From the Ground Up

EXPLORING SOIL QUALITY'S CONTRIBUTION TO ENVIRONMENTAL HEALTH

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Henry A. Wallace Institute for Alternative Agriculture

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"The earth is the mother of us all—plants, animals, and men. The phosphorus and calcium of the earth build our skeletons and nervous systems. Everything else our bodies need except air and sun comes from the earth.

Nature treats the earth kindly. Man treats her harshly. He overplows the cropland, overgrazes the pastureland, and overcuts the timberland. He destroys millions of acres completely. He pours fertility year after year into the cities, which in turn pour what they do not use down the sewers into rivers and the ocean. The flood problem insofar as it is man-made is chiefly the result of overplowing, overgrazing, and over-cutting of timber.

. . . The social lesson of soil waste is that no man has the right to destroy soil even if he does own it in fee simple. The soil requires a duty of man which we have been slow to recognize."

HENRY A. WALLACE
From *Soils and Men*, Yearbook of Agriculture, 1938

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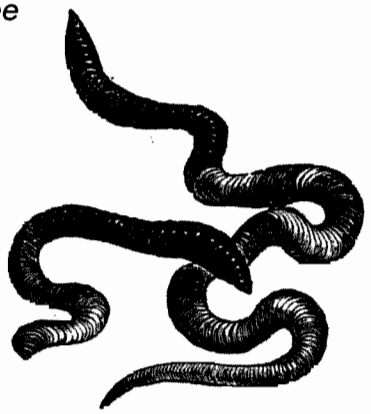

Henry A. Wallace Institute
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GREENBELT, MARYLAND

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ADDITIONAL COPIES
Copies of *From the Ground Up: Exploring Soil Quality's Contribution to Environmental Health* are available at a cost of $10.00 per copy, or may be downloaded from the Institute's Web site.

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Preface

FROM ITS INCEPTION, the Henry A. Wallace Institute for Alternative Agriculture has regarded soil quality as a central issue related to the sustainability of agriculture. Current, reinvigorated research that focuses on both private and social benefits of soil quality now provides the seeds for a more fully integrated natural resource and environmental policy agenda. The key to this process is understanding and documenting what a broad spectrum of scientists are now telling us: namely, that healthy soils help maintain water quality, regulate water quantity, prevent water and wind erosion, buffer global climate changes, ensure food safety, and enhance biodiversity—all while simultaneously promoting crop yields. In other words, improved soil health may provide private benefits to farmers, and social benefits to everyone else.

Links between the soil and environmental quality are not new. Soil erosion and its impacts on soil productivity have been studied intensively for the past 70 years. What is new, however, is the breadth implied by the "new" concept of soil quality, which is now defined by the soil's multiple functions.

The package of environmental benefits believed to be gained by improving soil quality is becoming more important as society places higher and higher values on environmental quality. If, for example, increasing costs are placed on greenhouse gas emissions, it may ultimately prove cost-effective to sequester carbon in the soil. Indeed, one energy company is already experimenting with a program that entices farmers to change their tillage practices to increase the levels of organic carbon in the soil. Farmers

taking advantage of programs like this one may boost their own net returns, while helping to reduce the level of atmospheric greenhouse gases.

Before soil quality can become a focus of policy, however, research must address the needs of farmers, policy makers, and everyone concerned with environmental health. We need to know whether soil degradation is a social problem, and if it is where to target policy. We need to be able to predict the expected health and environmental benefits from improving soil quality. And we need to know how much return farmers can expect from investing in soil quality. The environmental and farm benefit information is crucial to assessing whether added investments in soil quality will yield net benefits for farmers and for society. The Henry A. Wallace Institute believes the potential for net social benefits from soil-quality improvements merits more attention and, with this report, has attempted to fulfill two goals: (1) to summarize current research documenting private and social benefits of enhancing soil quality, and (2) to identify the knowledge gaps that must be addressed before fully evaluating a soil-quality policy agenda.

Partial funding for this study was provided by The Pew Charitable Trusts. The report's contents and conclusions, however, are solely the responsibility of the author and the Wallace Institute.

