African mother nurtures the future. (R. Weil)

20

GLOBAL SOIL QUALITY AS AFFECTED BY HUMAN ACTIVITIES

> *If we do not change our direction,*
> *we are likely to end up where we are headed.*
> —CHINESE PROVERB

During the past few decades, we have begun to recognize the global significance of almost everything we do. Economic development or stagnation in one country affects the economy of all of its trading partners around the world. Worldwide communication networks provide us with ready computer access to information, knowledge, and news from every corner of the globe. As a consequence, actions of each country, each community, or even each individual can have global implications.

This global perspective is equally pertinent for soils. Soil particles picked up by the wind during spring tillage in the Great Plains states can be detected in the rainfall in the eastern United States or even in Europe. Likewise, excess salts, nitrates, or phosphates in the drainage water from soils in one nation can make the water unfit for use in another nation downstream. Changes in soil productivity in one area affect food security and food prices, as well as biodiversity and water quality, in both nearby and distant places.

This growing global perspective is paralleled by the growing acceptance of the *ecosystem* concept as the prime basis for decisions on natural-resource management. This concept recognizes that the world is home for a series of communities of living organisms that interact with each other and with the environment at all scales, from the global terrestrial ecosystem to the ecosystem of a farm pond. Furthermore, components of one ecosystem may be impacted by other associated ecosystems. For example, an ecosystem in a downstream pond certainly may be affected by the chemicals coming from an ecosystem involving an upstream sewage plant or an overfertilized farm field.

Soils are integral components of agroecosystems, forest ecosystems, and grassland ecosystems. Likewise, they influence downstream freshwater and coastal ecosystems, as well as urban ecosystems. The ecosystem approach continually reminds us of the interaction among physical and biological entities in our environment. We cannot clear forest or range land, lime a soil, add a new irrigation scheme, or apply domestic or industrial wastes to a soil without influencing that soil and all soil organisms and higher plants growing in or on the soil. Likewise, how we manage plant communities influences the long-term stability and quality of the soils in which they grow.

In previous chapters we concentrated on the chemical, physical, and biological processes that may occur in various ecosystems involving soils, and on the action that individual land users might take to influence these processes. We now turn to the global implications of local land use decisions, and how these decisions affect the quality or health of the soil—which, through various ecosystems, affects the well-being of humans and all other living organisms.

20.1 THE CONCEPT OF SOIL QUALITY/SOIL HEALTH[1]

From the beginning of time, humans have evaluated the soils on which they work, play, and live. Terms such as "good," "bad," "worn-out soils," "productive," or "unproductive" soils have always been used. In recent years, scientists and users of the soils have realized that many of the world's soils are degrading, and they want to better understand and reverse that degradation. They want to learn how to improve the quality not only of degraded soils, but of other soils as well. Also, they want to provide farmers and natural resource planners with simple means of comparing the quality of soils from one ecosystem to another.

To make such comparisons meaningful, and to better understand how the full potential of a given soil can be realized, soil scientists are using the concept of **soil qual-**

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[1] For reviews on soil health and soil quality, see Doran, et al. (1996) and Doran and Jones (1996).

