4 Anthropogenic Changes and the Global Carbon Cycle

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4.1 INTRODUCTION

Although climatic fluctuations have occurred often over the past 420,000 years, the rates of increase in temperature in the last 100 years are unprecedented in both magnitude and cause. Similarly, the rates of increase in atmospheric greenhouse gas (GHG) concentrations over the 20th century do not appear in the paleo record, and are causally linked with the recent changes in global temperature. Significantly, human industrial development is clearly linked to for the changes in GHG concentrations. Over much of the preceding half million years, the fluctuations of atmospheric GHGs and global average temperature remained in a relatively narrow, correlated band (Chapter 2), implying a natural balance in the exchange of GHGs between the atmosphere and planetary surface.[1]

The 19th century, however, witnessed the start of a dramatic change in this balance which to date has already recorded a 32% increase in CO_2 relative to the average of the past 420,000 years, a change whose rate is still accelerating.[2] These changes have been driven by human perturbations to the global carbon (C) cycle — changes that have been both *direct,* introducing new C to the active cycle through fossil fuel use and land-use change (LUC), and *indirect,* affecting the biospheric portion of the active C cycle through environmental stresses and perturbations to other global biogeochemical cycles. The observed response of the global climate system to this change during the 20th century, expressed in terms of global mean temperature, is modest (+0.6°C) but has already led to detectable impacts.[3] The predicted changes in climate for the 21st century and beyond are now more certain and predicted to be higher, and faster, than previously estimated — perhaps +6°C or more by 2100.[2] Although terrestrial and oceanic ecosystems currently absorb an amount equal to about 60% of the direct anthropogenic emissions of CO_2 to the atmosphere, the natural physiological mechanisms that are thought to be responsible for this increased uptake are not expected to function as effectively in the future (Chapter 9). Thus, in the absence of purposeful mitigation strategies, the terrestrial CO_2 sink will likely decrease and could even become a source during the 21st century,[4] accelerating the changes in climate. Changes in the global C budget, dominated by CO_2 although CH_4 is also important, play a vital role in determining global climate.

4.2 GLOBAL CARBON CYCLE

Understanding the mechanisms that regulate the global C cycle and the exchange of C between the atmosphere and various natural and anthropogenic components (illustrated in Figure 4.1) is central to finding ways to mitigate or adapt to global climate change.

4.2.1 Carbon Pools

Five principal global C reservoirs can be identified: atmosphere, vegetation, soils, oceans, and fossil fuels. In 1999, the atmosphere contained about 767 gigatons of C (Gt C) in the form of CO_2.[2] This C corresponds to an average atmospheric concentration of CO_2 of 365 parts per million by volume (ppm), although the actual CO_2 concentration varies slightly from place to place and from season to season.[2] Notably, concentrations and seasonal variations are somewhat higher in the Northern than in the Southern Hemisphere because the main anthropogenic sources of CO_2 are located north of the Equator and because there are larger biospheric exchanges over land surfaces (which is greater in the Northern Hemisphere) than oceans (which is greater in the Southern Hemisphere). During the 1990s, the average concentration of CO_2 increased by 1.5 ppm/year,[5] and is continuing to rise in the first decade of the 21st century at an even higher rate. The 5 ppmv increase during 2001–2003 was the highest ever recorded.[6] Thus, by 2005 the atmosphere was estimated to contain 807 Gt C in the form of CO_2, an increase of 42 Gt C since 1999.

The terrestrial C pool, the third largest pool, comprises reservoirs in soil and vegetation. The vegetation pool, made up of all vegetation types but dominated in mass by trees, is estimated at 610 Gt C.[7] The soil C pool is made up of two components: the soil organic C (SOC) pool estimated at 1550 Gt C and the soil inorganic carbon (SIC) pool estimated at 950 Gt C.[8,9] Thus, the soil C pool of 2500 Gt C is about four times the size of the vegetation pool and about three times the

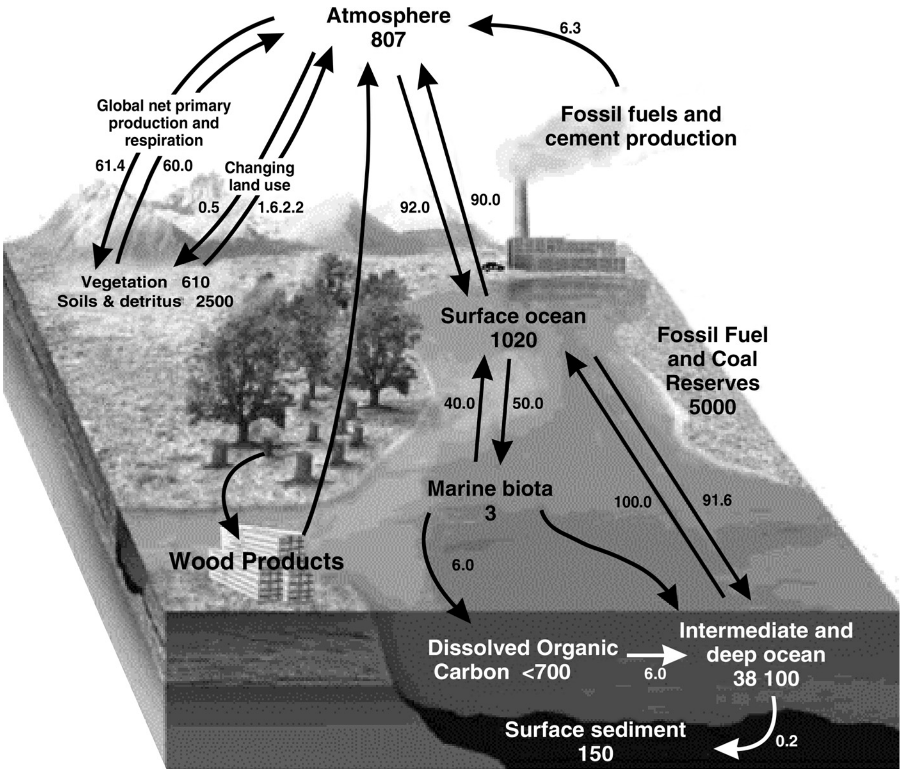

FIGURE 4.1 Overview of the global carbon cycle. The stocks and fluxes of C (Gt) between various components and the atmosphere. (Modified from Bhatti et al.[76])