1 *Introduction*

OVER THE PAST TEN YEARS OR SO, a quiet revolution has taken place in the way scientists view the health of the nation's soil. At one time, soil health—more properly known as soil quality—was defined simply in terms of its ability to perform a single function: promote crop growth. Today, soil quality is defined by the soil's ability to:[1]

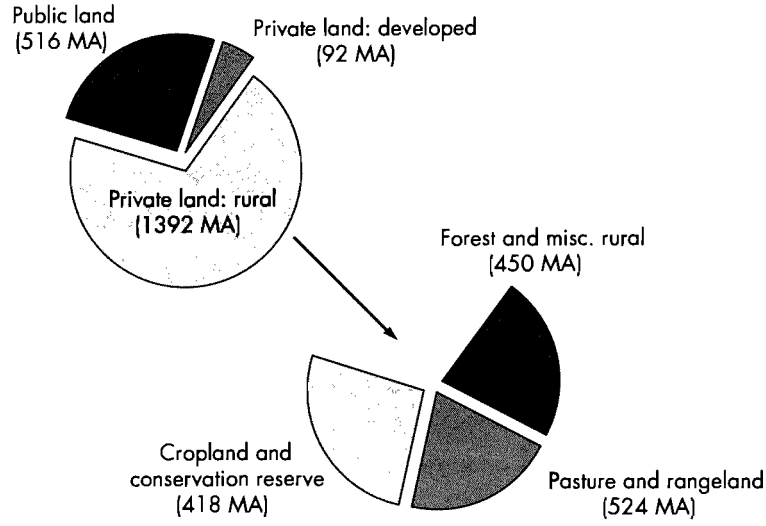
- prevent water and air pollution by resisting water and wind erosion, and by buffering potential pollutants such as agricultural chemicals, organic wastes, and industrial chemicals;
- protect watersheds by maximizing rainfall infiltration and storage in fields while minimizing runoff from fields;
- support human health and habitation; and
- promote the growth of crops and other plants.

In some cases, the pursuit of these multiple functions may go hand in hand. For example, a soil with high levels of organic matter can provide a good plant-growing medium by facilitating nutrient availability or water-holding capacity, while simultaneously providing a good environmental buffer by holding, storing, or otherwise tying up chemical nutrients. In other cases, pursuing one outcome may be at odds with another. For example, a soil with a high phosphorous concentration may enhance crop growth but cause excessive chemical runoff. The new view of soil quality characterizes soils based on all the functions collectively, whereas the old view characterized soils based primarily on crop productivity.

Source: U.S. Department of Agriculture, Natural Resources Conservation Service. 1996. *America's Private Land: A Geography of Hope.* Washington, DC: U.S. Department of Agriculture. p. 19.

FIGURE 1 America's land base in 1992

Millions of acres (MA) in the 48 contiguous states



A central hypothesis emerges from the broader view of soil health: improvements in soil quality provide broad social benefits that go beyond crop productivity. Thus, research that documents these multiple benefits of soil-quality improvements could lead to new, cost-effective strategies for attaining environmental goals. As society places ever more importance on clean water, clean air, and food safety, the rewards from finding profitable farming practices and systems that sustain environmental quality will grow. Because the 48 contiguous states contain about 15 times more private land that is farmed, ranched, or forested than private land given over to other uses—and about two and a half times more private than public land (Figure 1)—it is clear that conservation and enhancement of soil quality represent a first line of defense against air and water pollution.[2]

Despite these increasingly important potential benefits, soil quality continues to receive surprisingly little attention in policy circles. Why? In the past few years, there have been several volumes devoted to soil quality, its assessment, and its links to environmental health (Box 1). Nonetheless, an assessment of the efficacy and cost of pursuing policies designed to enhance soil quality currently is not feasible. Significant gaps still exist in our ability to quantify the soil's physical, chemical, and ecological relationship to environmental quality, including human health and food safety. We need a stronger scientific base before we can design reasonable soil-quality goals and recommend viable farming practices to achieve these goals.