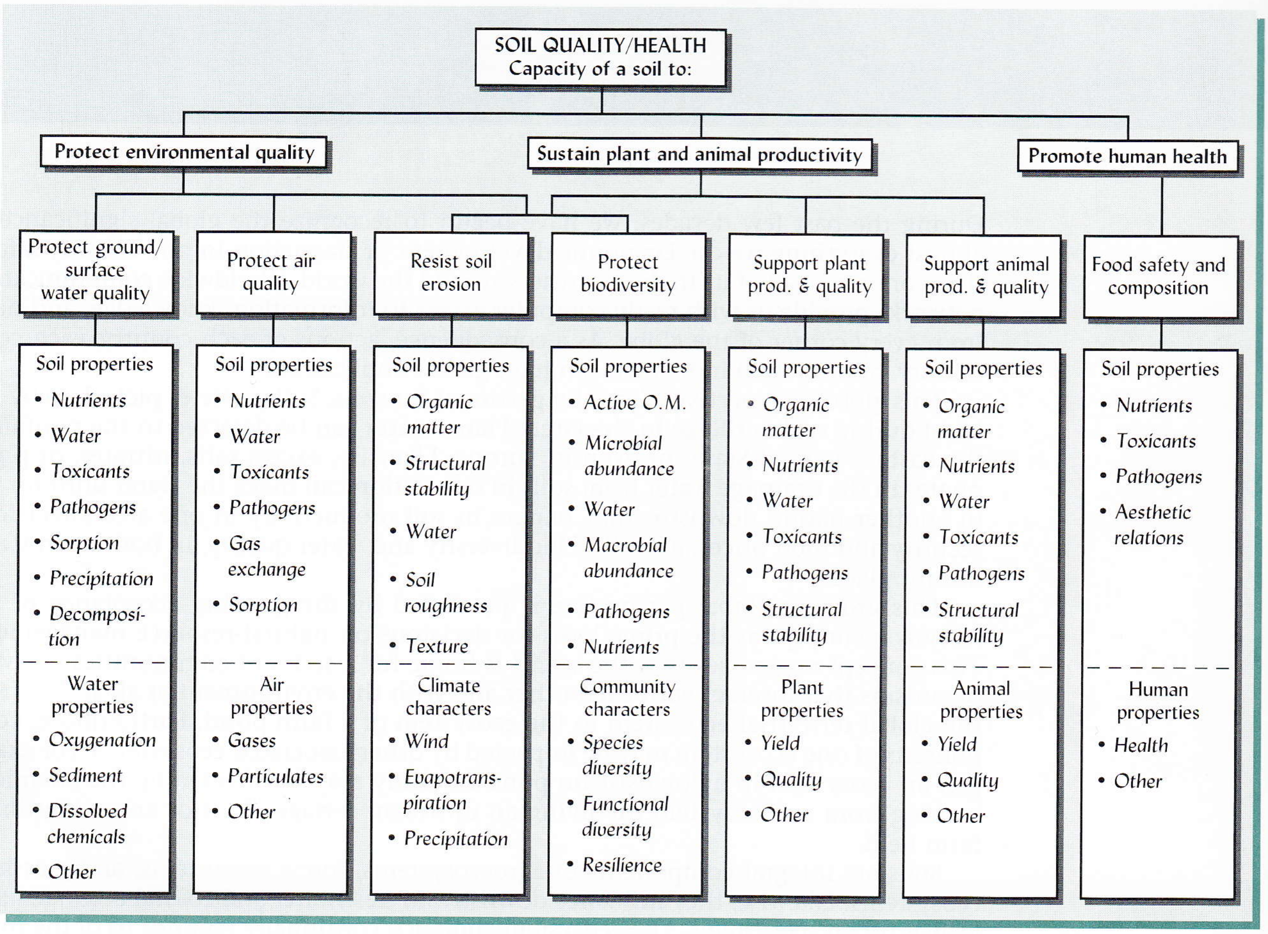

FIGURE 20.1 Schematic presentation of the definition and functions of soil quality or health, along with examples of indicator properties (soil and otherwise) that can be used to measure the quality or health of a soil. The definition of soil quality is in **bold print**, the expanded functions in normal print, and the categories of indicator properties supporting each function are in *italics*. For simplicity, many interdependencies among soil quality functions are not shown (e.g., protection of surface water quality is partially dependent on resistance to soil erosion, and so forth). As more knowledge is gained, additional and more specific indicator properties will likely be added to the list. [Modified from Harris, et al. (1996)]

Introductory slide show on soil quality or health: www.ag.ohio-state.edu/~prec/soil/slides/

ity or **soil health.**[2] Soil quality considers the soil's fitness for any given function, such as those concerned with biological production, road or building foundations, or disposal of wastes. However, we will emphasize the soil's fitness to serve three functions: (1) as a medium to promote the growth of plants and animals (including humans), while regulating the flow of water in the environment; (2) as an environmental buffer that assimilates and degrades environmentally hazardous compounds; and (3) as a factor in enhancing the health of plants and animals, including humans.

These three broad issues lead to the following definition: ***Soil quality*** is the capacity of a soil to function within (and sometimes outside) its ecosystem boundaries to sustain biological *productivity* and *diversity,* maintain *environmental quality,* and promote plant and animal *health.* The relationship between the definition of soil quality or health, its functions, and criteria for its measurement is shown in Figure 20.1.

Assessing Soil Quality

The soil's ability to perform a desired function is often dependent on one or more dynamic physical, chemical or biological processes that occur in soil ecosystems. Examples of such dynamic processes include the leaching of nutrients or pollutants through the soil to groundwater, the processes of soil erosion, exchanges between air and water that influence the soil's ability to perform, and the breakdown and synthesis of organic matter in soils. It is not always possible to measure directly the rates of these processes, but we can measure specific soil properties that are indicative of these rates. We can also use these measurements in simulation models to predict future changes in process rates and, in turn, soil quality. The properties measured are termed **indicators.** A minimum data set of such properties for the determination of soil quality or health is given in Table 20.1.

Research is underway to try to measure quantitatively a soil's ability to perform a given function. This is done by developing a **soil-quality index** for each soil ecosystem. The index is arrived at by weighting each indicator in accordance with its presumed

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[2] These terms are often used interchangeably in scientific literature and in the public press. Soil health is best used to refer to the condition of a soil as a result of its management. Soil quality may refer to both permanent soil properties and soil condition.

TABLE 20.1 **Possible Minimum Data Set of Physical, Chemical and Biological Indicators for Determining the Quality or Health of a Soil**

Other supporting indicators can be used to help establish the validity of the measurements. It may be possible to combine the values for each indicator into a single soil-quality index number. The weight given to each indicator would be determined by the particular functions of the soil.

Indicator	*Rationale for its use*
	Physical
Texture	Retention and transport of water and chemicals
Depth of soil and rooting	Estimate of productivity potential and erosion; normalizes landscape and geographic variability
Infiltration and soil bulk density	Potential for leaching, productivity, and erosion
Water-holding capacity	Related to water retention, transport, and erosivity
	Chemical
Total soil OM	Defines carbon storage, potential fertility, and stability
Active OM	Defines structural stability and food for microbes
pH	Defines biological and chemical activity thresholds
Electrical conductivity	Defines plant and microbial activity thresholds
Extractable N, P and K	Plant-available nutrients and potential for N loss; productivity and environmental quality indicators
	Biological
Microbial biomass C and N	Microbial catalytic potential and early warning of management effect on organic matter
Potentially mineralizable N	Soil productivity and N supply potential
Specific respiration	Microbial activity per unit of microbial biomass
Macroorganism numbers	Potential influence of such organisms as earthworms

Modified from Doran, et al. (1996).

importance in carrying out the function desired. A summation of the weighted indicators gives rise to the soil quality index as the example that follow illustrates.

Soil-Quality Index for Erosivity: An Example

A soil-quality index as related to soil erosion could be derived from the information in Table 20.2. Four functions of the soil in resisting water erosion are depicted: (1) *accommodating water entry,* (2) *facilitating water transfer and adoption,* (3) *resisting degradation,* and (4) *sustaining plant growth.* The relative weight of each soil function in resisting erosion is indicated, 50% assumed to be due to accommodating water entry, 35% to resisting particle degradation, 10% to facilitating water transport and absorption, and 5% to sustaining plant growth. Measurements that could serve as indicators of these four soil functions are shown along with their respective weights. Note the many physical, chemical, and biological properties that can help one assess the ability of a soil to resist erosion.

The analytical data for the major indicators, along with their respective weights, can be used to develop an overall soil-quality index relating to water erosion. For example, the component of such an index relating to resisting degradation was found to rate at 0.84 (out of a possible 1.0) for an Iowa soil where sustainable farming practices were being followed, compared to only 0.60 for an adjacent field where conventional intensive, high-input practices were being used. Such attempts to quantify assessments of soil quality are most welcome.

Time- and Place-Sensitive Functions

The relative importance of different soil functions and the weights given them will vary from one time to another, and from one location to another at a given time. This is illustrated in Table 20.3, which shows that in 1900 the food- and fiber-production function was paramount (highly weighted) compared to the five other nonproduction functions. But in our day, the elements concerned with the environment are perceived to be relatively more important, especially in the industrialized countries where food security is reasonably assured. The broader ecological roles of soils are becoming more widely

TABLE 20.2 Four Possible Soil-Quality Functions and Their Relative Weights in Determining the Resistance to Soil Erosion, Along with Measurable Indicators for Each Function and Their Weights

Note that with the exception of soil texture, most of the indicators are properties that can be significantly influenced by soil-management practices. Note that accommodating water entry, measurable by infiltration rate, is thought to provide about half (50%) of this function. Resisting degradation, measured primarily by aggregate stability, is of second importance. Most of the measurable indicators have been considered in previous chapters.