atmospheric pool. The total terrestrial C pool is about 3060 Gt C. The amount of C stored in the geological formations as fossil fuel is considerably larger — on the order of 5000 Gt C — of which the vast majority is in the form of coal (4000 Gt C) and the rest as oil and gas (500 Gt C each). In comparison, the terrestrial C pool of 3060 Gt C is about 61% of the estimated fossil fuel pool and about four times the atmospheric pool. The fossil fuel parts of the geological pools as reported here include only that carbon that originated from biological processes in the far distant past, and does not include carbonates in sedimentary rocks (1×10^6 Gt C), which were primarily formed through abiotic chemical and physical processes. These latter deposits contain about 1700 Gt C and occur primarily in arid and semiarid regions.[10]

The oceans contain the largest C pool at 38,000 Gt C — but most of these vast stores are effectively held out of circulation in the form of dissolved bicarbonate in the intermediate and deep ocean.[7]

4.2.2 Carbon Exchange

All these C reservoirs are interconnected by biotic, abiotic, and anthropogenic processes. For example, 60 Gt C is exchanged in each direction between vegetation and the atmosphere each year through the biological processes of photosynthesis (uptake) and respiration (release). Similarly, 90 Gt C is emitted and 92 Gt C absorbed by the ocean each year[7,11] through a combination of physical exchange and biological activity at the ocean surface. In comparison, only 6.3 Gt C/year is emitted by human combustion of fossil fuel and another 1.6 to 2.0 Gt C/year by land-use change, but these fluxes are emissions only, with no compensating uptake directly associated with them. Clearly, were it possible to enhance photosynthetic uptake and avoid the re-emission through decomposition (i.e., sequestering), even 5% of the photosynthetic C in terrestrial ecosystems would drastically offset the industrial emissions. Over short timescales (a few years), this is not difficult: the challenge, however, is whether such sequestration can be carried out in a sustainable way. Additional issues at hand are how much do each of the four terrestrial nongeological pools contribute to the enrichment of CO_2 concentration in the atmosphere, which pools are potential sinks of atmospheric CO_2, and can they be managed in some way to ensure this sink?

On the source side of the sink-source balance, combustion of fossil fuels and depletion of the geological pool is an obvious and readily quantifiable term. Another obvious but not easily quantifiable source is deforestation and the attendant biomass burning that occurs largely, but not exclusively, in the tropics. Yet another important but neither obvious nor easily quantifiable source is the emission of CO_2 and other GHGs through soil degradation. Each year, soils globally release about 4% of their pool (60 Gt C) into the atmosphere — about ten times the fossil fuel combustion. Although most of this is associated with the natural processes of decay, decomposition, and combustion that form part of the balanced carbon cycle, additional releases are associated with human land-use practices and changes in land use. The exact magnitude of the loss is not known, and may in fact be greater than 60 Gt C because of anthropogenic perturbations to ecosystems leading to degradation. On the other hand, the so-called "missing C" (the amount required to close the balance between estimates of total sink, total source, and atmospheric C increase; see Chapter 9) may also be associated with uptake by soils and other terrestrial ecosystems. These issues can be resolved only when the mechanisms that underlie all major fluxes of the global C cycle are understood.

Boreal forests and their associated peatlands represent the largest terrestrial reservoir of C,[2] as well as being located in a region especially sensitive to climate change. The boreal biome, therefore, plays a critical role in the global C cycle and has the capacity to either accelerate or slow climate change to some degree, depending on whether the forest ecosystems act as a net source or a net sink of C. This source or sink status is, however, not a static characteristic of the ecosystem, but changes over time as a result of alterations to forest age-class structure, disturbance regime, and resource use.[12,13]

Currently, about 78% of the direct human perturbations to the global C cycle are due to fossil fuel combustion, emissions of which now exceed 6 Gt C/year and continue to increase rapidly. (To put this global emission in perspective for a single year, it is equivalent to the total incineration of half of all trees in Canada — with no residues, charcoal, or shoot left behind. Alternatively, to offset the fossil emissions by growing forests, it would be necessary to create a forest biomass equal to half that in Canadian forests every year.) In addition, since the mid 19th century, LUC has resulted in the cumulative emission of ~156 Gt C of anthropogenic CO_2 to the atmosphere. This LUC flux is about 56% of that from fossil fuel use (~280 Gt C) and continues to be an important anthropogenic emission (2.2 Gt C/year).[14] Human land-use practices, therefore, play a significant role in the contemporary C cycle.

Of the 7.6 ± 0.8 Gt C/year of CO_2 added to the atmosphere by human activities during the period 1980 to 1995, less than half (3.2 ± 1.0 Gt C/year) remains there, with the rest taken up about equally by the oceans and by terrestrial ecosystems.[15] Earth's biosphere thus actively removes some of the new C that humans have added to the atmosphere and into the active C cycle. Terrestrial ecosystems, in particular, appear to have sequestered (taken up and retained) 2.3 ± 0.9 Gt C/year, even after accounting for the loss of between 2.0 and 2.2 Gt C/year from deforestation.[14] Likewise, the world's oceans sequester a similar amount of the new C added to the active cycle by human activities.

The biosphere thus appears to be attempting to restore the balance that prevailed for the previous 420,000 years. But it is losing the battle: atmospheric CO_2 concentrations are already at unprecedented levels and rising at a rate never before seen in the geological record (Chapter 9). Moreover, it is unclear whether the biosphere can continue to function as a net sink into the future. At the present, scientific know-how required to explain and predict changes in the mechanisms responsible for the present net biospheric uptake is severely limited. More specifically:

- Will these mechanisms continue to offset the direct anthropogenic emissions? Or will the mechanisms decline in strength, or even fail entirely as the C cycle–climate system moves into a new mode of operation,[16] as several terrestrial and ocean model simulations alarmingly suggest?[4,17]
- Are the changes in the C balance of Canada's forest associated with an altered natural disturbance regime,[12] a warning that the putative sink is already disappearing?

