process, there are numerous ancillary benefits of C sequestration in trees and soils. Importantly, improvement in soil quality is essential to advancing global food security and enhancing the environment. Yet, soil C sequestration also requires additional nutrients, especially N, P, and S. Conversion of biomass C with high C:N ratio into humus with low C:N, C:P, and C:S ratios require additional nutrients. Similarly, establishments of perennial vegetation require additional water (Table 1). It is justifiably argued that C sequestration in biota implies trading water. C. Jackson *et al.* (2005) synthesized data from 600 observations and concluded that establishment of tree plantations decreased stream flow and increased soil salinization and acidification. Plantations decreased stream flow by 227 mm per year globally (52%), with 13% of streams drying completely for at least one year (Jackson *et al.*, 2005).

IV. BIOFUEL AND CARBON OFFSET

Using biomass as a source of energy, either through direct combustion or conversion to liquid biofuels (e.g., cellulostic ethanol), can be C-neutral because it merely recycles the atmospheric CO_2. Establishment of energy plantations, growing dedicated species (short rotation woody perennials or warm-season grasses), increases the ecosystem C pool in both soil and the aboveground biomass. Pacala and Socolow estimated that 1 Gt C/yr can be recycled and saved through production of biofuels. While the C contained in the above-ground biomass can be recycled as biofuel, C sequestered in soils supporting energy plantations is a net gain. Yet, biofuel plantations require additional land, water, and nutrients. Similar to needs of good quality soil and inputs of nutrients and water, establishing successful and viable energy plantations also needs good quality soil and essential inputs. There is no such thing as a free biofuels grown on degraded soils without inputs. Further harvesting of crop residues for conversion to cellulosic ethanols can increase risk of soil erosion and degradation.

V. AQUATIC ECOSYSTEMS

Similar to terrestrial ecosystems, aquatic ecosystems also have possibilities of C sequestration in biota and soil. Aside from ocean, there are 3 distinct land-based aquatic ecosystems: wetlands, riparian lands, and coastal ecosystems (Fig. 4). Because of human encroachment and other anthropogenic perturbations, aquatic ecosystems have also lost their C pools. With restoration and adoption of RMPs these ecosystems can be managed to

TABLE 1
Merits and limitations of carbon sequestration in terrestrial and aquatic ecosystems

Merits	Limitations
1. Improvement in soil quality	1. Limited sink capacity
2. Increase in net primary production	2. Additional nutrients required
3. Improvement in water quality	3. Additional water required
4. Decrease in soil erosion	4. Uncertainty about permanence
5. Reduction in sedimentation	5. Precise assessment at landscape, regional, watershed, and national scale
6. Increase in use efficiency of input	
7. Improvement in soil biodiversity	
8. Decrease in anoxia of coastal ecosystems	
9. Cost effectiveness	
10. Natural process with numerous ancillary benefits	
11. Essential to advancing food security in developing countries	
12. Another income stream through trading of carbon credits	