Soil quality function	*Function weight*	*Measurable indicator*	*Indicator weight*
1. Accommodate water entry	50	Infiltration rate	50
2. Resist degradation	35	Aggregate stability	27
		Shear strength	4
		Soil texture	2
		Heat transfer capacity	2
3. Facilitate water transfer and absorption	10	Hydraulic conductivity	5
		Porosity	2
		Macropores	3
4. Sustain plant growth	5	Rooting depth	1
		Water relations	2
		Nutrient relations	1
		Chemical barriers	1

Modified from Karlen and Stott (1994).

TABLE 20.3 Importance Assigned to Various Soil Functions in Ascertaining Soil Quality in Different Times and Circumstances

Note the very high weights for the food- and fiber-production function in 1900 worldwide, and in developing countries today. Other functions concerned with environmental and habitat issues are much more prominent today in industrialized countries.

	Probable Weights		
Soil function	*Worldwide, 1900*	*Industrialized countries, 2000*	*Developing countries, 2000*
1. Food and fiber production	85	40	70
2. Resistance to erosion	3	15	10
3. Water and air quality	1	10	5
4. Food quality	5	10	5
5. Wildlife habitat	1	15	5
6. Construction and transport base	5	10	5

recognized. In developing countries, however, where hunger and even famine are still common, food and fiber production remains the soil-quality issue of prime importance, as indicated by the high weight given to this function in Table 20.3.

Management-Sensitive Indicators

There is considerable variation in the degree to which soil management can promptly alter properties that are indicators of soil quality. As shown in Figure 20.2; some properties such as soil texture, mineralogy, steepness of slope, and stoniness are inherent characteristics of the soil and are not subject to change through land and crop management. While these properties are important in determining the best management systems to be used, they will not be changed by whatever system is chosen.

At the other extreme are properties that may be subject to almost daily control so that their effect on soil quality is immediate. Examples are the soil water content as affected by irrigation and rainfall, and the nutrient element levels that are subject to prompt change as chemical fertilizers are applied. Also, the compaction of the soil can result from passes across the field in one day by trucks and farm machinery. These properties are likewise significant since they can influence the production of plant residues upon which other more long-term properties are dependent.

Intermediate between these two extremes we find properties that are subject to change only through long-term management efforts. Soil organic matter content and active carbon levels, along with microbial biomass and soil aggregation, are examples of this intermediate class of indicators of soil quality. It takes years of careful management to raise the level of these properties in soils, but once they are raised, they tend to remain high for an extended period of time. These properties are highly desirable because of their effects on dynamic soil processes such as water and air movement, soil erosion, and the generation of biodiversity. But they can be developed only if we as soil managers have at least a general understanding of the complex processes that generate them.

Ephemeral	**Intermediate**	**Permanent**
Changes within days or routinely managed	Subject to management over several years	Inherent to profile or site
• Water content	• Aggregation	• Soil depth
• Field soil respiration	• Microbial biomass	• Slope
• pH	• Basal respiration	• Climate
• Mineral N	• Specific respiration quotient	• Restrictive layers
• Available K		• Texture
• Available P	• Active C	• Stoniness
• Bulk density	• Organic matter content	• Mineralogy

FIGURE 20.2 Classification of soil properties contributing to soil quality based on their permanence and sensitivity to management. Some soil properties are quite ephemeral and change readily from day to day as a result of routine management practices or weather. Others are permanent properties inherent to the soil profile or site and are little-affected by management. A management-oriented soil-quality assessment would focus on properties that are intermediate, but all properties tend to be mutually reinforcing. [From Islam and Weil (2000)]

20.2 SOIL RESISTANCE AND RESILIENCE[3]

Before turning to specific agroecosystems that affect soil quality, two other concepts relating to soil quality should receive attention. First is *soil resistance,* or the capacity of a soil to resist change when confronted with any kind of force or disturbance. For example, the soil solution levels of potassium in some fine-textured soils high in hydrous micas are not seriously affected by the removal of this element in harvested crops. The potassium extracted from the soil solution by plant roots is quickly replenished from exchangeable and nonexchangeable forms found in the clay and silt fractions of these soils. In other words, the soil resists change, a characteristic not found in most sandy soils that lack significant levels of exchangeable and nonexchangeable potassium. A soil's capacity to resist change is an important component of soil quality.

A second important concept bearing on soil quality is that of *soil resilience,* or the capacity of a soil to rebound from changes stimulated by disturbances or external forces. A soil under natural forest or grassland vegetation is disturbed when the land is cleared for cultivation, and properties such as organic matter content, organic matter quality, and aggregate stability all decline, thereby reducing soil quality. If, however, the land is turned back to nature, or if other sustainable conservation systems of soil management are utilized, the soil will begin to recover and regain some of its lost properties. The degree to which recovery takes place and its speed in doing so are measures of soil resilience, a vital component of soil quality. Figure 20.3 illustrates how soil resistance and soil resilience relate to soil quality through soil functions, and how they can affect soil functions on two soils that vary in their capacity to resist and recover.

Factors Affecting Soil Resistance and Resilience

Soil resistance and resilience are affected by both inherited and dynamic or management-oriented characteristics. For example, inherited characteristics such as texture, type of clay minerals, slope, and climate largely determine soil resistance, and have significant

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[3] For a recent discussion of these two concepts see Seybold, et al. (1999).