Although it is not possible to address these questions with full certainty at this time, they are of obvious importance to humanity. Whether forests and agriculture ecosystems can continue to provide both the goods (e.g., food and fiber) and services (e.g., recreation, spiritual, and social) that humans have come to depend on is a question that remains to be answered. There is an urgent need to assess the impact of human activities on the terrestrial biosphere and its contribution to the global C cycle. Climate change affects both the distribution and character of the landscape through changes in temperature, precipitation, and natural disturbance patterns. These impacts are not entirely separable from the effects of other global changes such as increases in CO_2, NO_x, and O_3 levels, and anthropogenic pressures which may be exacerbated by climate change. Figure 4.2 illustrates the interactions among climate, vegetation, disturbance regimes, and C pools. The following sections (Land Use and Land-Use Change; Land Degradation and Soil Erosion; CO_2 Fertilization; Drainage; and NO_2 Fertilization) deal with the impacts of various anthropogenic agents on ecosystems and their contributions to the C cycle.

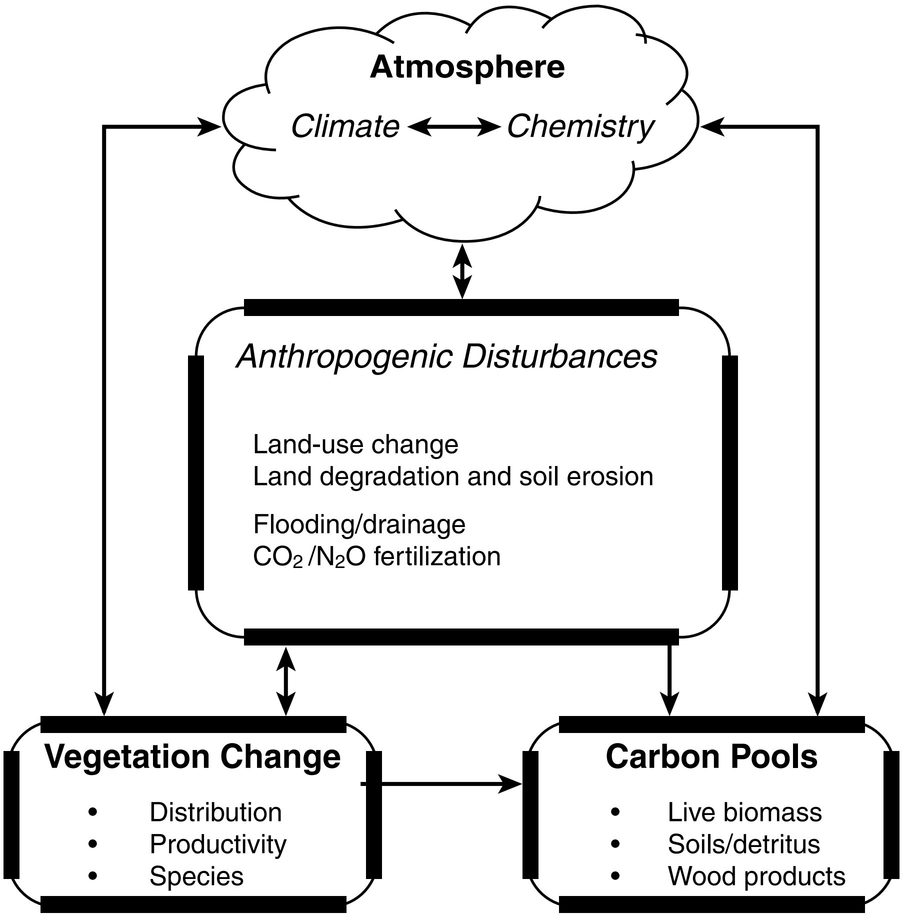

FIGURE 4.2 Feedbacks between the atmosphere and various components of the boreal forest. (Modified from Bhatti et al., 2002.)

4.3 LAND USE AND LAND-USE CHANGE

Loss of forested areas is a major conservation issue with important implications for climate change. The proportion of land surface covered with agriculture is relatively small (7%) in Canada compared to that under forest (50%).[18] With increases in population and food demand over the last century, large forested areas of the boreal region are being converted to agricultural use.[15] However, the rate of forest loss and fragmentation of different ecosystems in the boreal biome, and the associated anthropogenic factors that influence these rates, is not well established.

Forested lands are influenced by natural and anthropogenic causes, including harvesting, degradation, large-scale wildfire, fire control, pest and disease outbreaks, and conversion to nonforest use, particularly agriculture and pastures. These disturbances often cause forests to become sources of CO_2 because the rate of net primary productivity is exceeded by total respiration or oxidation of plants, soil, and dead organic matter — net ecosystem production (NEP) < 0.[20]

Between 1975 and 2001, 18.7 million hectare (Mha) of forest was harvested in Canada and 15.2 Mha successfully regenerated.[18] The harvest techniques (site preparation, planting and spacing, and thinning) as well as harvest methods (clear-cutting or partial cutting) and factors that affect how much and what type of material is removed from the site have a significant influence on the C balance. After harvesting, a forest stand's net C balance is a function of the photosynthetic uptake minus the autotrophic and heterotrophic respiration that occurs. While a stand is young, the losses through decomposition outweigh the gains through photosynthesis, resulting in a net source (Chapter 9).

Increasing the C uptake can be accomplished through techniques that reduce the time for stand establishment (such as site preparation, planting, and weed control), increase available nutrients for growth, or through the selection of species that are more productive for a particular area. Decreasing the losses can be accomplished through modification of harvesting practices such as engaging in lower-impact harvesting (to reduce soil disturbance and damage to residual trees), increasing efficiency (and hence reducing logging residue), and managing residues to leave C on site[21] (Chapter 9).

