12.9 CARBON BALANCE IN THE SOIL–PLANT–ATMOSPHERE SYSTEM

Whether the goal is to reduce greenhouse gas emissions or to enhance soil quality and plant production, proper management of soil organic matter requires an understanding of the factors and processes influencing the cycling and balance of carbon in an ecosystem. Although each type of ecosystem, whether a deciduous forest, a prairie, or a wheat field, will emphasize particular compartments and pathways in the carbon cycle, consideration of a specific example, such as that described in Box 12.2, can help us develop a general model that can be applied to many different situations.

Agroecosystems

The rate at which soil organic matter either increases or decreases is determined by the balance between *gains* and *losses* of carbon. The gains come primarily from plant residues grown in place and from applied organic materials. The losses are due mainly to respiration (CO_2 losses), plant removals, and erosion (Table 12.5).

Conservation of Soil Carbon. In order to halt or reverse the net carbon loss shown in Figure 12.18, management practices would have to be implemented that would either *increase the additions* of carbon to the soil or *decrease the losses* of carbon from the soil. Since all crop residues and animal manures in the example are already being returned to the soil, additional carbon inputs could most practically be achieved by growing more plant material (i.e., increasing crop production or growing cover crops during the winter).

Specific practices to reduce carbon losses would include better control of soil erosion and the use of conservation tillage. Using a no-till production system would leave crop residues as mulch on the soil surface where they would decompose much more slowly. Refraining from tillage might also reduce the annual respiration losses from the original 2.5% to perhaps 1.5%. A combination of these changes in management would convert the system in our example from one in which soil organic matter is degrading (declining) to one in which it is aggrading (increasing).

Natural Ecosystems

Those interested in natural ecosystems may want to compare the carbon cycle of a natural forest with that of the cornfield in Figure 12.18. If the forest soil fertility were not too low, the total annual biomass production would probably be similar to that of the cornfield. The standing biomass, on the other hand, would be much greater in the forest since the tree crop is not removed each year. While some litter would fall to the soil surface, much of the annual biomass production would remain stored in the trees.

The rate of humus oxidation in the undisturbed forest would be considerably lower than in the tilled field because the litter would not be incorporated into the soil through tillage and the absence of physical disturbance would result in slower soil respiration. The litter from certain tree species may also be rich in phenolics and lignin, factors that greatly slow decomposition and C losses (see Figure 12.8). In forest soils, decomposition of leaf litter produces copious quantities of dissolved organic carbon (DOC) compounds such as fulvic acids, and 5 to 40% of the total C losses may occur by leaching—a much greater proportion than from all but the most heavily manured cropland soils. However, losses of organic matter through soil erosion would be much smaller on the forested site. Taken together, these factors allow annual net gains in soil organic matter in a young forest and maintenance of high soil organic matter levels in mature forests.

Grasslands. Similar trends occur in natural grasslands, although the total biomass production is likely to be considerably less, depending mainly on the annual rainfall. Among the principles illustrated in Box 12.2, and applicable to most ecosystems, is the dominant role that plant root biomass plays in maintaining soil organic matter levels. In a grassland, the contribution from the plant roots is relatively more important than in a forest. Therefore, a greater proportion of the total biomass produced tends to accumulate as soil organic matter, and this soil organic C is distributed more uniformly with depth.

BOX 12.2 CARBON BALANCE—AN AGROECOSYSTEM EXAMPLE

The principal carbon pools and annual flows in a terrestrial ecosystem are illustrated in Figure 12.18 using a hypothetical cornfield in a warm temperate region. During a growing season the corn plants produce (by photosynthesis) 17,500 kg/ha of dry matter containing 7500 kg/ha of carbon (C). This C is equally distributed (2500 kg/ha each) among the roots, grain, and unharvested aboveground residues. In this example, the harvested grain is fed to cattle, which oxidize and release as CO_2 about 50% of this C (1250 kg/ha), assimilate a small portion as weight gain, and void the remainder (1100 kg/ha) as manure. The corn stover and roots are left in the field and, along with the manure from the cattle, are incorporated into the soil by tillage or by earthworms.

The soil microbes decompose the crop residues (including the roots) and manure, releasing as CO_2 some 75% of the manure C, 67% of the root C, and 85% of the C in the surface residues. The remaining C in these pools is assimilated into the soil as humus. Thus, during the course of one year, some 1475 kg/ha of C enters the humus pool (825 kg from roots, plus 375 from stover, plus 275 from manure). These values are in general agreement with Figure 12.10, but they will vary widely among different soil conditions and ecosystems.

At the beginning of the year, the upper 30 cm of soil in our example contained 65,000 kg/ha organic C in humus. Such a soil cultivated for row crops would typically lose about 2.5% of its organic C by soil respiration each year. In our example this loss amounts to some 1625 kg/ha of C. Smaller losses of soil organic C occur by soil erosion (160 kg/ha), leaching (10 kg/ha), and formation of carbonates and bicarbonates (10 kg/ha).

Comparing total losses (1805 kg/ha) with the total gains (1475 kg/ha) for the pool of soil humus, we see that the soil in our example suffered a *net annual* loss of 330 kg/ha of C, or 0.5% of the total C stored in the soil humus. If this rate of loss were to continue, degradation of soil quality and productivity would surely result.