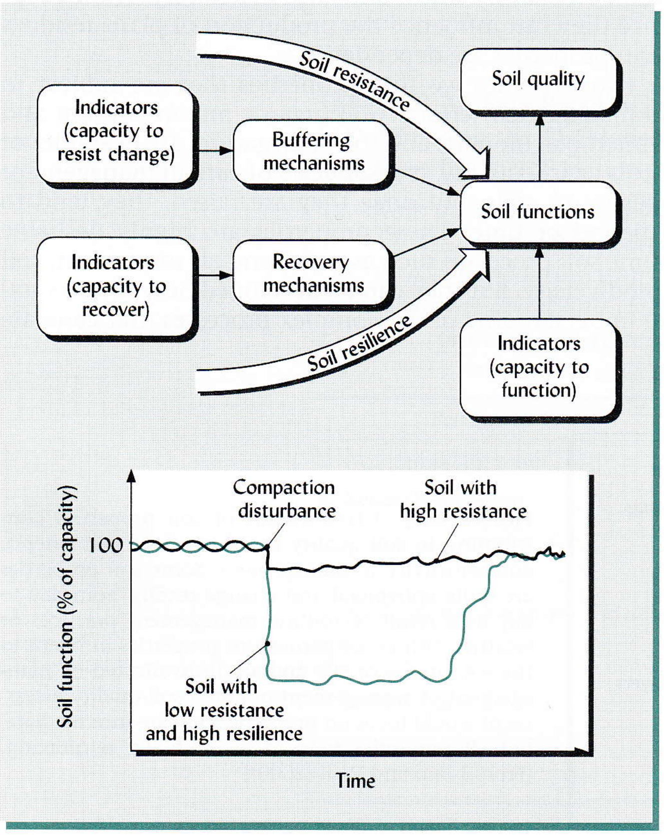

FIGURE 20.3 (*Upper*) The concept of how soil resistance and soil resilience relate to soil quality through soil functions. Resistance acts as a buffer in slowing down change stimulated by a disturbance, while resilience mechanisms help the soil recover from the negative effects of the disturbance. (*Lower*) The effect of a disturbance such as compaction on the functioning capacity of two soils differing in their resistance and resilience. The first soil, with low resistance to change, functions very poorly after the disturbance. In contrast, the disturbance only modestly affects the function of the second soil with its high resistance. Fortunately, the first soil has high resilience, so in a matter of time, its function recovers to the original level. Resistance assured the second soil's function in spite of the disturbance, while resilience brought the first soil back up to it's original function level. [Upper modified from Seybold, et al. (1999); used with permission of Lippincott, Williams, and Wilkins, Baltimore]

effects on soil resilience. Dynamic properties such as those associated with the type of vegetation, nutrient cycling, water and land management, as well as the underground community of organisms, play a vital role, especially for soil resilience. For example, properly managed cropland systems can not only increase the amount and quality of soil organic matter in a degraded soil, but can speed up the rate of organic matter buildup. In other words, these systems can enhance soil resilience, an important component of soil quality. The significance of both soil resistance and soil resilience will be seen later on as we focus on more specific ecosystems that are affecting soil quality.

We now turn to the three primary **functions** of soils that must be performed if soil quality is to be considered satisfactory. Our initial focus will be on biological productivity, since all life is dependent on it. However, the other two functions—maintaining environmental quality and enhancing human and animal health—will also receive attention, particularly as they are influenced by the attempts of humans to maximize biological productivity.

20.3 SUSTAINING BIOLOGICAL PRODUCTIVITY

No other soil function affects all living creatures more than does the sustenance of *biological productivity.* Human survival through the ages has depended on this function, and will likely continue to do so. Likewise, the survival of countless numbers of soil organisms is dependent on the soil's capacity to support biological productivity. We turn our attention to satisfying human needs for food and fiber, since the survival of other organisms is often determined by how we satisfy these human needs. We will review the world's food production problems, how they have been coped with, and how soil quality has benefitted and suffered from the actions we have taken.

The First 10,000 Years

Since the dawn of agriculture some 10,000 years ago, people have cleared forests and prairies so that the land could be used to grow food and fiber for their growing families. Initially, because there was an abundance of land and relatively few people, the change from the more sustainable natural vegetation to the less stable agricultural systems had only local effects on soil quality.

As humans became more numerous, soil productivity suffered over wider areas. Examples include the salinization of the once very productive irrigated lands of ancient Mesopotamia in the Middle East (see Section 10.3) and the severe water erosion of hilly lands upon which the Greeks and Romans depended for food (see Figure 17.24). These peoples turned to less densely settled lands in North Africa and Europe for the production of food. Consequently, the degradation of soil quality in these early periods had only modest global effects.

As human populations increased further and the productivity of farmed soils faltered, food production was increased primarily by expanding the area of land under cultivation, not by increasing yields per hectare. This was particularly true after the Europeans "discovered" the Western Hemisphere, whose virgin soils soon produced food not only for the local inhabitants, but for export to the food-deficient parts of the globe.

Past Half Century

It is only in the past half century that pressures on land for crop production have become so acute, forcing people to consider alternatives to expansion of cultivated land as means of meeting human needs for food and fiber.[4] This change stems both from the unprecedented increases in the numbers of people to be fed, and from those people's enhanced ability to purchase food and fiber that others produce. We will start with the population explosion.

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[4] Human demands for fiber that is used to manufacture cloth, paper, lumber, rope, machinery covers, and so forth also grow with human population numbers. Plants such as cotton, hemp, and trees are used to help meet these demands. While our major focus will be on expanding food needs, demands for fiber also increase.