Rapid expansion of agriculture along its southern boreal has been recognized as at risk for more than 50 years.[22] The conversion of native upland and lowland into agriculture and urban lands has escalated, resulting in the contemporary patchwork of ecosystem types.[19] Losses of C include both the initial depletion associated with the removal of natural vegetation and the subsequent losses from soil through mineralization, erosion, and leaching in the perturbed ecosystems. In the prairie provinces of Canada alone, it is estimated that there was a net deforestation of 12.5 Mha between 1869 and 1992.[23] Using the Canadian Land Inventory Database to examine changes between 1966 and 1994, Hobbs[24] estimated that forests of the southern boreal plains of Saskatchewan declined from 1.8 Mha in 1966 to 1.35 Mha by 1994,[24] an overall conversion of 24% of the boreal transition zone to agriculture since 1966. A more recent study suggests that forestland is being converted into agriculture, industrial, and urban development at the rate of 1215 ha/year along the southern boreal zone of Canada.[25] This rate is approximately three times the world average: the loss of boreal forests and wetlands is equal to, and in some regions greater than, that occurring in tropical rainforests. These estimates suggest that all the wetland and forested areas in the boreal transitional zone will be lost by 2050 unless purposeful action is taken to reverse the present trend.

Conversion of natural to agricultural ecosystems causes a net emission of CO_2 and other GHGs into the atmosphere. In addition to decomposition of biomass with the attendant release of CO_2, agricultural activities also deplete the soil C pool through reduction of biomass inputs and changes in temperature and moisture regimes, which further accelerate decomposition. Soil drainage aimed at managing water table depth and soil cultivation (to control weeds and prepare seedbeds) also accelerates soil erosion and mineralization of the SOC pool. Most agricultural soils in the North America have lost 30 to 50% (30 to 40 Mg C/ha) of the preexisting carbon pool following conversion from natural to agricultural ecosystems. Thus, SOC pools in most agricultural soils are well below their potential capacity by an amount equal to the historic C loss since conversion to agricultural ecosystems.

The above discussion has focused on CO_2, but similar conclusions can be drawn for other GHGs, such as CH_4 and N_2O.[2] For example, N_2O emissions are influenced by the timing and amount of fertilizer applications and hence, intensity of management. Changes in land cover also alter the uptake of CH_4 by soils, and different agricultural practices differ in their CH_4 emission profiles. Increases in animal populations have also contributed to the increase in atmospheric CH_4. Enteric fermentation, the digestion process in ruminant animals such as cattle, sheep, and goats, adds an estimated 100 Gt of CH_4 per year to the atmosphere.

Virtually all these emissions also vary with alterations in climatic and ecological conditions, leading to a heterogeneous spatial and temporal pattern of GHG emissions from the terrestrial biosphere that is strongly influenced by physical, biogeochemical, socioeconomic, and technical factors. Actual land use and the resulting land cover are important controls on these emissions, and when mitigation policies are evaluated, aggregated assessments using global averages to calculate the emissions are no longer valid. State-of-the-art assessments must be dynamic, geographical and regionally explicit, and include the most important aspects of the physical subsystem, the biogeochemical subsystem, and land use and changes therein.

Farm operations also incur hidden C costs. The average emission (calculated in carbon equivalent units) per hectare is 15 kg C for moldboard plowing,[1] 11 kg C for sub-soiling, 8 kg C for heavy tandem disking, 8.0 kg C for chiseling, 6.0 kg C for standard disking, 4.0 kg C for cultivation, and 2.0 kg C for rotary hoeing.[26] Thus, emissions are 35 kg C/ha for complete conventional tillage operations compared with 6.0 kg C/ha for disking only, and none for no-till farming. Emissions associated with pump irrigation are 150 to 285 kg C/ha/year depending on the source of energy and depth of the water table.[27,28]

Other agricultural activities also led to emission of GHGs, especially CO_2 and N_2O (Figure 4.3). In addition, there are hidden C costs for application of nitrogenous fertilizers and pesticides.[26] Estimates of emissions (given in equivalent C units) for production, transportation, and packaging of fertilizer are 1 to 3 kg C/kg for N, 0.2 kg C/kg for P, 0.15 kg C/kg for K, and 0.16 kg C/kg for lime.[26] The hidden C costs are even higher for pesticides and range from 6.3 kg C/kg for herbicides, 5.1 kg C/kg for insecticides and 3.9 kg C/kg for fungicides.[26]

Enhancing the use efficiency of agricultural chemicals and irrigation water can have beneficial C implications. The use efficiency of N is generally low, and fertilizer use is a significant cause of increased N_2O emission.[29] It is thus important to minimize losses of fertilizers (especially nitrogenous fertilizers) by erosion, leaching, and volatilization.[30,31] Integrated nutrient management and integrated pest management can be valuable strategies for reducing emissions. While increasing N stocks through incorporation of cover crops in the rotation cycle is a useful strategy, N_2O emission and leaching of NO_3 into the groundwater can also occur when the N is biologically fixed. Sustainable management must seek to enhance the use efficiency of C-based inputs while simultaneously decreasing losses of these fertilizers, thereby achieving both environmental and economic benefits.

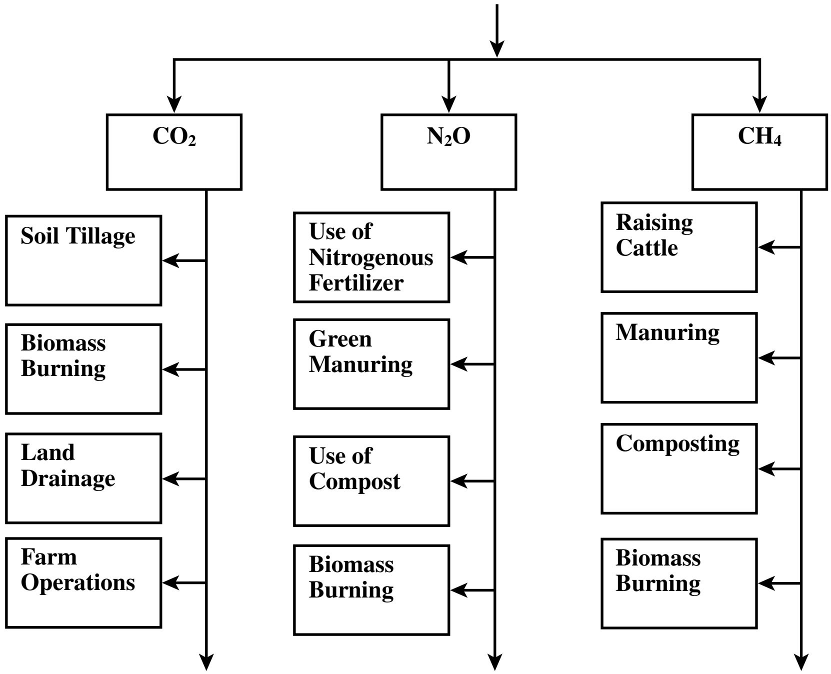

FIGURE 4.3 Emission of greenhouse gases from agricultural activities.