The Henry A. Wallace Institute believes that the potential for social benefits from soil-quality improvements over and above yield improvements merits more scientific attention, especially in light of

BOX 1 Top ten soil quality reading list

- Acton, D.F. and L.J. Gregorich (eds.). 1995. *The Health of Our Soils: Toward Sustainable Agriculture in Canada.* Ottawa, ON: Centre for Land and Biological Resources Research. Research Branch Publ. 1906/E.
- Doran, J.W. and A.J. Jones (eds.). 1996. *Methods for Assessing Soil Quality.* Madison, WI: Soil Science Society of America. SSSA Special Publ. no. 49.
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- Doran, J.W., et al. (eds.). 1994. *Defining Soil Quality for a Sustainable Environment.* Madison, WI: Soil Science Society of America. SSSA Special Publ. no. 35.
- Gershuny, G. and J. Smillie. 1995. *The Soul of Soil: A Guide to Ecological Soil Management.* 3rd ed. Davis, CA: agAccess.
- Lamarca, C.C. 1996. *Stubble Over the Soil: The Vital Role of Plant Residue in Soil Management to Improve Soil Quality.* Madison, WI: American Society of Agronomy.
- Magdoff, F. 1992. *Building Soils for Better Crops: Organic Matter Management.* Lincoln: University of Nebraska Press, 1992. Our Sustainable Future vol. 2.
- National Research Council. 1993. *Soil and Water Quality: An Agenda for Agriculture.* Washington, DC: National Academy Press.
- U.S. Dept. of Agriculture, Natural Resources Conservation Service. 1996. *America's Private Land: A Geography of Hope.* Washington, DC: U.S. Dept. of Agriculture.
- Youngberg, Garth (ed.). 1992. *American Journal of Alternative Agriculture* 7(1/2). Special Issue on Soil Quality. Papers from a workshop, "Assessment and Monitoring of Soil Quality," held July 11-13, 1991, Emmaus, PA.

precision agriculture and other emerging technologies that allow a more detailed examination of, and possibly some new thinking about, managing soil resources. This background report has two goals: (1) to summarize the known private and public benefits of enhancing soil quality, and (2) to identify critical knowledge gaps that, when remedied, would clarify the efficacy and cost of using soil-quality-based policies to pursue improved productivity and environmental quality. An improved knowledge base will bring clearer focus to both the merits and shortcomings of soil-quality-based policies. Research targeting soil quality requires public expenditures; likewise, adoption of farm-management practices to improve soil quality requires private expenditures. These expenditures are the cost of investing in soil quality. The return on this investment has not yet been and cannot be calculated until the knowledge gaps are remedied. However, the productivity and environmental benefits of such policies to current and future generations could be substantial not only in the U.S., but in other parts of the world where soil degradation continues to be one of the causes of poverty and other social ills.[3]

BOX 2 Soil quality success story: Cedar Meadow Farm

Steve and Cheri Groff
Holtwood, Pennsylvania

Steve Groff and his family farm 175 acres of corn, alfalfa, tomatoes, pumpkins, soybeans, small grains, and a few other vegetables in southern Lancaster County, Pennsylvania. Groff says they started using no-till methods in the early 1980s to help curb soil erosion, and he began using cover crops in 1991 as another soil conservation measure. But Groff says he likes the way the combination of cover crops and no tilling does more than cut erosion—it improves soil tilth, increases organic matter levels (to as high as 5 percent in some fields), enhances water infiltration, and lessens pest pressures. Groff says, "We have slashed our pesticide and fertilizer bill nearly in half, while building our valuable topsoil and not sacrificing yields."

Groff is still fine-tuning his cover crop system and now chooses his cover based on the succeeding crop. For example, he transplants tomatoes into a three-way mix of hairy vetch, crimson clover, and rye. He plants pumpkins into a mix of vetch and spring oats. He plants soybeans into a rye cover that takes a round-about route into the soil. He spins the rye on top of cornstalks, and then rolls the stalks "to help shake the rye seeds down into the soil."

Lately, Groff has been enhancing his system to control his cover crops without herbicides. He's been trying a rolling stalk chopper originally designed to flatten and chop corn stalks to crimp the cover and force it down. Groff says he used the stalk chopper on vetch, rye, pumpkin residues, and six-foot-high forage soybeans, which were rolled down and planted with broccoli.

Groff says his cropping system has proved itself with hard results: "Soil conservation, pesticide reduction, and improved water quality."