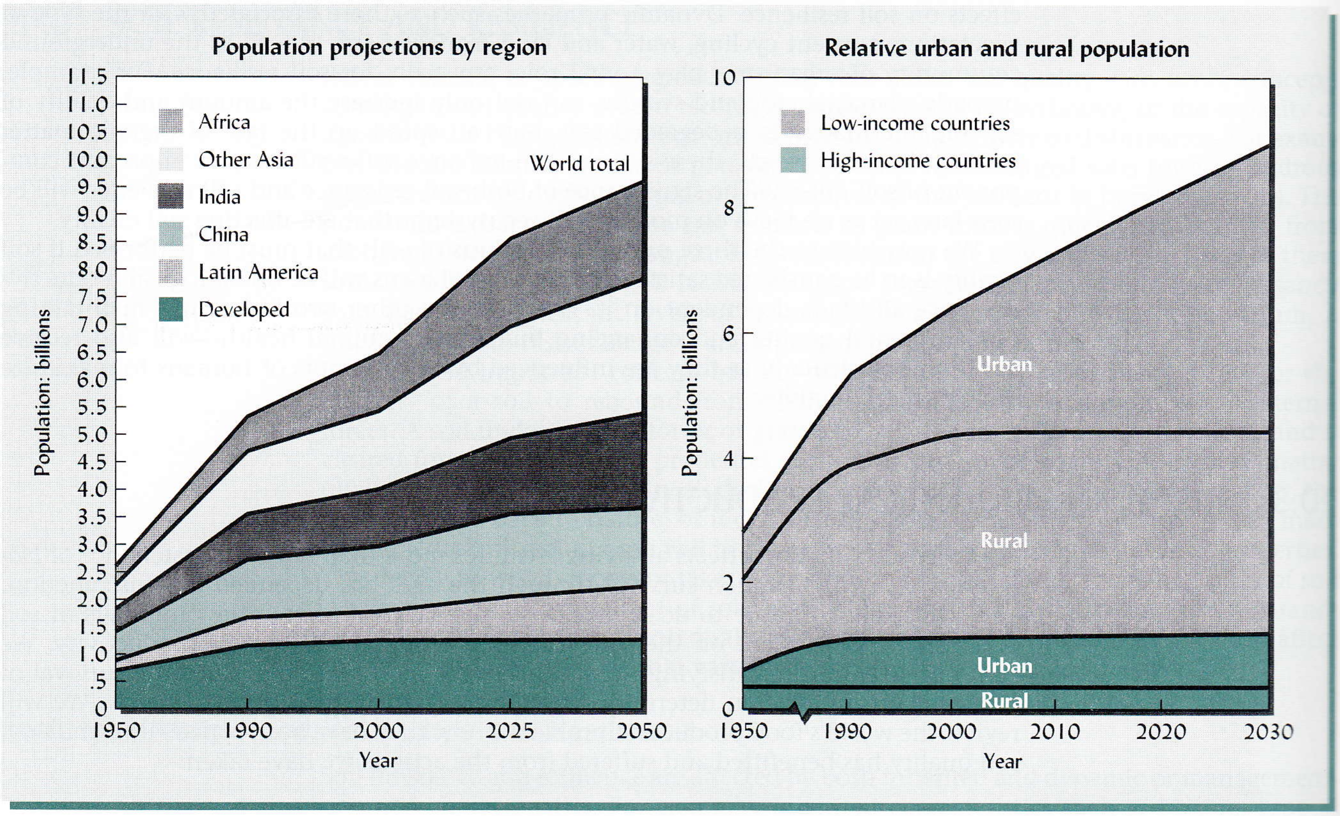


FIGURE 20.4 From the beginning of the human race until 1960, the world's population increased to about 3 billion. Less than 40 more years were needed to provide the second 3 billion. The total is expected to rise to 8.5 billion by the year 2025. (*Left*) Note that essentially all the growth is in the lower-income developing countries and regions that are already pressed to provide food for their growing populations. Also note (*right*) the increasing proportion of the developing country populations that live in urban areas. While considerable quantities of vegetables and other food crops are grown in or around the cities, most of the food required for the urbanites must be produced out in the rural areas. Also, urban living provides little opportunity for family and community sharing, commonly found in many rural areas. [Sources: (*Left*) UNFPA (1992); (*Right*) United Nations (1996)]

20.4 THE POPULATION EXPLOSION

U.N. Food and Agriculture Organization (FAO): www.fao.org/

Modern medical advances following World War II stimulated unparalleled increases in human populations and in demands for food (Figure 20.4). These demands were met by farmers who produced more food in the past half century than had been produced in the previous 10,000 years of the history of agriculture.

TABLE 20.4 Percent of Increase in Food Production in Different Regions Between 1961 to 1963 and 1989 to 1990 Attributable to Increases in Area Cropped and to Increases in Yields Per Hectare

	Increase attributable to	
Region	*Increased area, %*	*Increased yields,*[a] *%*
Low-income countries		
Sub-Saharan Africa	47	52
Latin America	30	71
Middle East/North Africa	23	77
South Asia	14	86
East Asia	6	94
High-income countries	2	98
World	8	92

[a] Includes both increasing the number of crops per year and increased yields per hectare.

Data from the Food and Agriculture Organization (FAO).

To achieve this target, it was necessary either (1) to clear and cultivate native forests or water-deficient grasslands, much of which were ill-suited for cultivation; or (2) to greatly increase the cropping intensity and the yields per hectare on the more productive lands already under cultivation. Both sources of enhanced food production were utilized, but most of the needed food came from increased production on existing farmlands (Table 20.4). As we shall see, both of these approaches to increased food production resulted in serious consequences for the quality of the world's soils.

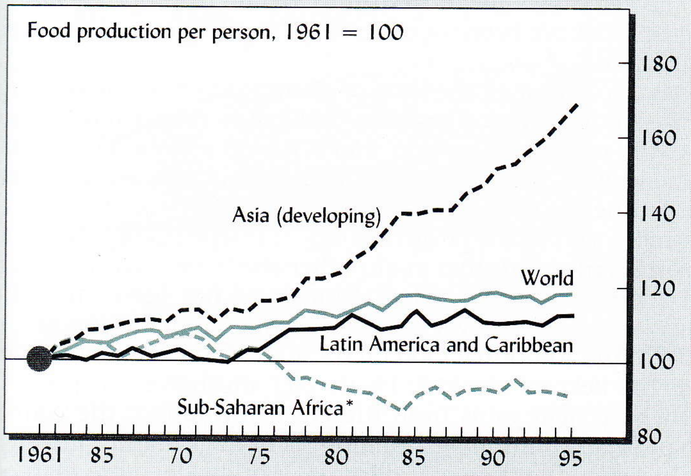
20.5 INTENSIFIED AGROECOSYSTEMS—THE GREEN REVOLUTION

When the human population explosion became evident after World War II, many experts predicated widespread starvation. Their predictions were based primarily on the assumption that, as in the past, expansion of cultivated land would be the primary means of increasing food production. They ignored possibilities for increased production intensity on land already in cultivation, and they were wrong.

Scientists and their farmer collaborators developed and put to use intensified soil-, water-, and crop-management systems that gave unparalleled increases in food production, especially in the developing countries of Asia and Latin America. Food production increased more rapidly than population in all major regions except sub-Saharan Africa (Figure 20.5). Grain harvests nearly tripled worldwide from 1950 to 1990. As a result, the threat of massive starvation was averted, and the cost of foods (primarily cereals) actually fell. Lowered food prices benefitted poor people everywhere, in cities as well as rural areas.

The vastly increased production resulted from farming systems that integrated newly created high-yielding cereal varieties (wheat, corn, and rice) with increased water availability through irrigation and dramatic increases in nutrient inputs from chemical fertilizers (Figure 20.6). Monoculture systems were intensively used, and two or three crops were harvested annually.

More than 70% of the increase came from intensified farming, the remainder from increases in cultivated land area. The results were most spectacular in Asia and Latin America, where the term *green revolution* was used to describe the process. Wheat yields in India, for example, increased by nearly 400% from 1960 to 1985, and yields of rice in Indonesia and China more than doubled. The global caloric intake increased to about 2700 kilocalories, about 16% above minimum needs. Although millions still remained hungry, human nutrition among the poor was greatly enhanced since the real cost of these cereals declined by about 75%, making them more easily available to low-income citizens.