4.4 CO_2 FERTILIZATION

CO_2 fertilization, discussed in Chapters 5, 9, and 16, theoretically has the potential to increase photosynthetic uptake of CO_2 in terrestrial plants by up to 33%.[32] The CO_2 fertilization effect may be expected to enhance the growth of some tree species and forest ecosystems, allowing them to absorb more C from the atmosphere (Chapter 16). Whether the enhancement of photosynthesis by elevated CO_2 actually results in net removal of CO_2 from the atmosphere at the ecosystem level, however, is a subject of intense debate (e.g., Reference 33). Notably, forest inventory data indicate that the net effect on C-stocks is less than the enhancement of gross photosynthesis alone would suggest, and may account for less than a few percent increase in accumulated C in forest vegetation.[34]

Many of the experimental studies on elevated CO_2 response have been conducted on tree seedlings, often in growth chambers, under conditions not otherwise limiting plant growth.[32,35] Several field experiments are currently under way that employ free air CO_2 enrichment (FACE) technology by which the CO_2 (and other gases) around growing plants may be modified to simulate future levels of these gases under climate change.[33,36] These experiments, however, have not been conducted for long enough to determine what the long-term effects of elevated CO_2 levels might be once canopy closure is reached.[37] While the response of mature forests to increases in atmospheric CO_2 concentration has not been demonstrated experimentally, it will likely be different from that of individual trees and young forests (see References 34 and 38 and Chapter 15).

Chen et al.[39] and others have hypothesized that Canada's forest net primary productivity (NPP) may be increasing, and that this increase may be due in part to CO_2 fertilization.[39] This disagrees with the inventory measurements reported for U.S. forests over the past century.[34] Forest age-class dynamics, LUC, and alterations in natural disturbance patterns appear to have a much larger influence than CO_2 fertilization on forest growth in North American forests.[12,34] There is a growing consensus in the scientific community that CO_2 fertilization effects, to the extent that they exist, can be expected to saturate (that is, their contribution to continued net CO_2 removals will go to zero) over the next 100 years or so,[37,40] or even reverse. This occurs because increases in CO_2 levels stimulate increases in gross photosynthesis at a diminishing rate, while increases in temperature stimulate increases in respiration at an exponential rate thereby reducing the net photosynthetic uptake.[37] Additional increases in decomposition further reduce the net sink and may even result in a source.[41]

The difference in the response of C_3 and C_4 plants to increasing CO_2 concentrations is also well documented, and different biomes have significantly different proportions of C_3 and C_4 plants.[42] Based on this factor alone, temperate and boreal forests would be expected to be more sensitive to CO_2 fertilization than grasslands. Even within a biome, between plant species or even genotypes there is a marked differential response to CO_2 fertilization. A managed temperate forest planted with a highly sensitive species may store larger amounts of C than an otherwise equivalent forest planted with less sensitive species, or a comparable tract of old forest. Therefore, the CO_2 fertilization effect is quite heterogeneous over time and space.

4.5 NO_X FERTILIZATION AND OZONE

The concentration of N_2O in the atmosphere increased about 0.25% per year during the 1990s, and has increased about 13% since pre-industrial times (from 275 to 312 ppbv).[2] The primary sources of N_2O are the combustion of fossil fuels, use of fertilizers, livestock, and burning of biomass. Because of the widespread use of anhydrous ammonia, it is estimated that about 5% of the N in fertilizer applied to fields in Ontario, Canada is converted to N_2O and about 11% to NO_x.

In boreal forest ecosystems, N is a limiting factor to vegetation growth because most of it occurs in forms that cannot be readily used by most plants. Human activities have increased the supply of N in some regions of the eastern boreal forest. It has been suggested that increased N deposition (due to NO_x atmospheric pollution) may temporarily enhance forest C sequestration in N-limited ecosystems, leading to a short-term C gain in net primary productivity (NPP).[43]

Different forest ecosystem types vary greatly in their potential for C sequestration. Woody tissues typically have C:N ratios >300 and lifetimes >100 years. Hence, it might be expected that if higher wood production with excess N can be obtained, it would result in large removal of C from the atmosphere over long time periods.

Even if the high C:N ratios are maintained, however, the positive effect on forest growth from N deposition in boreal forests will likely be negated in the medium term as other factors, such as other nutrients and water,[44] become limiting to their growth. In North America, N deposition has not appreciably affected C accumulation rates at the landscape level.[34] On the contrary, the evidence is that excess deposition has harmful effects at the stand level, on both forested and aquatic ecosystems.[45]

Nevertheless, lack of available N is a limiting factor in most of boreal ecosystems. In addition to the direct effects of nutrient addition in stimulating NPP, enhanced N supply operates synergistically with CO_2 fertilization, and may also increase the soil C storage capacity. The net effect of these increases with the increased oxidation and microbial decomposition at the projected higher future temperatures on both biomass production and soil humification, however, is difficult to predict with present data and understanding.

Annual mean ground-level ozone (O_3) concentrations in Canada are increasing, particularly in urban areas.[46] At least 2 Mha of Canada's productive eastern forest is exposed annually to damaging levels.[47] Exposure of western forests to O_3 is difficult to estimate with the present lack of ground-level monitoring data, but some southeastern forest ecosystems are likely to be more exposed because of significant industrial expansion in these areas. O_3 can adversely affect forest ecosystems by impairing tree physiology, in particular by decreasing the rate of photosynthesis in some species and altering carbohydrate allocation patterns in others.[48] With respect to the latter, C transfer is commonly increased to the shoots, but decreased to the roots. While this gives an apparent increase in their growth rates, it also makes trees more vulnerable to drought, nutrient deficiencies, and winter damage.