Source: http://www.cedarmeadowfarm.com

2 *How the Soil Affects Our Air, Water, and Food*

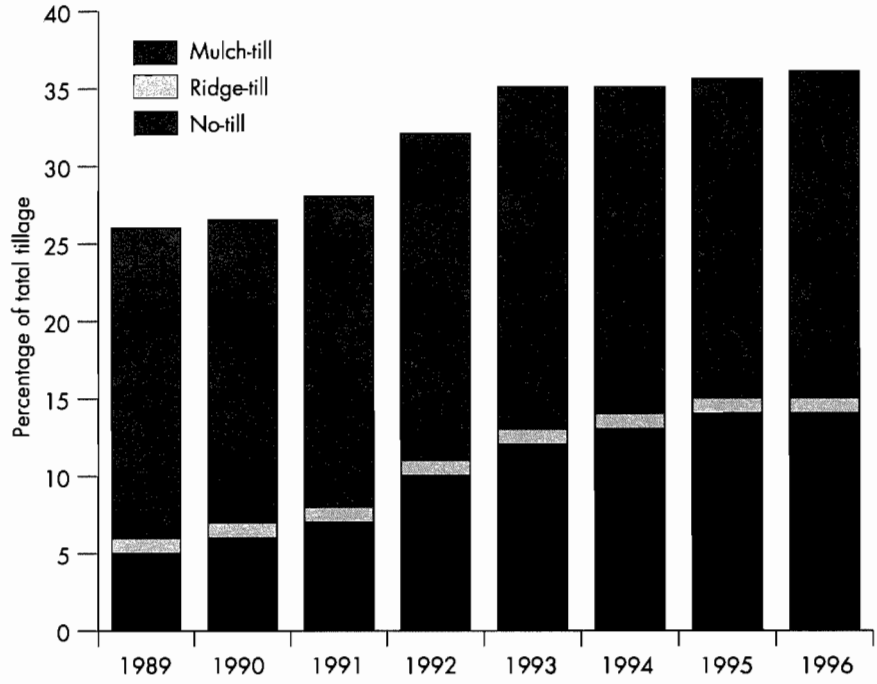
THE SOIL AFFECTS ENVIRONMENTAL QUALITY in many direct and indirect ways. Doran and Jones describe the soil as a living filter, through which water is cycled and chemicals are altered.[4] Soil, therefore, helps not only to produce food and fiber, but also to maintain local, regional, and global environmental quality. Lal and Pierce point out that mismanagement and neglect can degrade soil and so threaten our very survival.[5]

Water quantity: Soils regulate water conservation and storage

When rain falls on the soil surface, it either infiltrates the soil or moves across its surface into streams or lakes. The condition of the soil surface—one indicator of soil health—determines whether rainfall infiltrates or runs off. If it infiltrates the soil, it may be stored and later taken up by plants; it may also move vertically into groundwater or laterally to appear later in springs or other surface waters. In this way, the soil regulates and partitions water, determining whether a storm results in a "replenishing rain or a damaging flood."[6] When water runs off, it tends to carry soil particles. The costs on the farm from water and sediment runoff can be measured in decreased farm productivity; the costs beyond the farm gate include damage to commercial and recreational fishing, increased pressure on water treatment facilities, increased flood damages, and repairs for or redredging of damaged waterways. Annual damages to U.S. waterways due to soil erosion have been estimated to range from $2 billion to $17 billion, and are generally considered to be much greater than on-farm erosion costs.[7]

Source: U.S. Department of Agriculture, Economic Research Service, Natural Resources and Environment Division. 1997. *Agricultural Resources and Environmental Indicators, 1996-97.* Agricultural Handbook No. 712. Washington, DC: U.S. Department of Agriculture. pp. 157-158.

FIGURE 2 National use of conservation tillage practices, 1989-96



CONSERVATION TILLAGE: Any tillage practice that covers 30 percent or more of the soil surface with crop residue, after planting, to reduce soil erosion by water.

No-till: The soil is left undisturbed from harvest to planting except for nutrient injection. Planting or drilling is accomplished in a narrow seedbed or slot.