Source: FAO

*Excluding South Africa

FIGURE 20.5 Changes in per capita food production in different regions of the world between 1961 and 1995. Food production per person worldwide increased nearly 20%, but in the developing countries of Asia, the increase was nearly 70%. Only in sub-Saharan Africa (excluding South Africa) did the per capita food production decline. Most of the increases resulted from agricultural intensification. [Data from FAO]

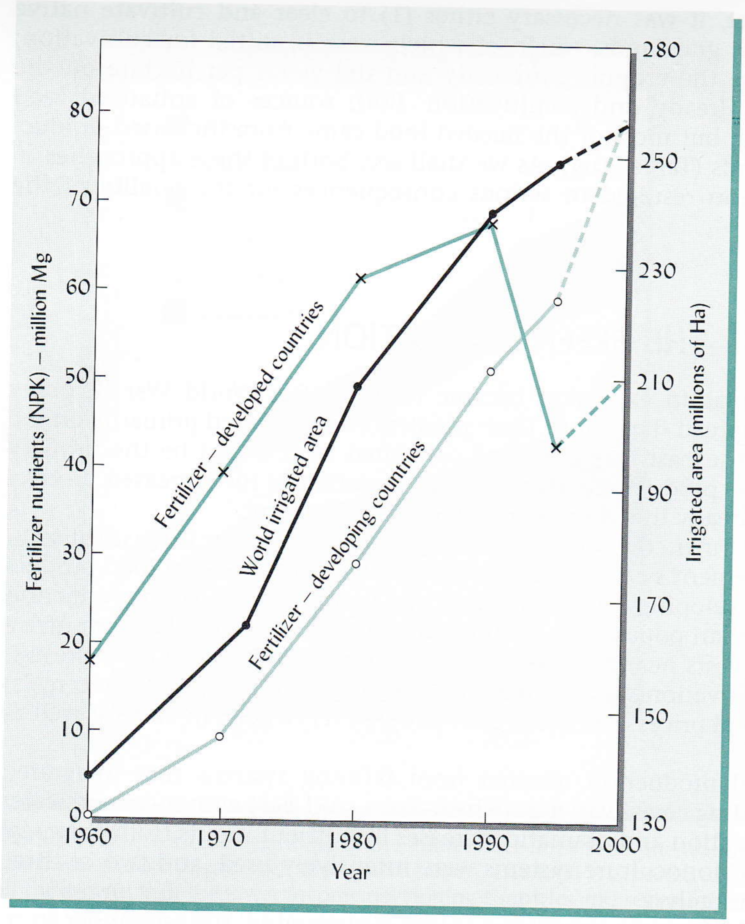


FIGURE 20.6 Increases in fertilizer use in industrial and developing countries and in world irrigated area since 1960. Note the 25-fold increase in fertilizer use in developing countries and the worldwide doubling of land under irrigation. The drop in industrialized country fertilizer use since 1990 is due primarily to decreases in the states of the former Soviet Union, although use in the United States and Europe has leveled off. (From FAO data and author's calculations)

20.6 EFFECTS OF INTENSIFIED AGROECOSYSTEMS ON SOIL QUALITY OR HEALTH

Few quantitative studies have been made of the effect of production intensification on soil quality. But indirect evidence suggests that both positive and negative effects have occurred.

Positive Effects

On the positive side, intensified agriculture has generally maintained or even increased the level of some **macronutrients** in soil, since these elements are commonly supplied from outside sources, such as manures, lime, or fertilizers. Where appropriate modest applications of chemical fertilizers have been used, the N, P, and K components of soil quality have often been enhanced.

Intensified agriculture has also increased the level of plant production, permitting a corresponding increase in the amount of **crop residues** that can be returned to the soil. Such residues provide soil cover, reduce soil erosion, and can help maintain or increase soil organic matter levels (Table 20.5). Soil quality is thus positively affected if a greater amount of crop residues is returned to the soil.

A third and likely even more significant positive effect of intensification is its tendency to **reduce pressures on fragile lands** that might otherwise have been cleared and cultivated to produce the additional food needed. Agriculture has been intensified mostly on the more productive, relatively level soils, where risks from erosion are not too high. By producing most of the additional food on these soils, the need for expanding onto more fragile lands has been minimized. Figure 20.7 illustrates this point for India. Were it not for the wheat yield gains from the green revolution, the country would have been forced to plow an additional 42 million ha of fragile lands, mostly in forests, an area equivalent in size to the state of California. Worldwide, more than 600 million ha—equal to the area of the great Amazon basin—have been "saved" due to

TABLE 20.5 The Effect of Nearly 30 Years of Continuous Rice Cropping (3 Crops per Year) with and without Nitrogen Fertilizer on the Organic Carbon and Total Nitrogen in a Soil in the Philippines

Note the higher organic carbon and N levels in the soil to which heavy applications of nitrogen (330 kg/ha/yr) were applied. Phosphorus and potassium were applied to all plots.

	Organic carbon in soil, g/kg		*Total N in soil, g/kg*	
Year	*No N applied*	*330 Kg N/ha/yr applied*	*No N applied*	*330 Kg N/ha/yr applied*
1963	18.3	18.3	1.94	1.94
1978	18.8	21.4	1.97	2.22
1983	18.7	21.4	1.95	2.14
1985	20.4	23.9	2.07	2.38
1991	20.4	23.5	1.97	2.27
1992	20.7	23.0	2.09	2.30

Modified from Cassman, et al. (1997).

increased yields of all cereal crops. It is almost certain that the quality of soils would have declined significantly on the forest and prairie lands that would have been brought into cultivation had crop intensification not been used.

Another possible aspect of the green revolution is the increased **efficiency of nutrient use** by some of the improved cereal varieties (Figure 20.8). For example, when 75 kg N/ha was applied to the traditional wheat varieties of 1950, only 45 kg of wheat was produced for each kilogram of nitrogen added. Improved varieties of the mid-1980s produced 70 kg of wheat per kilogram of added nitrogen. Note, however, the lower efficiencies of all varieties when high nitrogen rates are used.