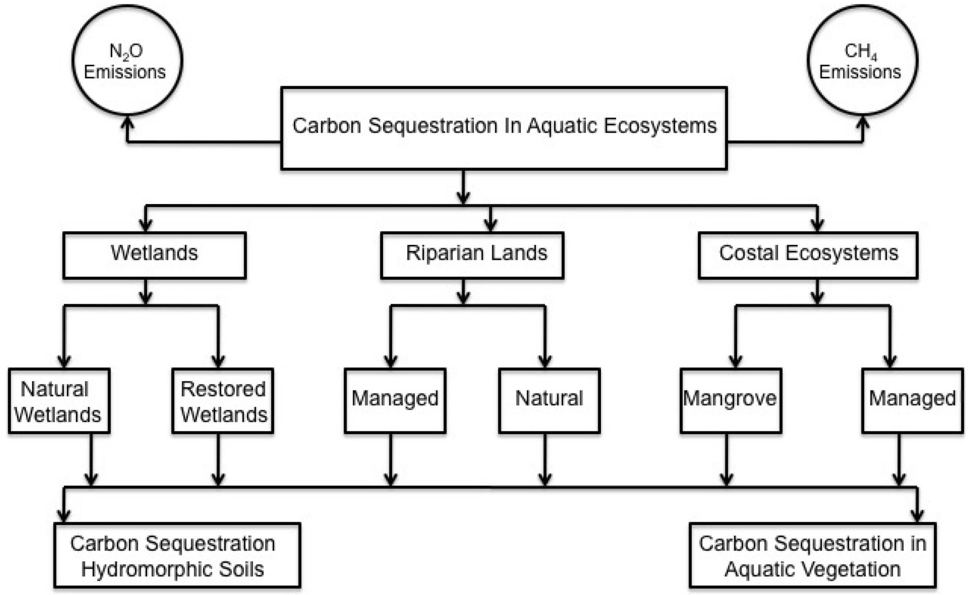


FIG. 4. Processes of carbon sequestration in soil and vegetation of natural and managed aquatic ecosystems. The net carbon sequestration must be adjusted for emission of CH_4 (methanogenesis) and N_2O (denitrification) in aquatic ecosystems.

sequester atmospheric CO_2. Restoration of wetlands, management of riparian zones, restoration of damaged coastal wetlands and inland swamps can increase total ecosystem C pool. In contrast to the terrestrial ecosystems, there is little quantitative data on the net rate of C sequestration in aquatic ecosystems. The net rate of C sequestration in wetlands must be assessed with consideration of emissions of CH_4 and N_2O due to methanogenesis and dentrification (Fig. 4). In addition to C sequestration, restoration of wetlands, riparian zones and coastal ecoregions is also important to minimizing risks of anoxia, non-point source pollution and sedimentation.

VI. FARMING CARBON

Increasing C pool in terrestrial/aquatic ecosystems necessitates conversion to a restorative land use of degraded/desertified soils, adoption of RMPs on agricultural soils (croplands and grazing lands), establishment of biofuel plantations using dedicated species appropriate for the region, and restoration of land-based aquatic ecosystems (wetlands and riparian lands) and coastal regions. Carbon sequestration in soils and biota of these ecosystems can be traded as an economic commodity to generate another income stream for land managers. However, there are some specific protocol/methodological issues that need to be resolved (Harper *et al.*, 2006; Flugge and Abadi, 2006). Important among these are: (i) standardize C accounting methodology at landscape, farm, watershed or regional scales to predict, measure, verify, and certify the ecosystem C pool and flux; (ii) establish a fair and just price of C based on transparent systems and in due consideration of the inherent societal values, risk assessment, and uncertainties; (iii) identify risk discount factor for C sequestered in soils and trees; and (v) assess the degree of permanence of C sequestered in relation to the land use and specific management. An uncertain future for soil C is an issue that needs to be addressed (Thumbore and Czimczik, 2008).

Despite the challenges listed above, paying farmers/land managers for C sequestration and other ecosystem services is an important strategy for promoting the adoption of RMPs. It is appropriate to pay land managers for ecosystem services rather than as subsidies, handouts, or emergency aids. Making C newly accrued/sequestered on terrestrial/aquatic ecosystems a tradable commodity (similar to corn, wheat, soybean, milk, meat, etc.) is essential to realizing the C sink capacity of terrestrial and land-based aquatic ecosystems, mitigating the climate change and improving the environment. Land managers, farmers, and foresters must be compensated for the services provided to the global community.

VII. CONCLUSIONS

Sequestration of atmospheric CO_2 is essential to mitigating climate change. Of the two options of C sequestration based on geoengineering and terrestrial/aquatic ecosystems, there are specific niches for each strategy. While geoengineering techniques have more sink capacity, C sequestration in terrestrial ecosystems is costeffective and has numerous ancillary benefits. Restoration of degraded/desertified soils/lands, because of the drastic depletion of their ecosystem C pool, has a large potential of C sequestration in both soil and biota. Increasing C pool in agricultural soils is also essential to advancing global food security, especially in developing countries. Yet, C sequestration in soil and biota requires land and other resources. Additional inputs (land, water, nutrients) are also needed for biofuel production through establishment of energy plantations. Life cycle analysis, based on C accounting, is needed to determine the net C gains in managed ecosystems. Farming carbon and trading C credits, for generating another income stream for farmers and land managers, are needed to promote conversion to a restorative land use and adoption of recommended management practices. To make terrestrial C a tradable commodity requires development of appropriate protocol(s) to predict, measure, verify, and certify C pool and flux at landscape, farm, watershed and regional scales. Identifying a mechanism/market to establish just, fair, and transparent price of C sequestered in soil and biota is essential to promote the strategy of "farming carbon." Carbon sequestration in terrestrial ecosystem is a win-win situation. It is a low-hanging fruit, a natural process, and a bridge to the future until non-carbon, low-carbon and other renewable fuel and energy sources take effect.

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