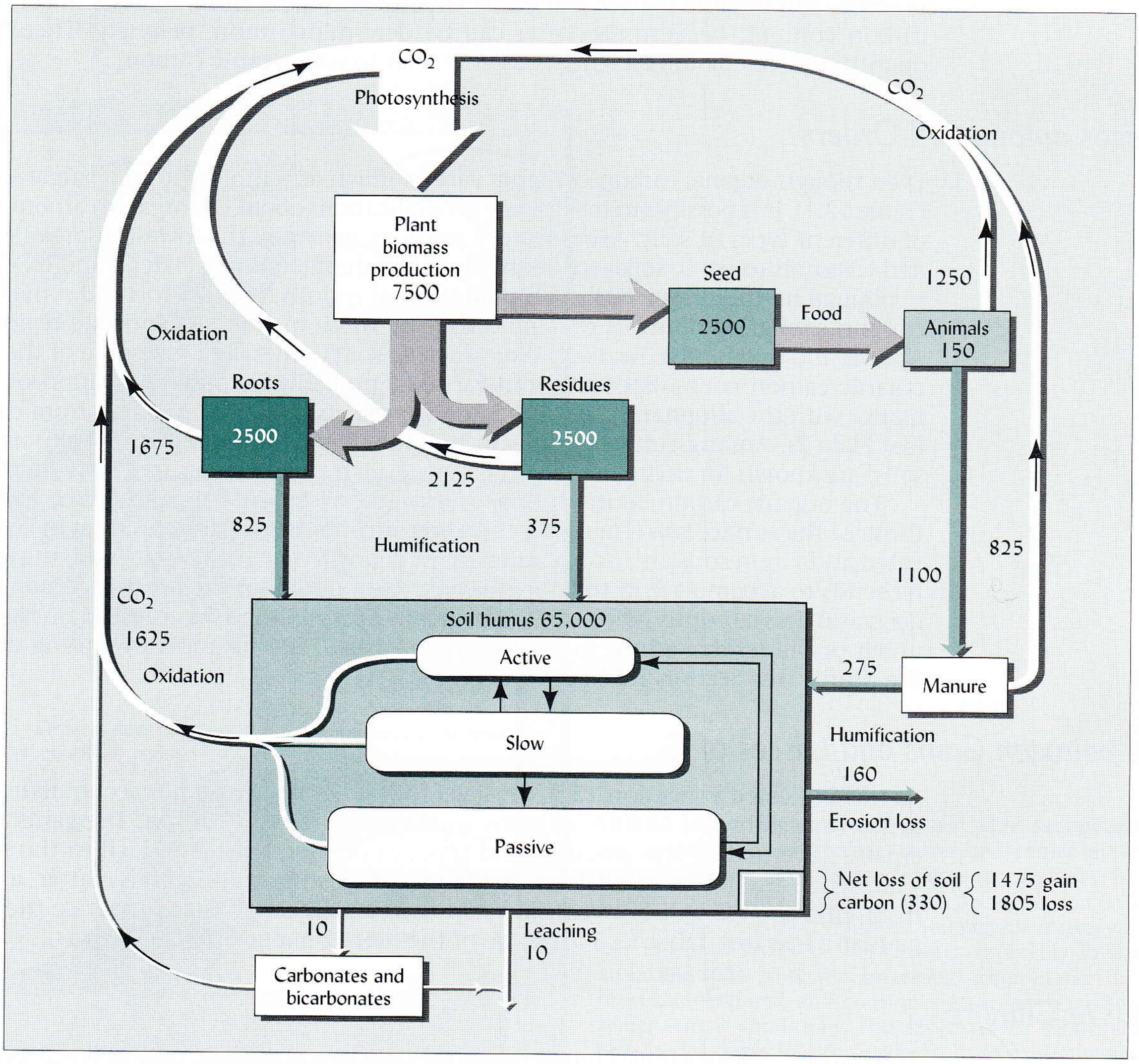

FIGURE 12.18 Carbon cycling in an agroecosystem.

TABLE 12.5 **Factors Affecting the Balance between Gains and Losses of Organic Matter in Soils**

Factors promoting gains	*Factors promoting losses*
Green manures or cover crops	Erosion
Conservation tillage	Intensive tillage
Return of plant residues	Whole plant removal
Low temperatures and shading	High temperatures and exposure to sun
Controlled grazing	Overgrazing
High soil moisture	Low soil moisture
Surface mulches	Fire
Application of compost and manures	Application of only inorganic materials
Appropriate nitrogen levels	Excessive mineral nitrogen
High plant productivity	Low plant productivity
High plant root:shoot ratio	Low plant root:shoot ratio

12.10 FACTORS AND PRACTICES INFLUENCING SOIL ORGANIC MATTER LEVELS

The amount of organic matter in soils varies widely; mineral surface soils contain from a mere trace (sandy, desert soils) to as high as 20 or 30% (some forested or poorly drained A horizons). Some soils contain even more organic matter, but those that do are considered to be organic—not mineral—soils and will be discussed in Section 12.12. In practice, soil organic matter content is usually estimated from analysis of soil organic carbon content, because the latter can be determined more precisely. Therefore, for quantitative discussions scientists usually refer to soil organic carbon.

Differences among Soil Orders

Even though organic carbon contents vary as much as tenfold within a single soil order (Table 12.1), it is possible to make a few generalizations about the organic carbon contents of different types of soils. Aridisols (dry soils) are generally the lowest in organic matter, and Histosols (organic soils) are definitely the highest (compare Plates 3 and 6). Contrary to popular myth, forested soils in humid tropical regions (e.g., Oxisols and some Ultisols) contain similar amounts of organic carbon to those in humid temperate regions (e.g., Alfisols and Spodosols). Andisols (volcanic ash soils) generally have some of the highest organic carbon contents of any mineral soils, probably because association of organic matter with the allophane clay in these soils protects the organic carbon from oxidation (see Plate 2). Among cultivated soils in humid and subhumid regions, Mollisols (prairie soils) are known for their dark, organic, carbon-rich surface layers (see Plate 8).

The organic carbon contents of subsurface horizons are generally much lower than those of the surface soil (Figure 12.19). Since most of the organic residues in both cultivated and virgin soils are incorporated in, or deposited on, the surface soil, organic matter tends to accumulate in the upper layers. Also, note that the organic carbon content decreases less abruptly with depth in grassland soils than in forested ones, because much of the residue added in grasslands consists of fibrous roots extending deep into the profile (see Section 2.14).

Balance between Gains and Losses of C

As was indicated in Section 12.9, the level to which organic matter accumulates in soils is determined by the balance of gains and losses of organic carbon. The gains are principally governed by the amounts and types of organic residues added to the soil each year, while the losses result from oxidation of existing soil organic matter, as well as from erosion. We will now consider the numerous factors that influence the rates of gain and loss (see Table 12.5 for some of the management-oriented factors).

Influence of Climate

TEMPERATURE. Mean annual temperature influences soil organic matter levels because of the different manner in which the processes of organic matter production (plant growth) and organic matter destruction (microbial decomposition) respond to increases in this climatic variable. Figure 12.20 shows that at low temperatures plant growth out-

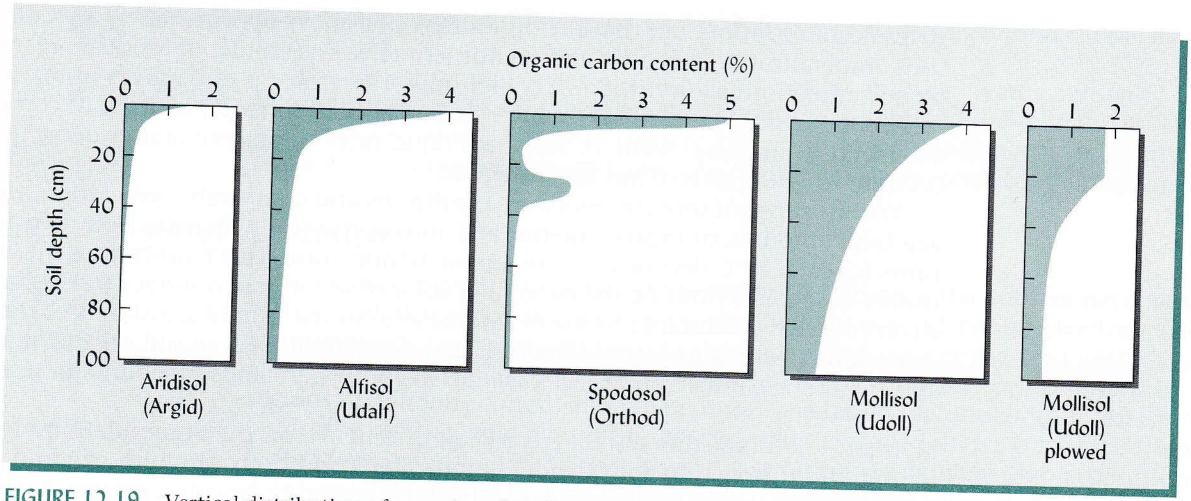

FIGURE 12.19 Vertical distribution of organic carbon in well-drained soils of four soil orders. Note the higher content and deeper distribution of organic carbon in the soils formed under grassland (Mollisols) compared to the Alfisol and Spodosol, which formed under forests. Also note the bulge of organic carbon in the Spodosol subsoil due to illuvial humus in the spodic horizon (see Chapter 3). The Aridisol has very little organic carbon in the profile, as is typical of dry-region soils.