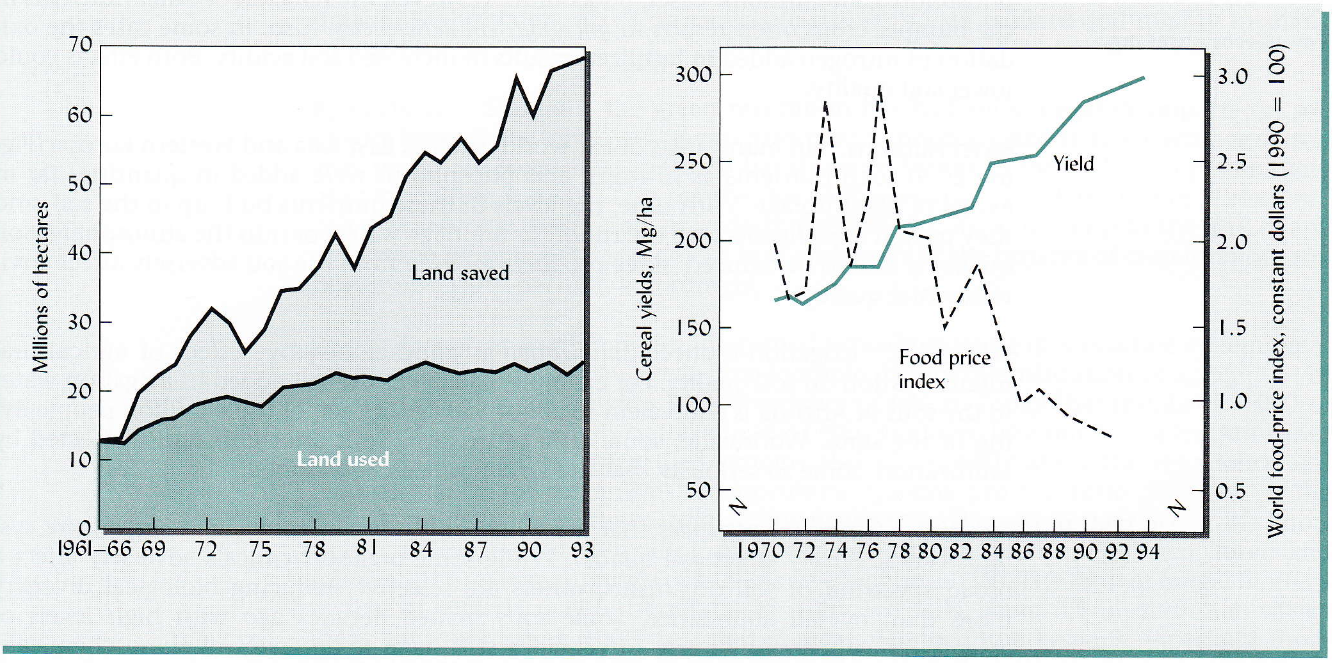


FIGURE 20.7 (*Left*) In the 1990s, if India had been forced to produce its wheat with technologies and varieties of the 1960s, farmers would have needed about 40 million more hectares of farmland. Most of this extra farmland would have to come from easily erodible forestlands that are characterized by steep slopes. (*Right*) The increase in global per-hectare yields of cereal crops (wheat, corn, and rice) from 1970 to 1994 was associated with a reduction in the world food price index for these foods, meaning that consumers paid less for them. The poor people in developing countries (urban as well as rural) were the greatest beneficiaries of these reductions. [Right from CIMMYT (1995); left from *The Economist*, June 10, 1995]

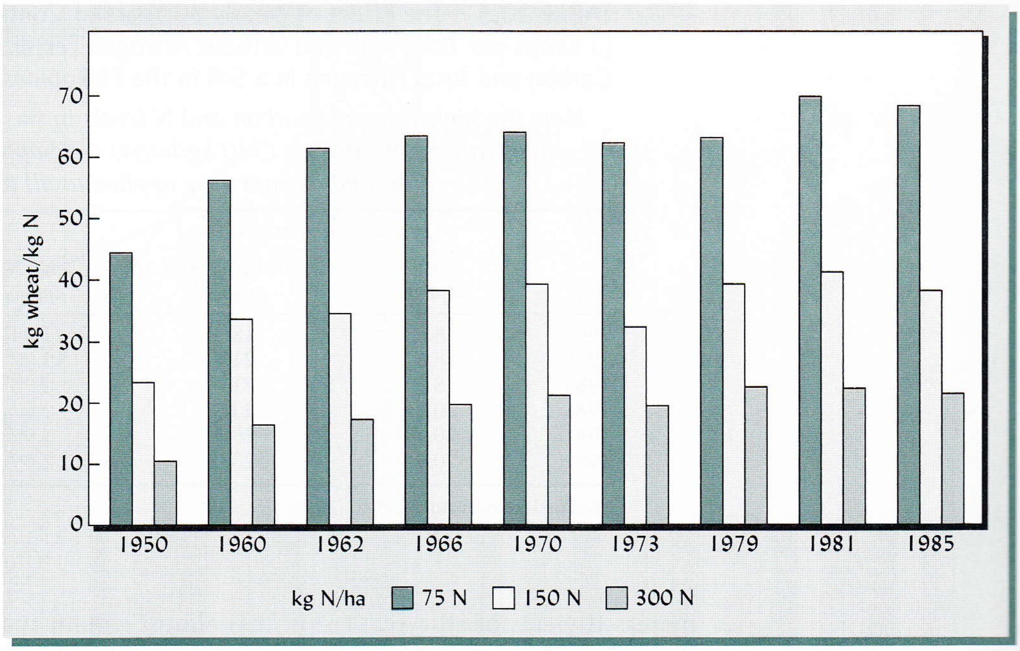


FIGURE 20.8 The efficiency of nitrogen utilization of traditional wheat cultivars of 1950 compared with that of the steadily improved cultivars that have since been used in intensified agriculture in developing countries. At all fertilizer nitrogen application rates, the improved cultivars are more efficient than the traditional varieties of 1950. Note, however, that nitrogen use efficiency is much lower at the higher rates (150 and 300 kg N/ha) than at the more modest rate of 75 kg N/ha. [From CGIAR (1997)]

Negative Effects

Technical notes on the state of the nation's ecosystems, croplands, and soil nutrient levels:
www.us-ecosystems.org

Intensive agriculture also has had negative effects on the quality of some soils. The application of chemical fertilizers generally provides ample quantities of nitrogen, phosphorus, and, in some cases, potassium.[5] However, the removal of other nutrients in the bumper crops often results in *micronutrient deficiencies.* Also, in some cases the oxidation of nitrogen added in fertilizers results in increased soil acidity. Both effects could lower soil quality.