FACE study results indicate that the growth rate increases due to CO_2 fertilization observed in some tree species are often negated by the effects of tropospheric O_3.[49] For example, Isebrands et al.[49] reported negative responses in aspen (*Populus tremuloides*) and birch (*Betula papyrifera*) aboveground estimated stem volumes relative to the controls after 3 years of fumigation with O_3 and $O_3 + CO_2$. A stimulation of 20 to 30% increase with CO_2 alone was also completely offset by O_3. While experimental studies have shown reduced growth rates in some forest species exposed to O_3,[49] there is no evidence that changes in O_3 levels result in any significant changes (either negative or positive) in forest growth rates at the landscape level. Any effects are likely to be region specific and occur against a longer-term background of climate and forest change.

Carbon is only one of several important constituents of soil organic matter. Even if C is supplied to the soil through application of crop residues and other biomass, it may not be converted into humus if there is not enough N and other essential elements (e.g., P, S, Ca, Mg). The C:N ratio in crop residues is often 80:1 or 100:1. In contrast, the C:N ratio in humus is typically between 10:1 and 12:1. The implication is that humification of C in crop residues and other biosolids is limited by availability of N. It is estimated that sequestration of 1000 kg of C in humus requires 83.3 kg of N, 20 kg of P, and 14.3 kg of S.[50] Because of this requirement for N, more C is sequestered in croplands that are fertilized.[51] Counteracting the GHG benefits of this uptake, however, is the fact that addition of N fertilizers for crop growth and humification of biosolids also increases the quantity of mineralized N,[52] with an attendant emission of N_2O and leaching of NO_3 into the groundwater.

4.6 LAND DEGRADATION

Land degradation can occur through either degradation of the vegetation cover or the underlying soil but ultimately results in reduced performance of both parts of the ecosystem. Degradation of soil occurs as a result of excessive utilization, environmental changes, and/or careless management of agricultural areas or lands used for pasture or forestry. Degradation can span the range of vegetation cover reduction to severe soil erosion. Soil degradation may be physical, chemical, or biological (Figure 4.4). These degradation processes adversely affect NPP both directly and indirectly, and reduce the amount of biological material returned to the soil. Consequently, the C input into the system is lower than the C out of the system, resulting in depletion of the soil C pool and an atmospheric source.

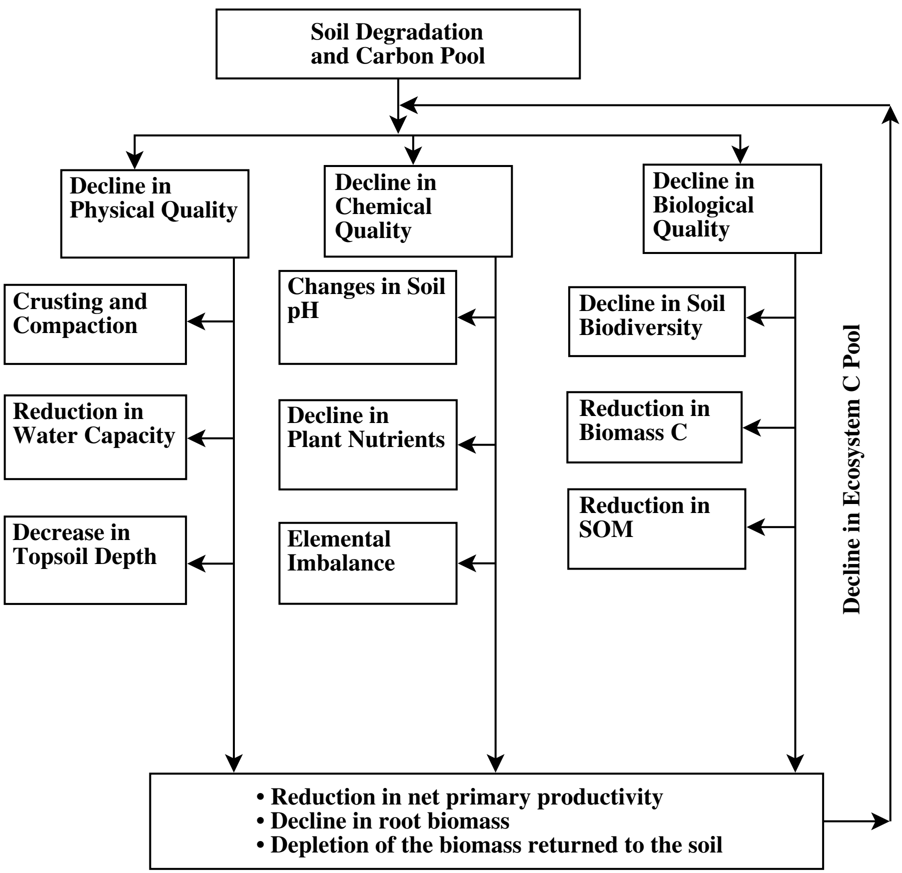

FIGURE 4.4 Soil degradation effects on soil carbon pool.

LUC associated with a loss of vegetation typically has an initial rapid loss of C and nutrients that is generally ascribed directly to the LUC itself; it can, however, result in a longer-term degradation that generates additional depletion. The loss of belowground C is especially significant because this loss can be much more rapid than the rate of its formation or replacement; these pools are usually regarded as long-term storage. The magnitude of these degradation processes is relevant because they occur in at least 70% of drylands[53] that occupy almost 40% of the land surface. They are also an important factor in the carbon balance in humid areas, such as rain forests and tundra. Is there a CO_2 fertilization effect on these degraded lands? If antidesertification or land management measures are taken, will the C stocks return to their original values, or will they be higher or lower?

These environmental stresses, combined with other factors such as increased fire frequency, and the introduction of exogenous plant and animal species, pests, and diseases to natural and managed biomes contribute to further magnify the uncertainty in predictions of the future of the terrestrial sink and the effect of CO_2 fertilization and climate change.