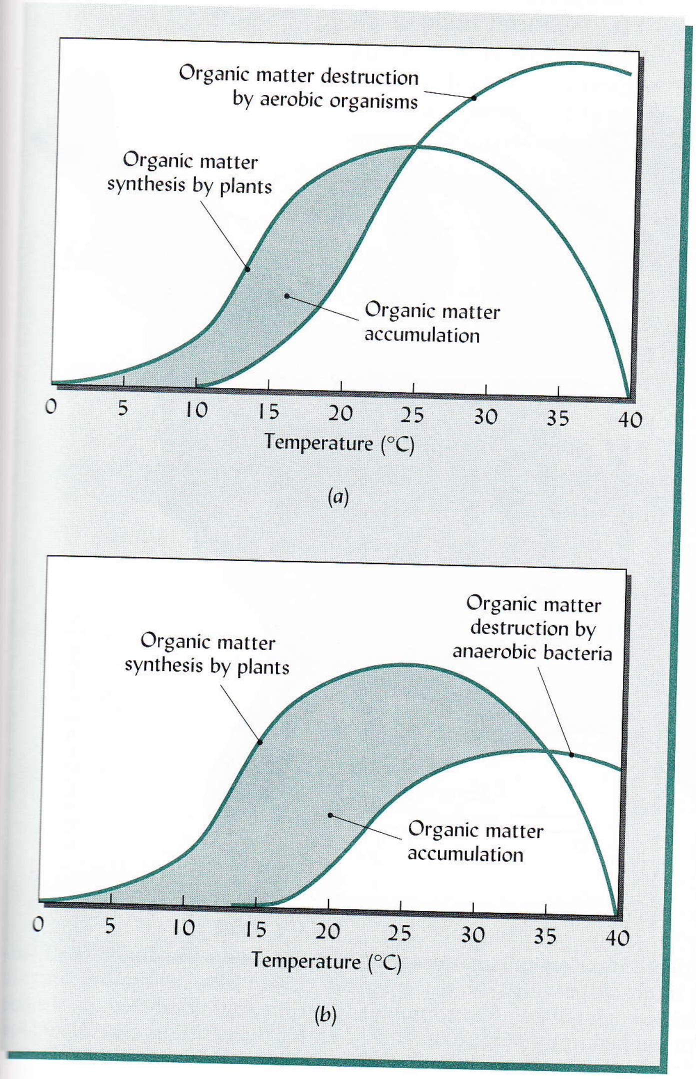

FIGURE 12.20 The balance between plant production and biological oxidation of organic matter determines the effect that temperature has upon organic matter accumulation in soils. The shaded areas indicate organic matter accumulation under aerobic (*a*) and anaerobic (*b*) conditions. Soil organic matter will accumulate to higher levels in cool climates, especially in waterlogged, anaerobic soils. Note that anaerobic accumulation is greater at most temperatures, and continues at higher temperatures than under aerobic conditions. This explains why subtropical areas in Florida can contain both organic soils (e.g., the Everglades) and soils containing very little organic matter (e.g., in better drained parts of the state). [Adapted from Mohr and van Baren (1954)]

strips decomposition, but that the opposite is true above approximately 25°C. In warm soils, mineralization is accelerated, so nutrient release is rapid, but residual organic matter accumulation is lower than in cooler soils. Therefore, as one moves from a warmer to a cooler climate, the organic matter and associated nitrogen content of comparable soils tend to increase. Some of the most rapid rates of organic matter decomposition occur in irrigated soils of hot desert regions.

Within zones of uniform moisture conditions and comparable vegetation, the average total amounts of organic matter and nitrogen in soils increase from two to three times for each 10°C decline in mean annual temperature. This temperature effect can be readily observed by noting the darkening color of well-drained surface soils as one travels from south (Louisiana) to north (Minnesota) in the humid grasslands of the North American Great Plains region (Figure 12.21). Similar changes in soil organic matter are evident as one climbs from warm lowlands to cooler highlands in mountainous regions.

Moisture. Soil moisture also exerts a major influence on the accumulation of organic matter and nitrogen in soils. Under comparable conditions, the nitrogen and organic matter content of soils increase as the effective moisture becomes greater. At the same time, the C/N ratio tends to be higher in the more thoroughly leached soils of the higher rainfall areas. These relationships are illustrated by the darker and thicker A horizons encountered as one travels across the North American Great Plains region (within a belt of similar mean annual temperature), from the drier zones in the west (Colorado) to the higher rainfall east (Missouri and Illinois). The explanation lies mostly in the sparser vegetation of the drier regions. In determining this rainfall correlation, however, it must be remembered that the level of organic matter in any one soil is influenced by

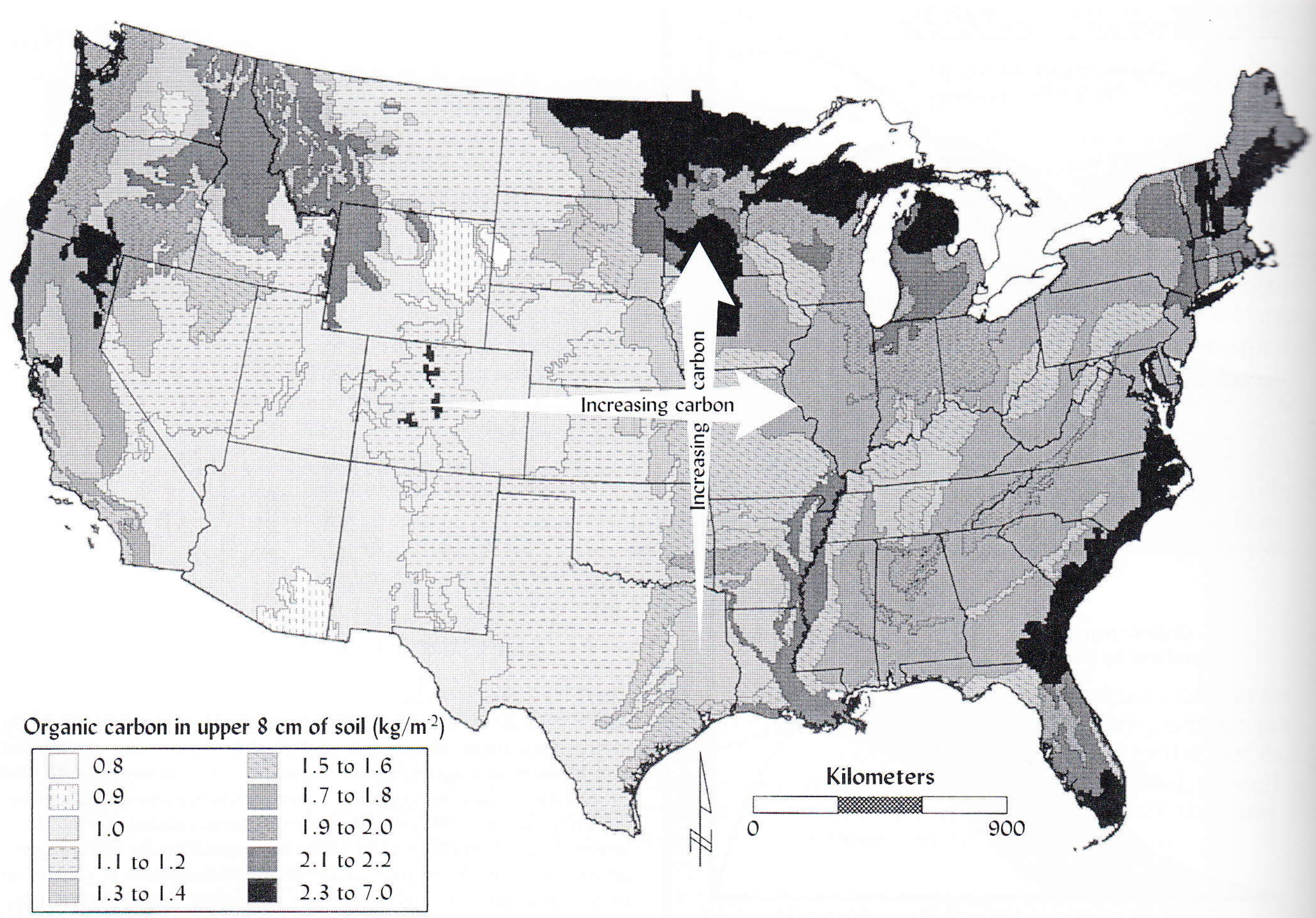

FIGURE 12.21 Influence of mean annual temperature and precipitation on organic matter levels in soils and on the difficulty of sustaining the soil resource base. The large white arrows on the map indicate that in the North American Great Plains region, soil organic matter increases with cooler temperatures going north, and with higher rainfall going east, provided that the soils compared are similar in texture, type of vegetation, drainage, and all other aspects except temperature and rainfall. These trends can be further generalized for global environments. [Kern (1994); Map courtesy of J. Kern, U.S. Environmental Protection Agency.]

both temperature and precipitation, as well as by tillage, vegetation, slope, aspect and soil texture.