Excess Nutrients. In many areas of the world, such as East Asia and Western Europe (Figure 20.9) such nutrients as nitrogen and phosphorus were added in quantities far in excess of plant uptake. With time, the levels of these nutrients built up in the soil, and they moved as *pollutants* into the runoff or drainage waters or into the atmosphere. Soil quality is said to be reduced, since products moving from the soil adversely affect environmental quality.

Salinization. Irrigation-induced *salinization* is another negative effect of agricultural intensification on soil quality. For example, each year the salt added in irrigation water to the soils of Arizona is equivalent to about 350 kg for each of the 4 million people living in the state. Worldwide, some 30% of irrigated soils are significantly affected by salinization, some so seriously that the land has been abandoned.

Pesticides. Chemical *pesticides* that are commonly used in intensified agriculture systems can adversely affect soil quality. While some organochemicals adversely affect a broad spectrum of soil organisms, others are selective, reducing biological diversity more than overall abundance. Some soils treated decades ago with high levels of arsenic- or copper-containing insecticides still have toxic levels of these chemicals. Because of the uncertain effects of today's pesticides on soil quality, *integrated pest management* systems that minimize the use of these chemicals should be emphasized.

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[5] When cleared lands are cultivated, deficiencies of nitrogen and phosphorus are first to appear, and fertilizers are applied to meet these needs. However, crop removals soon lower the potassium levels of some soils, especially those that are highly weathered and low in 2:1-type clays, such as illite.

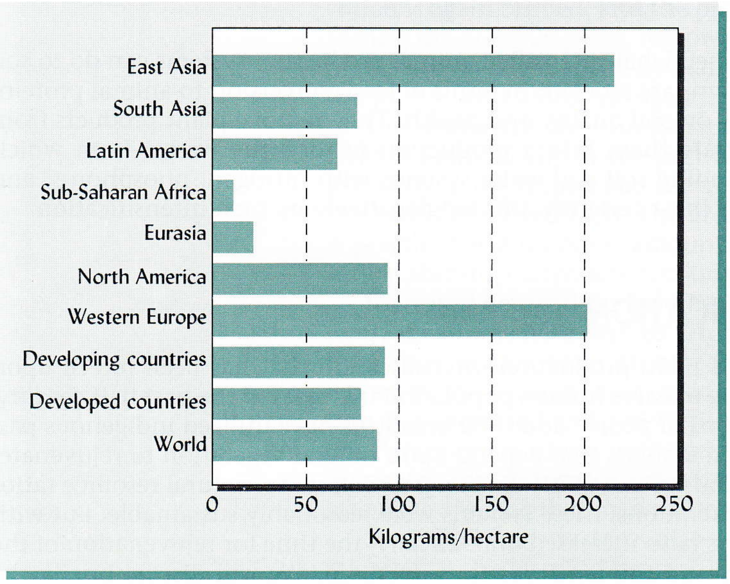

FIGURE 20.9 Rates of fertilizer nutrient use in selected regions of the world in 1995. Note the very high use in East Asia, where multiple cropping is common, and in Western Europe, where highly intensive agriculture is practiced. In both regions some excessive-use sites have been identified. Also note the very low rates in sub-Saharan Africa and in Eurasia (the newly independent states of the former Soviet Union), where plant production is constrained by nutrient deficiencies. Fertilizer use in the United States is about average for the world. While there are some high-use systems in irrigated and humid areas, these are balanced by the very low rates in vast areas of dryland farming where water, rather than nutrient deficiencies, is the first limiting factor. [Data from FAO published in Bumb and Baanante (1996)]

HEALTHY DIET. Intensive agricultural systems have focused primarily on cereal crops, such as wheat, corn, and rice, which provide about half the world's calories and are quite responsive to external inputs, such as water and fertilizers. Unfortunately, less attention has been paid to the pulses (beans, peas, and lentils), fruits, and vegetables. As a result, the area planted to these crops actually decreased in some countries. For example, in India, the area of land devoted to pulses decreased by 13% from 1970 to 1995. This has implications for *human health* because, compared to the cereals, the pulses are generally higher in proteins and micronutrients, and leafy vegetables are higher in vitamins. Human diseases associated with *deficiencies of micronutrients,* such as iron and zinc, and with vitamin A, are widespread in tropical countries. Also, the pulse legume residues provide some organic nitrogen that is released slowly for subsequent crop uptake. Exclusive emphasis on cereals has thus indeed reduced soil quality in many countries of the world.

PLANT DISEASE. Similarly, the green revolution has had some negative impacts on soil quality because the improved cereals have commonly been grown in *monoculture* season after season. In some areas, research has shown a decline in the biological productivity of monoculture systems. This may be due to the buildup of *pathogens* or of *allelochemicals* that are toxic to the crop, or to declining levels of micronutrients in the soil. In any case, when cropping systems do not take advantage of the benefits of crop rotation, soil health or quality declines accordingly.

REDUCED BIODIVERSITY. High input, intensified agriculture using monoculture systems generally adversely affects *biodiversity.* For example, before intensification of agriculture in China, farmers were growing 10,000 varieties of wheat. Today that number is 1000 or less. Furthermore, the bulk of the wheat is being produced by a much smaller number of high yielding varities. Intensified systems also significantly affect the abundance and biodiversity of soil organisms. Monoculture systems provide little diversity in the organic residues and in the associated organisms that take part in their decay. We know that the clearing and cultivation of forested lands reduces the number of fungi and increases the relative numbers of bacteria (see Section 11.15). The ratio of fungal biomass to that of bacteria may be about 1:1 in cultivated soils, about 3:1 in minimum tillage areas, and more than 100:1 in forested areas. Monoculture systems, especially those where the crop residues are removed or burned, also reduce the number of earthworms and other macroorganisms, compared to their numbers in systems with crop rotation.

Effects of intensification on the biodiversity among species of bacteria is somewhat less certain because their extremely small size makes it difficult to measure their diversity. However, the advent of new molecular biological tools that provide DNA analyses has already shown the close interaction of numerous microbes in soils and has indicated that this interaction is modified as soil and plant environments change.

Animal Feedlots

In Section 16.5 we discussed what intensified animal production systems can do to soil quality. While these systems are efficient in terms of feed conversion to animal protein, they have adverse effects on soil quality and health. They remove plant products from wide areas and concentrate them into a production factory, the wastes from which often pollute the surrounding soil and water systems with nitrogen, phosphorus, and pathogens. Soil quality is most certainly affected negatively by such intensification.