Soil degradation and desertification are serious global issues affecting both large areas and diverse ecosystems (Table 4.1). Soil degradation and desertification are severe in warm and arid climates. These are biophysical processes, but they are driven by socioeconomic and political forces. The problem of soil degradation is exacerbated by overexploitation of natural resources through deforestation of steep slopes, excessive grazing, cultivation of steep or marginal lands, and mining of soil fertility by low-input- or no-input-based extractive agricultural practices.

Soil degradation adversely affects soil quality and depletes the SOC pool. Biological soil degradation, in comparison with physical and chemical degradation processes, is directly related to the depletion of the SOC pool and the reduction in soil biodiversity. Soil degradation has positive feedback elements due to the

TABLE 4.1
Global Extent of Soil Degradation

Land Degradation Process	Global Areas* Affected (10^6 ha)
1. Soil degradation	
i. Water erosion	749
ii. Wind erosion	280
iii. Chemical degradation	146
iv. Physical degradation	39
2. Desertification	
i. Irrigated cropland	43
ii. Rainfed cropland	216
iii. Rangeland	3334

*These estimates include moderate, severe, and extreme forms of soil degradation.
Source: Adapted from Lal.[30]

interactions among the difference processes involved, so that, once triggered, the degradation may accelerate over time in both magnitude and rate.

As a result of these feedback effects, most degraded soils are severely depleted of their SOC pool. The historic loss of the SOC pool in degraded soils and ecosystems, however, has created the potential for creating a C sink: restoring degraded soils and ecosystems provides an opportunity to restore some of the depleted SOC.

4.7 SOIL EROSION

Accelerated soil erosion is the most widespread form of soil degradation. Globally, the total land area affected is estimated at more than 1 billion hectares — about 750 Mha through water erosion and 290 Mha by wind erosion (Table 4.2). Regionally, hot spots of erosion include the Himalayan-Tibetan ecosystem in South Asia, the Loess Plateau in China, sub-Saharan Africa and the East African highlands, the highlands of Central America, the Andean region, Haiti and the Caribbean.[31] The annual sediment transport into the ocean by the world's rivers is estimated at 15 to 20 Gt C.[54] Global transport of C in rivers is estimated at 0.74 Gt C/year.[55]

Soil erosion leads to a preferential removal of soil organic material, because it is a light fraction and is concentrated in the vicinity of the soil surface. The enrichment ratio (i.e., the concentration of organic carbon in the eroded soil relative to that in the non-eroded soil) of the sediments is generally more than 1, and often as high as 5 to 10. Consequently, the SOC pool of eroded soils is severely depleted, often by as much as 30 to 45 Mg C/ha. The fate of C displaced by erosion is obviously important but a highly debated topic. Some sedimentologists[56,57] argue that C transported to and buried under the aquatic ecosystems and ocean is permanently sequestered. Others[31] suggest that a sizable proportion of the displaced C is

TABLE 4.2
Global Extent of Moderate, Severe, and Extreme Forms of Soil Erosion by Water and Wind

Region	Area Affected (106 ha)	
	Water Erosion	Wind Erosion
Africa	169	98
Asia	317	90
South America	77	16
Central America	45	5
North America	46	32
Europe	93	39
Oceanic	4	16
World	751	296

Note: Figures in Tables 4.1 and 4.2 differ because of different sources of data and in some cases a slight form of erosion is also included in Table 4.2.
Source: Adapted from Lal.[31]

emitted to the atmosphere as CO_2 prior to its burial in aquatic ecosystems and floodplains. Lal[31] estimated that on the global scale, water erosion translocates about 4.0 to 6.0 Gt C/year. Of this, 2.8 to 4.2 Gt C/year is redistributed over the landscape and transferred to local depressional sites, 0.4 to 0.6 Gt C/year is transported into the ocean by world rivers, and 0.8 to 1.2 Gt C/year is emitted to the atmosphere as CO_2. Thus, adoption of conservation-effective measures can drastically reduce the erosion-induced emission of soil into the atmosphere.

Restoration of eroded and degraded soils has a large potential to sequester C and offset a fraction of the anthropogenic emissions. The data in Table 4.3 show the potential of soil C sequestration through restoration of eroded soils and degraded ecosystems. The total potential of C sequestration in these ecosystems is 0.1 to 0.2 Gt C/year over a 50-year period.[30] Suggested cropping practices that may restore some of the depleted SOC in eroded agricultural soils include reduction in tillage, growing of perennial forages cover, and application of organic amendments to the soil. An almost 70% increase in total C over a 5-year period has been observed in the Canadian Prairies with continuous legume/cereal production, reduced tillage, and nutrient additions via fertilizer or composted manure applications.[58]

4.8 WETLAND DRAINAGE

In Canada, most peatlands occur in the boreal zone and are generally unaffected by agricultural, urban, ports/harbors, and industrial development. Flooding forested and wetland areas in the boreal zone for hydroelectric reservoirs generates massive fluxes of dissolved organic carbon (DOC) into the water, accelerates peat decomposition, and increases methane and CO_2 fluxes to the atmosphere.[46,59,60] For example, Kelly et al.[59] experimentally flooded a boreal wetland in Ontario, causing the carbon dynamics of the site to change from a sink of 6.6 g C/m^2/year to a source of 130 g C/m^2/year. Turetsky et al.[60] estimated that 0.8 ± 0.2 Gt C/year is released from approximately 780 km^2 of hydroelectric reservoirs in peatlands across western boreal Canada.