The lowest natural levels of soil organic matter and the greatest difficulty in maintaining those levels are found where annual mean temperature is high and rainfall is low. These relationships are extremely important to the productivity and conservation of soils and to the relative difficulty of sustainable natural resource management.

Influence of Natural Vegetation

Climate and vegetation usually act together to influence the soil contents of organic carbon and nitrogen. The greater plant productivity engendered by a well-watered environment leads to greater additions to the pool of soil organic matter. Grasslands generally dominate the subhumid and semiarid areas, while trees are dominant in humid regions. In climatic zones where the natural vegetation includes both forests and grasslands, the total organic matter is higher in soils developed under grasslands than under forests (see Figure 12.19). With grassland vegetation, a relatively high proportion of the plant residues consist of root matter, which decomposes more slowly and contributes more efficiently to soil humus formation than does forest leaf litter.

Effects of Texture and Drainage

While climate and natural vegetation affect soil organic matter over broad geographic areas, soil texture and drainage are often responsible for marked differences in soil organic matter within a local landscape. All else being equal, soils high in clay and silt are generally higher in organic matter than are sandy soils (Figure 12.22). The finer-textured soils accumulate more organic matter for several reasons: (1) they produce more plant biomass, (2) they lose less organic matter because they are less well aerated, and (3) more of the organic material is protected from decomposition by being bound in clay–humus complexes (see Section 12.4) or sequestered inside soil aggregates. A given amount and type of clay can be expected to have a finite capacity to stabilize organic matter in organomineral complexes. Once this capacity is saturated, further additions of organic matter are likely to add little to humus accumulation, as they will remain readily accessible to microbial decomposition.

Drainage Effects. In poorly drained soils, the high moisture supply promotes plant dry-matter production and relatively poor aeration inhibits organic matter decomposition (see Figure 12.19*b*). Poorly drained soils therefore generally accumulate much higher levels of organic matter and nitrogen than similar but better-aerated soils (Figure 12.23). Histosols represent an extreme example of this principle.

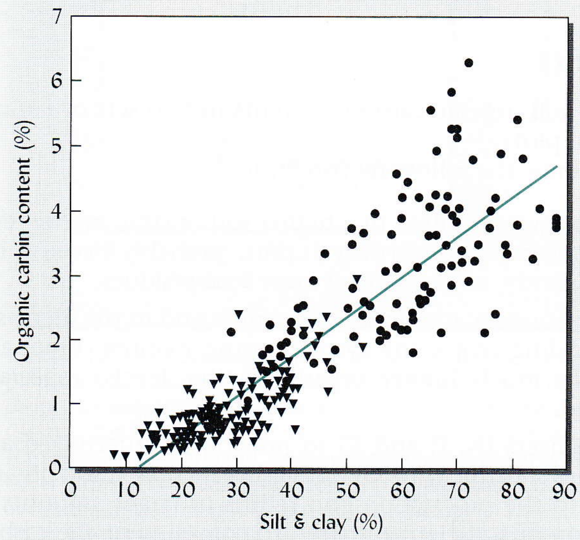

FIGURE 12.22 Soils high in silt and clay tend to contain high levels of organic carbon. The data shown are for surface soils in 279 tilled maize fields in subhumid regions of Malawi (▼) and Honduras (●). All soils were moderately well to well-drained and tilled. Variability (scatter of data points) among soils with the same silt + clay content is probably due to differences in (1) the type of clay minerals present (2:1 silicates tend to stabilize more organic carbon), (2) site elevation (cooler, high elevation locations being conducive to greater organic carbon accumulation), and (3) years since cultivation began (longer history of cultivation leading to lower organic carbon levels). (Data courtesy of R. Weil and M. A. Stine, University of Maryland, and S. K. Mughogho, University of Malawi)

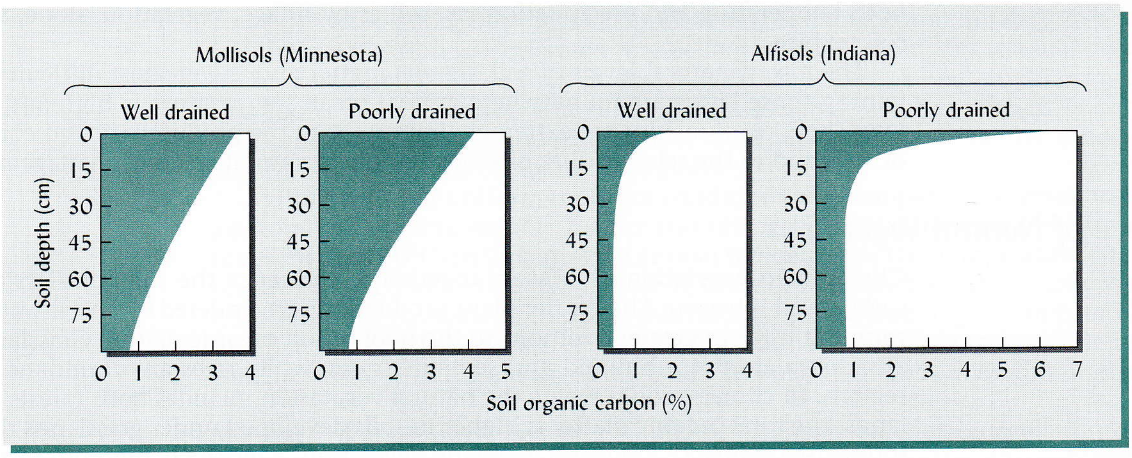

FIGURE 12.23 Distribution of organic carbon in four soil profiles, two well drained and two poorly drained. Poor drainage results in higher organic carbon content, particularly in the surface horizon.

Influence of Agricultural Management and Tillage

It is safe to generalize that cultivated land contains much lower levels of both soil nitrogen and organic matter than do comparable areas under natural vegetation. This is not surprising; under natural conditions all the organic matter produced by the vegetation is returned to the soil, and the soil is not disturbed by tillage. In contrast, in cultivated areas much of the plant material is removed for human or animal food and relatively less finds its way back to the land. Also, soil tillage aerates the soil and breaks up the organic residues, making them more accessible to microbial decomposition.

CONVERSION TO CROPLAND. A very rapid decline in soil organic matter content occurs when a virgin soil is brought under cultivation. Eventually, the gains and losses of organic carbon reach a new equilibrium and the soil organic matter content stabilizes at a much lower value. This pattern of decline is illustrated in Figure 12.24a, which shows the changing organic matter contents of a Mollisol during the first century after the native prairie was first plowed and several different cropping systems were imposed. Similar declines in soil organic matter are seen when tropical rain forests are cleared; however, the losses may be even more rapid because of the higher soil temperatures involved. Organic matter losses are not so dramatic if forests or prairies are converted to pasture or hay production.

Conservation tillage practices can help maintain or restore high surface soil organic carbon levels (Figure 12.25). Compared to conventional tillage, practices such as stubble mulching and no-till leave a higher proportion of the residues on or near the soil surface. These techniques protect the soil from erosion and also discourage the rapid decomposition of crop residues.

Influence of Rotations, Residues, and Plant Nutrients

Figure 12.24 shows changes in the soil organic carbon contents in two sets of famous long-term soil fertility experimental plots.

From the Morrow plots we can draw the following conclusions.

1. A rotation of corn, oats, and clovers resulted in a higher soil organic matter level than did continuous corn, regardless of fertility inputs, probably because the rotation used tillage less frequently, and produced more root residues.
2. Because of greater additions of organic matter in the manure and in the increased residues from the higher-yielding crops, the systems using manure, lime, and phosphorus helped maintain much higher organic matter levels, especially where a rotation was followed.
3. Application of lime and fertilizers (N, P, and K) to previously unfertilized and unmanured plots (dashed lines starting in 1955) noticeably increased soil organic matter levels, probably due to the production and return of larger amounts of crop residues and the addition of sufficient nitrogen to compliment the carbon in humus formation.

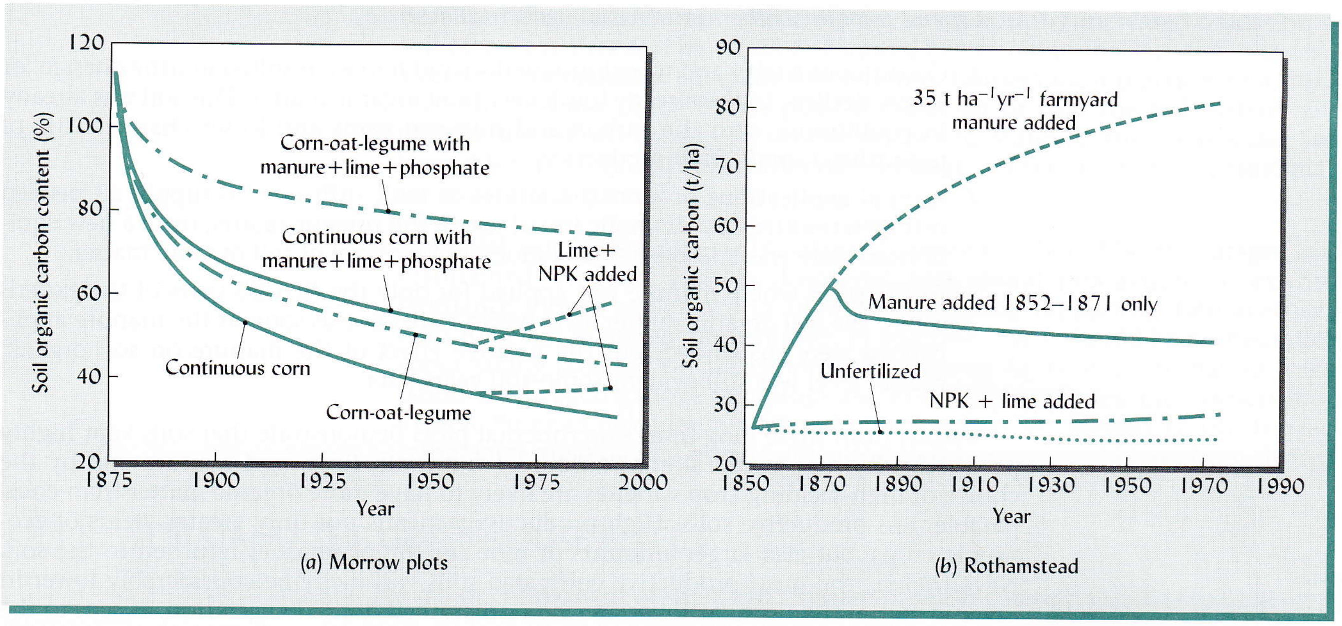

FIGURE 12.24 Soil organic carbon contents of selected treatments of (*a*) the Morrow plots at the University of Illinois and (*b*) of the classical experiments at Rothamstead Experiment Station in England. The Morrow plots were begun on virgin grassland soil in 1876 and so suffered rapid loss of organic carbon in the early years of the experiment. The Rothamstead plots were established on soils with a long history of previous cultivation. As a result, the soil at Rothamstead had reached an equilibrium level of organic carbon characteristic of the unfertilized small-grains (barley and wheat) cropping system traditionally practiced in the area. [Data recalculated from Darmody and Peck (1997) and Jenkinson and Johnson (1977); used with permission of the Rothamstead Experiment Station, Harpenden, England]

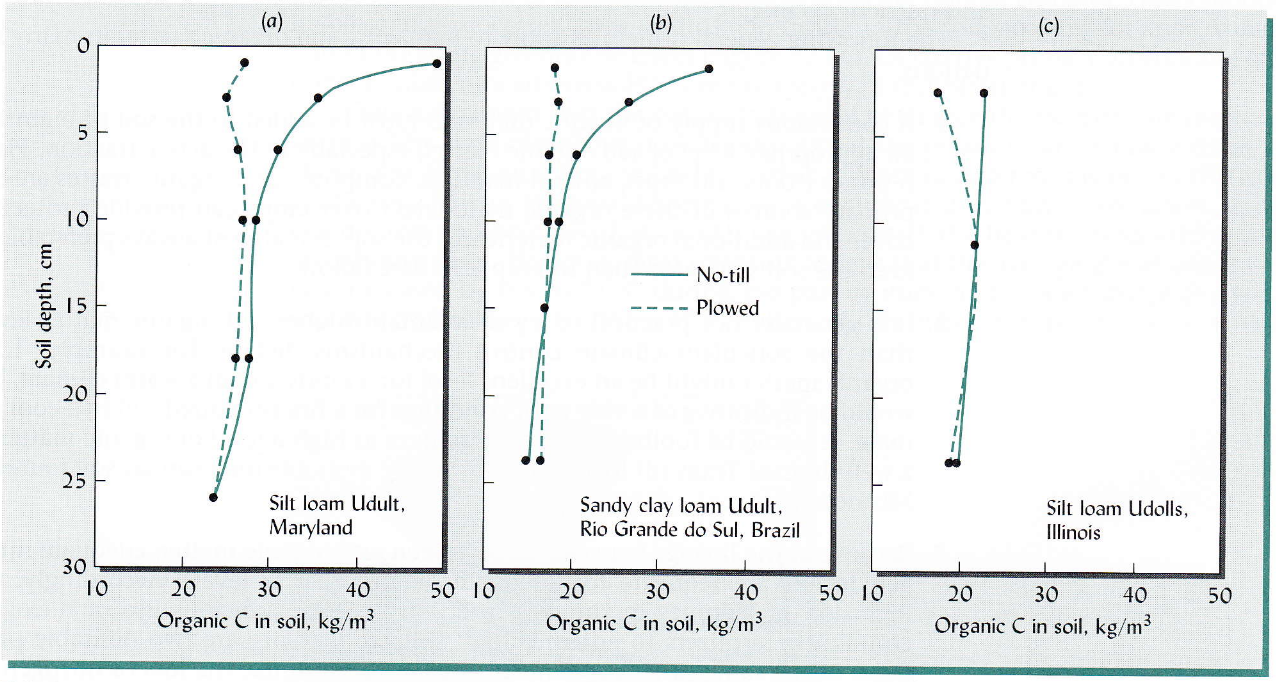

FIGURE 12.25 Less tillage means more soil organic carbon. In each case, the no-till system had been used on the experimental plots for 8 to 10 years when the data were collected. In the plowed plots, the soil was disturbed annually by tillage to about 20 cm deep. The soils in Maryland (*a*) and Brazil (*b*) were well-drained Ultisols and the climate was temperate (Maryland) to subtropical (Brazil). The Illinois data (*c*) are means for two soils, both somewhat poorly drained Mollisols (an Aquic Argiudoll and an Aquic Haplaquoll). In Maryland, corn was grown every year with a rye cover crop. In Brazil, oats were rotated with corn using legume cover crops in between. In Illinois, a corn/soybean rotation without cover crop was followed. In all cases, no-till encouraged the accumulation of organic C, but only in the upper 5 to 10 cm of the soil. The Illinois data typifies the common tendency for no-till to have less effect on C accumulation in fine-textured, wet soils of cool climates. [Data from Weil, et al. (1988), Bayer, et al. (2000) and Wander, et al. (1998)]

Lessons from the Rothamstead experiments include:

1. Continuous barley and wheat production and harvest resulted in little change, or a slow decline, in the already low level of soil organic matter. This soil was already in equilibrium with the carbon and nitrogen gains and losses characteristic of unfertilized small-grain production.
2. Annual applications of animal manures at rates sufficient to supply all needed nitrogen resulted in a dramatic initial rise in soil organic matter, until a new equilibrium state was approached at a much higher level of soil organic matter.
3. In the plots where manure was applied for only the first 20 years of the experiment, the soil organic matter level began to decline as soon as the manure applications were suspended, but the positive effect of the manure on soil organic matter level was still evident some 100 years later.