TABLE 4.3
Potential of Soil Carbon Sequestration in Eroded and Degraded Soils of the World

Degraded Soil	Land Area That Can Be Restored (10^6 ha)	Mean Rate of SOC Sequestration (kg/ha/yr)	Annual Rate of Sequestration (Gt C/yr)
Water and wind erosion	500	200–400	0.1–0.2
Physical degradation	75	100–200	0.01–0.02
Chemical degradation	20	100–200	0.002–0.004
Total			0.112–0.224

Source: Adapted from Lal.[30]

In the Canadian Prairie/parkland, drainage is still a current practice, although the major peat deposits lie farther north in the boreal forest. Approximately 17% of farmers whose lands supported wetlands had drained one or more of them between 1990 and 1992.[61] Drainage has serious consequences because it changes the habitat entirely and lowers the water table, altering both the processes of photosynthesis (C uptake) and decomposition (C release). Since 1950, the U.S. has lost 87 Mha of its original wetlands, primarily due to expansion of agriculture.[53] In Canada, agriculture alone accounts for an estimated loss of 20 Mha of the pre-settlement wetlands.[62] Losses in Europe are along the same lines — 67% in France (1990–1993), 57% in Germany (1950–1985), and 60% in Spain (1948–1990).[63] Peatlands/wetlands have been drained for the growth of crops and trees, production of fuel, and the harvesting of horticultural moss.[64] The emission of CO_2 increases when northern peatlands are drained or degraded.[65,67] Drained and cut-over boreal peatlands remain an ongoing source of CO_2 emissions for a long time, even in wet years.[68] Globally, the long-term drainage of peatlands has resulted in the emission of about 0.0085 Gt C/year of CO_2, while burning of fuel peat adds an additional 0.026 Gt C/year.[69] In Sweden, farmed organic soils represent less than 10% of total arable land, but contribute as much as 10% of the total national anthropogenic CO_2 emission.[70] In Canada, it has been suggested that draining an additional 5% of Canadian peatlands would be sufficient to offset the putative existing peatland carbon sink of the country.[68] Draining of peatlands also significantly increases nitrous oxide emissions.[71,72] In Finland, N_2O emissions from farmed organic soils amount to 25% of total anthropogenic N_2O emissions.[70]

In western Canada, it has been estimated that at least 75% of prairie/parkland wetlands have already been lost through agricultural drainage, many of which are subsequently only marginally productive under crop management.[73] The loss of SOC from such wetlands when converted to agricultural usage may be as much as 50%.[74,75] Another key element is the degradation of riparian zones and associated uplands via cultivation or overgrazing. This has the direct impact of reducing the amount of vegetated habitat available to sequester C, but also has a negative impact on the remaining wetland through nutrient loading associated with transport of fertilizer and pesticides in runoff with sediments.

4.9 CONCLUSION

This chapter centers on a key question: Will the present source–sink relationship of the terrestrial biosphere be maintained? More specifically, will the currently observed sequestration by terrestrial ecosystems decrease with time, or can it be maintained and even increased over the next 100 years?

To answer these questions, a reliable projection of the C budget for 50 to 100 years into the future is needed. However, such predictions are difficult to make with certainty given the present state of knowledge. In Chapters 5, 6, 7, 9, 10, and 11 some of these uncertainties are laid out in more detail. In Chapters 15, 16, and 17 the research that appears to be needed to improve the reliability of the predictions is examined. With present knowledge and data, however, it is possible to predict the likely trends in the ecosystems — whether there will be increase or decrease in the relative importance of different components of the terrestrial ecosystems — so that a general trend in the C budget can be projected. Based on the analysis presented above, the following trends appear to be likely:

- Emissions from land-use or land cover change from forest and wetland/peatlands to agriculture will almost surely increase given the sustained increase in food and fiber demand over the next 50 years.
- The emission of CO_2 from the soils (agricultural and forest) as climate warms will become an increasingly important source through the 21st century.
- Increased CO_2 fertilization coupled with N deposition may partially offset these expected increases in emissions with increased plant productivity, but the magnitude of these offsets remains highly debated.
- Risks of soil erosion and other degradation processes, with attendant emission of CO_2 and other GHGs, are likely to increase with high demographic pressure and warming climate.
- The frequency and severity of disturbances (fire, dieback due to insects) are expected to change, with the expected increases over the short term in northern ecosystems leading to increase in mortality and shifts in the age-class structure of the existing forests.
- Where increases in the disturbance regime (fire, insects, disease, wind throw) occur due to climate change, forest carbon stocks will be reduced, with large emissions of carbon to the atmosphere.
- In some locales these emissions may be offset by increased uptake stimulated by better growing conditions.
- Methane emissions from wetlands and peatlands are expected to decrease in southern regions but these GHG emission reductions will to some extent be offset by increased CO_2 releases. Moreover, there may be an increase in CH_4 emissions in northern regions associated with higher temperature, longer growing seasons, and permafrost melting.

Over the medium term (one to two centuries), shifts in the distribution of vegetation will lead to a reduction in tree cover as regeneration processes greatly lag those of mortality. During this period, the terrestrial ecosystems will tend to lose C and act as sources. In the longer term (longer than one to two centuries) if a stable, warmer, and wetter climate prevails, the terrestrial ecosystems will favor higher vegetation densities and hence provide the potential for increased C stocks, acting as sinks while this transition takes place. Whether such potential can be achieved is critically dependent on human actions.

It is possible that the current C source–sink relationships for the terrestrial biosphere may remain approximately in balance, especially if the current sinks could be increased. However, a more likely outcome for the foreseeable future is that the biosphere as a whole will become a net source. This will have important implications for the development of strategies to stabilize the concentration of GHGs in the atmosphere.

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Climate Change and Managed Ecosystems

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CRC Taylor & Francis
Taylor & Francis Group
Boca Raton London New York

A CRC title, part of the Taylor & Francis imprint, a member of the Taylor & Francis Group, the academic division of T&F Informa plc.

Part II

Managed Ecosystems — State of Knowledge

Published in 2006 by
CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8493-3097-1 (Hardcover)
International Standard Book Number-13: 978-0-8493-3097-1 (Hardcover)
Library of Congress Card Number 2005028910

Library of Congress Cataloging-in-Publication Data

Climate change and managed ecosystems / edited by J.S. Bhatti ... [et al.].
p. cm.
Includes bibliographical references and index.
ISBN-10: 0-8493-3097-1 (hardcover)
1. Climatic changes. 2. Ecosystem management. I. Bhatti, J. S. (Jagtar S.)

QC981.8.C5C5113823 2006
333.95--dc22 2005028910

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