Results from these long-term experimental plots demonstrate that soils kept highly productive by supplemental applications of nutrients, lime, and manure and by the choice of high-yielding crop varieties are likely to have more organic matter than comparable, less productive soils. High productivity means not only greater yields of economic crops, but also larger amounts of root and shoot residues returned to the soil. Nevertheless, the most productive cultivated soils will likely be considerably lower in organic matter than similar soils carrying undisturbed natural vegetation, except in the case of irrigated soil in desert areas, where natural vegetation is sparse.

Recommendations for Managing Soil Organic Matter

While the total carbon stabilized in the soil is important in relation to the global greenhouse effect (see Section 12.11), in terms of productivity and other ecological functions, achieving a particular level of total soil organic matter is far less important than maintaining a substantial proportion in the active fraction. It is the active fraction C that fuels the food web and allows biological metabolism to constantly enhance soil tilth and nutrient cycling.

The following general principles apply to managing soil organic matter in many situations:

1. A continuous supply of organic materials must be added to the soil to maintain an appropriate level of soil organic matter, especially in the active fraction. Plant residues (roots and tops), animal manures, composts, and organic wastes are the primary sources of these organic materials. Cover crops can provide protective cover and additional organic material for the soil. It is almost always preferable to keep the soil vegetated than to keep it in bare fallow.

2. It is generally not practical to try to maintain higher soil organic matter levels than the soil–plant–climate control mechanisms dictate. For example, 1.5% organic matter might be an excellent level for a sandy soil in a warm climate, but would be indicative of a very poor condition for a finer-textured soil in a cool climate. It would be foolhardy to try to achieve as high a level of organic matter in a well-drained Texas silt loam soil as might be desirable for a similar soil found in Minnesota.

3. Because of the linkage between soil nitrogen and organic matter, adequate nitrogen inputs are requisite for adequate organic matter levels. Accordingly, the inclusion of legumes in the crop rotation and the judicious use of nitrogen-containing fertilizers to enhance high soil productivity are two desirable practices. At the same time, steps must be taken to minimize the loss of nitrogen by leaching, erosion, or volatilization (see Chapter 13).

4. Maximum plant growth will increase the amount of organic matter added to soil from crop residues. Even if some plant parts are removed in harvest, vigorously growing plants provide below- and aboveground residues as major sources of organic matter for the soil. Moderate applications of lime and nutrients may be needed to help free plant growth from the constraints imposed by chemical toxicities and nutrient deficiencies.

5. Because tillage accelerates organic matter losses both by increased oxidation of soil organic matter and by erosion, it should be limited to that needed to control weeds and to maintain adequate soil aeration. Conservation practices that minimize tillage leave much of the plant residues on or near the soil surface, and thereby slow down the rate of residue decay and reduce erosion losses (see Sections 4.8 and 17.6). In time, conservation tillage can lead to higher organic matter levels (see Figure 12.25).

6. Perennial vegetation, especially natural ecosystems, should be encouraged and maintained wherever feasible. Improved agricultural production on existing farmlands should be pursued to allow land currently supporting natural ecosystems to be left relatively undisturbed. In addition, there should be no hesitation about taking land out of cultivation and encouraging its return to natural vegetation where such a move is appropriate. In the United States, the Conservation Reserve Program provides incentives for such action (see Section 17.14). The fact is that large areas of land under cultivation today never should have been cleared.

12.11 SOILS AND THE GREENHOUSE EFFECT

Intergovernmental Panel on Climate Change: www.ipcc.ch/

Soil is a major component of the Earth's system of self-regulation that has created (and, we hope, will continue to maintain) the environmental conditions necessary for life on this planet. Biological processes occurring in soils have major long-term effects on the composition of the Earth's atmosphere, which in turn influences all living things, including those in the soil.

Global Warming. Of particular concern today are increases in the levels of certain gases in the earth's atmosphere. Known as **greenhouse gases,** they cause the earth to be much warmer than it would otherwise be. Like the glass panes of a greenhouse, these gases allow short-wavelength solar radiation in, but trap much of the outgoing long-wavelength radiation. This heat-trapping **greenhouse effect** of the atmosphere is a major determinant of global temperature and, hence, global climates. Gases produced by biological processes, such as those occurring in the soil, account for approximately half of the rising greenhouse effect (Figure 12.26). Of the five primary greenhouse gases, only chlorofluorocarbons (CFCs) are exclusively of industrial origin.

While it is certain that the concentrations of most greenhouse gases are increasing, there is less certainty about how rapidly global temperatures are actually rising and about how these increases are likely to affect climate in different regions of the world. Predicting changes in global temperature is complicated by numerous factors, such as cloud cover and volcanic dust, which can counteract the heat-trapping effects of the greenhouse gases. However, most scientists believe that the average global temperature has increased by 0.5 to 1.0°C during the past century, and predict that it is likely to increase by another 1 to 2°C in this century. If this increase in fact takes place, major

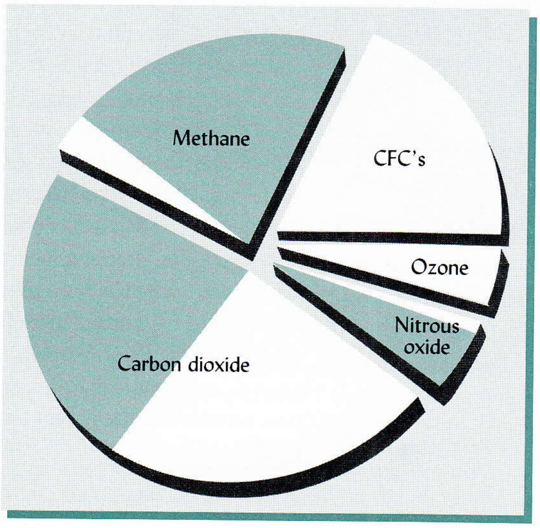

FIGURE 12.26 Relative contribution of different gases to the global greenhouse effect. The shaded portions indicate the emissions related to biological systems (in which soils play a role), the white portions being industrial contributions. [Modified from Dale, et al. (1993)]

changes in the earth's climate are sure to result, including changes in rainfall distribution and growing season length, increases in sea level, and greater frequency and severity of storms. The rise in sea level alone, as predicted by some climate models, would threaten the homes of hundreds of millions of people living in coastal areas, mainly in Asia and North America. Through national programs and international treaties (such as those growing out of the Kyoto Protocols), much effort and expense are currently being directed at reducing the anthropogenic (human-caused) contributions to climate change. Soil science has the potential to contribute greatly to our ability to deal with global warming and the increasing levels of greenhouse gases.

CARBON DIOXIDE. In 2000, the atmosphere contained about 370 ppm CO_2, as compared to about 280 ppm before the industrial revolution. Levels are increasing at about 0.5% per year. Although the burning of fossil fuels is a major contributor, much of the increase in atmospheric CO_2 levels comes from a net loss of organic matter from the world's soils. Through aerobic decomposition, the carbon in plant biomass and soil organic matter—carbon that originated from CO_2 in the atmosphere—is eventually converted back into CO_2 and returned to the atmosphere. Box 12.3 illustrates the

BOX 12.3 CARBON CYCLE IN MINIATURE

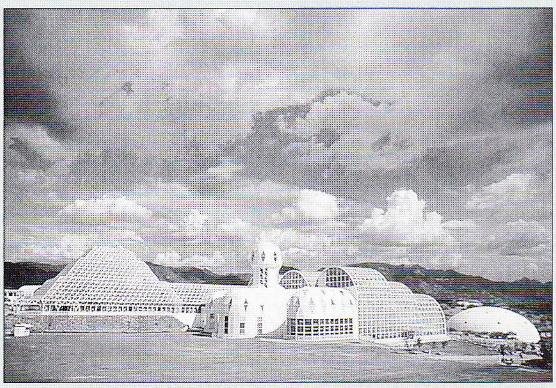

FIGURE 12.27 The Biosphere 2 structure, a huge, sealed, ecological laboratory. (Photo by C. Allen Morgan, © 1995 by Decisions Investments Corp. Reprinted with permission.)

FIGURE 12.28 Biospherians at work growing their own food supply in the intensive agriculture biome with compost-amended soils rich in organic matter. (Photo by Pascale Maslin, © 1995 by Decisions Investments Corp. Reprinted with permission.)

An interesting experience with the global impact of soil organic matter dynamics was had by the eight biospherians who lived in Biosphere 2, a 1.3-ha sealed glass building in the Arizona desert (Figure 12.27). This structure was designed to hold a self-contained, self-supporting ecosystem in which scientists could live and study as part of the ecosystem. Costing over $200 million to build, Biosphere 2 contains a miniature ocean, coral reef, marsh, forests, and farms designed to maintain the ecological balance. However, not only did the biospherians have a very hard time growing enough food for themselves (Figure 12.28), their atmosphere soon ran so low on oxygen and became so enriched in carbon dioxide that engineers had to pump in oxygen and install a scrubber to cleanse carbon dioxide from the air. It turned out that the ecosystem was thrown out of kilter by the organic-matter-rich soil hauled in for the Biosphere farms. The soil, made from a mixture of pond sediment (1.8% C), compost (22% C) and peat moss (40% C) was installed uniformly about 1 m deep. This artificial soil contained about 2.5% organic C at all depths. In contrast, the organic C content of a natural soil from the desert environment would probably be only 1 to 2% in the surface soil, and would decline sharply with depth. The designers had underestimated the rate at which soil organic matter would decompose when placed in the warm environment and aerated by garden tillage (see Section 12.2). The decomposition of the soil organic matter was carried out by aerobic soil microbes, which use up oxygen and give off carbon dioxide as they respire. For more information on Biosphere 2 in general, see www.bio2.com/research; for information on the soil used, see Torbert and Johnson (2001).

importance of soil organic matter in regulating atmospheric CO_2 levels. Research (Figure 12.29) indicates that the feedback between the soil and atmosphere works both ways—changes in the levels of gases beneficial or harmful to plants influence the rate at which carbon accumulates in soil organic matter.

We have already discussed many ways that land managers can increase levels of soil organic matter (Section 12.10) by changing the balance between gains and losses. Gains in soil organic matter occur first in the active fractions, but eventually some of the carbon moves into the stabile passive fraction, where it may be *sequestered* for hundreds or thousand of years. The opportunities for sequestering carbon are greatest for degraded soils that currently contain only a small portion of the organic matter levels they contained originally under natural conditions. Reforestation of denuded areas is one such opportunity. Others include switching cropland from conventional tillage to no-tillage practices or converting it to perennial vegetation.

By slowly increasing soil organic matter to near precultivation levels, such management changes could significantly enhance society's efforts to stem the rise in atmospheric CO_2, and at the same time improve soil quality and plant productivity. Some estimates suggest that during a 50-year period, improved management of agricultural lands could provide about 15% of the CO_2 emission reductions that the United States is obligated to make. It should be noted, however, that in accordance with the factors discussed in Section 12.10, soils have only a finite capacity to assimilate carbon into stable soil organic matter. Therefore carbon sequestration in soils can only buy time before other kinds of actions (shifts to renewable energy sources, increased fuel efficiency, etc.) are fully implemented to reduce carbon emission to levels that will not threaten climate stability.

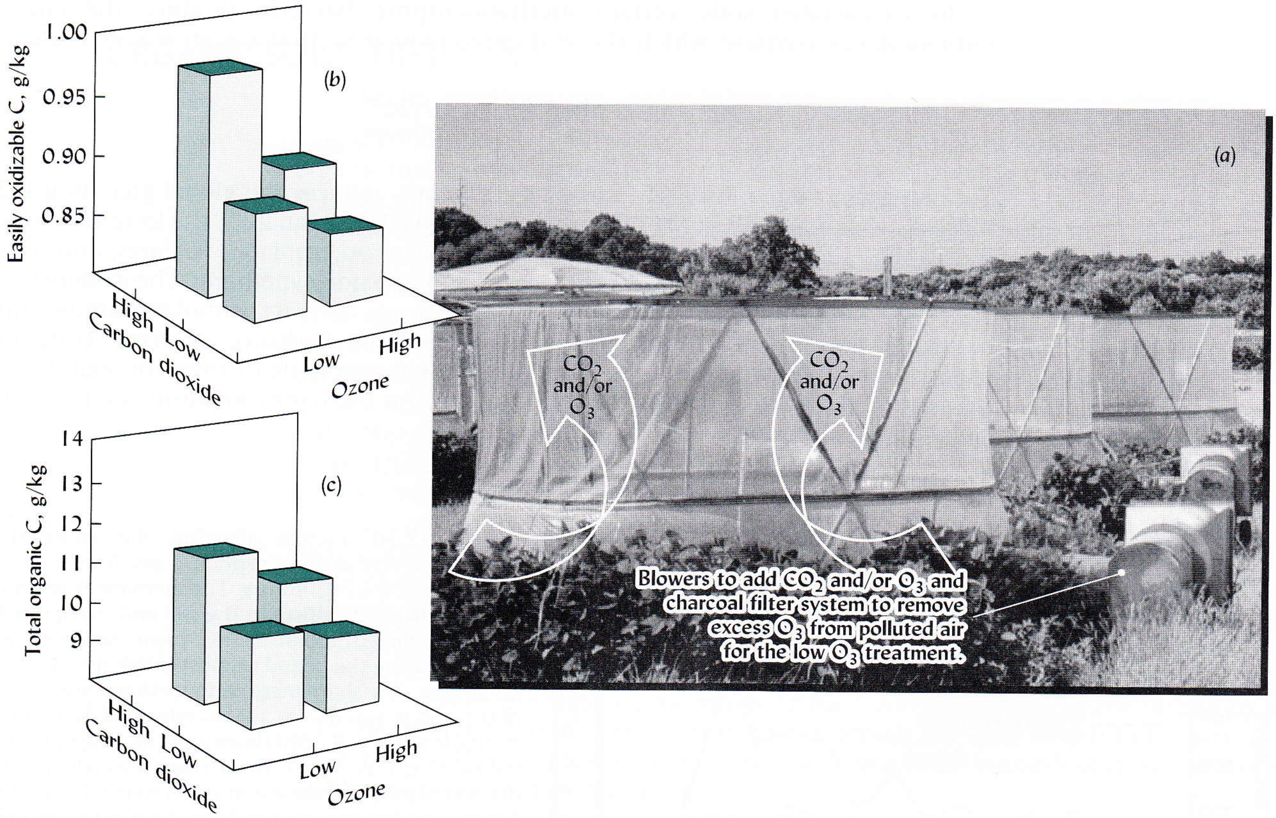

FIGURE 12.29 Atmospheric composition in these open-top field chambers (*a*) altered plant growth and physiology, and thereby also affected the amounts and forms of soil organic carbon. Increasing atmospheric CO_2 from low (260 mg/L, the ambient level) to high (500 mg/L, the level expected by 2050) enhanced photosynthesis in the plant, and thus increased the amount of fixed carbon available for translocation to the roots and eventually to the soil. (*b*) Increased root growth and exudation of carbon compounds contributed first to the active fraction of soil carbon (easily oxidized C), as suggested by the pronounced effect after only 5 years of elevated atmospheric CO_2. (*c*) The level of total soil carbon, most of which is stable humus, was also beginning to increase. Ozone, a pollutant at ground level, injures plants, reducing photosynthesis and therefore impacting the soil in a manner opposite that of CO_2. The data suggest an interaction between the two gases, by which the full effect of CO_2 is seen only when ozone is kept low. [Data from Weil et al. (2000); photo courtesy of R. Weil]

METHANE. Methane (CH_4) occurs in the atmosphere in far smaller amounts than CO_2. However, methane's contribution to the greenhouse effect is nearly half as great as that from CO_2 because each molecule of CH_4 is 30 to 50 times as effective as CO_2 in trapping outgoing radiation. The level of CH_4 is rising at about 0.6% per year. In 2000 there were about 1.8 ppm CH_4 in the atmosphere, more than double the preindustrial level. Soils serve as both a source and a sink for CH_4—that is, they both add CH_4 and remove it from the atmosphere.

Biological soil processes account for much of the methane emitted into the atmosphere. When soils are strongly anaerobic, as in wetlands and rice paddies, bacteria produce CH_4, rather than CO_2, as they decompose organic matter (see Sections 7.4 and 12.2). Among the factors influencing the amount of CH_4 released to the atmosphere from wet soils are: (1) the maintenance of a redox potential (Eh) near 0 mV, (2) the availability of easily oxidizable carbon, either in the soil organic matter or in plant residues returned to the soil, and (3) the nature and management of the plants growing on these soils (70 to 80% of the CH_4 released from flooded soils escapes to the atmosphere through the hollow stems of wetland plants). Figure 12.30 shows how these factors can influence CH_4 emissions from flooded rice paddies. Although not part of the study illustrated here, it has been demonstrated that periodically draining rice paddies prevents the development of extremely anaerobic conditions, and therefore can substantially decrease CH_4 emissions. Such management practices should be given serious consideration, as rice paddies are thought to be responsible for up to 25% of global CH_4 production.

Wetland soils are not the only ones that contribute to atmospheric CH_4. Significant quantities of methane are also produced by the anaerobic decomposition of cellulose in the guts of termites living in well-aerated soils (see Section 11.5), and of garbage buried deep in landfills (see Section 18.10).

In well-aerated soils, certain **methanotrophic bacteria** produce the enzyme *methane monooxygenase,* which allows them to oxidize methane as an energy source:

$$\underset{\text{Methane}}{CH_4} + {}^1/_2O_2 \longrightarrow \underset{\text{Methanol}}{CH_3OH}$$

This reaction, which is largely carried out in soils, reduces the global greenhouse gas burden by about 1 billion Mg of methane annually. Unfortunately, the long-term use of inorganic (especially ammonium) nitrogen fertilizer on cropland, pastures, and forests has been shown to reduce the capacity of the soil to oxidize methane. The evidence suggests that the rapid availability of ammonium from fertilizer stimulates ammonium-oxidizing bacteria at the expense of the methane-oxidizing bacteria. Long-term experiments in Germany and England indicate that supplying nitrogen in organic form (as manure) actually enhances the soil's capacity for methane oxidation (Table 12.6).

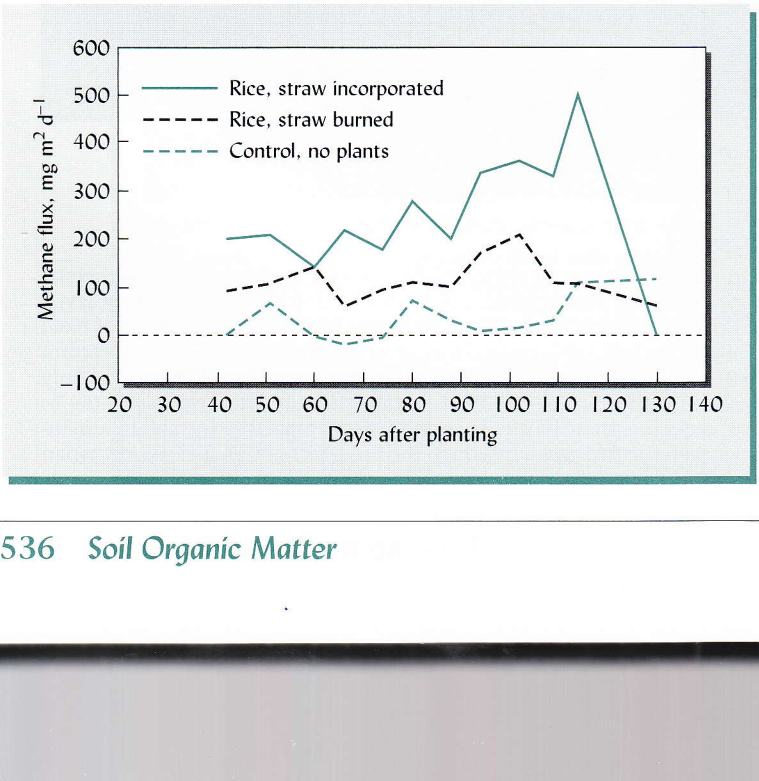

FIGURE 12.30 Factors affecting the emission of methane, a very active greenhouse gas, from a flooded rice paddy soil in California. The methane is generated by microbial metabolism in the soil and transported to the atmosphere through the rice plant. Emissions were greatest during the period of most active rice growth in midseason. The sharp increase in methane near the end of the season was due to a rapid release of accumulated methane as the soil dried down and cracks opened up in the swelling clay. Very little methane was released if no rice was planted. Moderate amounts were released if rice was planted but rice residues from the previous crop had been burned off. The highest amounts of methane were released where rice was planted and the straw from the previous crop had been incorporated into the soil. Once the soil was drained at the end of the season, no more methane was produced. [Redrawn from Redeker et al. (2000) with permission of the American Association for the Advancement of Science.]

TABLE 12.6 **Effect of Nitrogen Fertility Management Systems on Methane Oxidation by an Arable Soil (Mollisol) in Germany**

The four nitrogen treatments were applied annually for 92 years to a rotation of sugar beets, spring barley, potatoes, and winter wheat. The measurements were made on soil sampled in spring, just before the annual nitrogen applications were made. Note that farmyard manure increased methane oxidation, while inorganic nitrogen fertilizer (NH_4NO_3) reduced methane oxidation from the levels in the control and the manure-only treatment.

Soil treatment	*Soil pH*	*Soil NO_3^--N, kg/ha*	*Soil NH_4^+-N, kg/ha*	*Methane oxidation rate, nL CH_4 L^{-1}/hr^{-1}*
1. Control—no N added in any form	6.8	0.83	0.20	4.60
2. Fertilizer N—40 to 130 kg/ha N as NH_4NO_3 to meet crop needs	6.9	15.36	3.1	1.34
3. Farmyard manure applied at 20 Mg/ha	7.0	1.98	0.22	11.2
4. Farmyard manure plus N fertilizer as in #3.	7.2	5.01	0.71	3.76

Data from the Static Fertilization Experiment begun in 1902 at Bad Lauchstädt, Germany and reported in Willison, et al. (1996).

Nitrous oxide (N_2O) is another greenhouse gas produced by microorganisms in poorly aerated soils, but since it is not directly involved in the carbon cycle, it will be discussed in the next chapter (see Section 13.10).

Because the soil can act as a major source or sink for carbon dioxide, methane, and nitrous oxide, it is clear that, together with steps to modify industrial outputs, soil management has a major role to play in controlling the atmospheric levels of greenhouse gases.