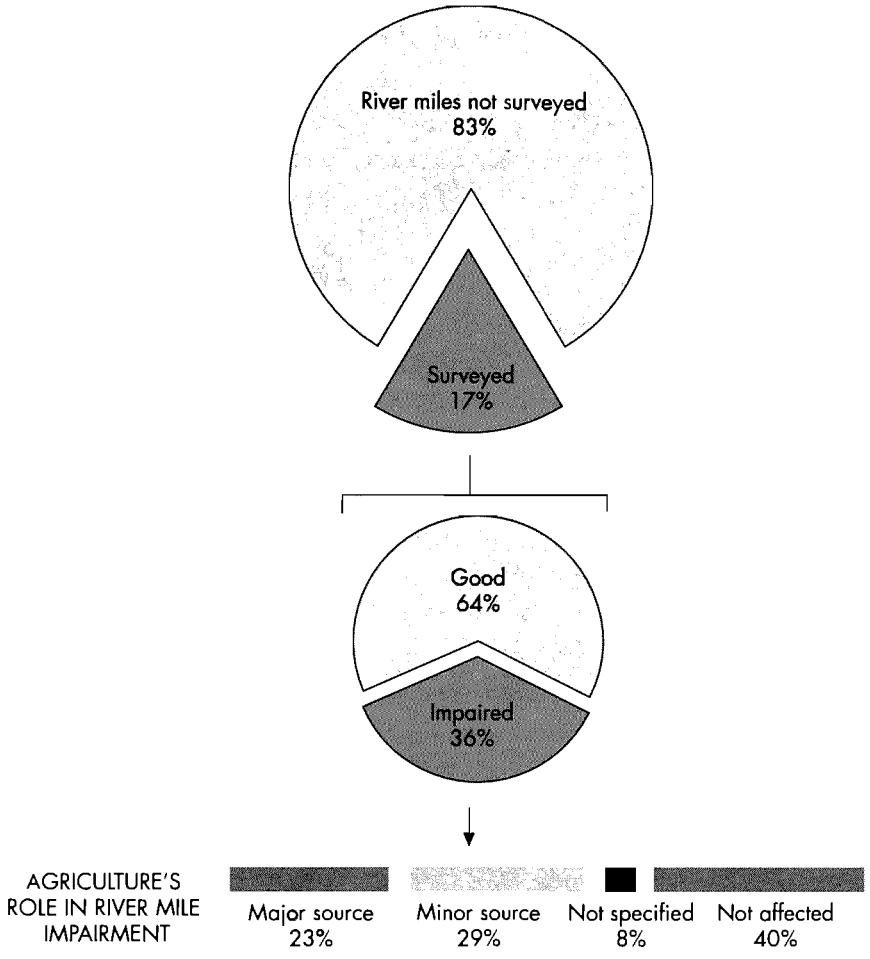
Ridge-till: The soil is left undisturbed from harvest to planting except for nutrient injection. Planting is completed in a seedbed prepared on ridges. Residue is left on the surface between ridges. Ridges are rebuilt during cultivation using special, ridge-making equipment.

Mulch-till: The soil is disturbed prior to planting.

Scientists are beginning to discover that severe storms generate the bulk of soil erosion losses.[8]

Management factors, such as keeping a plant cover on the soil or reducing tillage intensity (Figure 2), play a large role in the soil's erodibility; but the soil's inherent properties play an important role, too. The soil erodibility factor used in the Erosion-Productivity Impact Calculator (EPIC) is a function of soil texture and organic matter content.[9] Soils with higher organic matter and soils with better structure and texture, all else equal, will be less susceptible to water erosion.

FIGURE 3 Agriculture is the leading cause of pollution of U.S. rivers



Source: U.S. Department of Agriculture, Natural Resources Conservation Service. 1996. *America's Private Land: A Geography of Hope.* Washington, DC: U.S. Department of Agriculture. p. 40.

Abstract: Agriculture contributed to aggravating pollution in 60 percent of the country's impaired rivers that were surveyed. Other sources of pollution, in descending order, are municipal points sources, hydro/habitat modification, urban runoff/storm sewers, resource extraction, removal of streamside vegetation, and forestry.

Water quality: Soils buffer chemical runoff and leaching

Agricultural production is the single largest contributor to nonpoint source pollution problems in the nation (Figure 3).[10] Sediment/siltation and nutrient runoff from agriculture are the most frequent sources of adverse impacts to rivers, lakes, estuaries, and wetlands.[11] Mitigating practices such as planting buffer strips along riparian zones or building dams to intercept silt before it reaches economically important waterways can effectively address some of agriculture's water-quality problems, at least in the short run.

However, the National Research Council stresses that water quality and soil quality are directly linked, and that changes in farm practices that attempt to address nonpoint-source pollutants such as nitrogen, phosphorus, and pesticides will be effective in the long run only if soil quality is also protected or improved.[12]

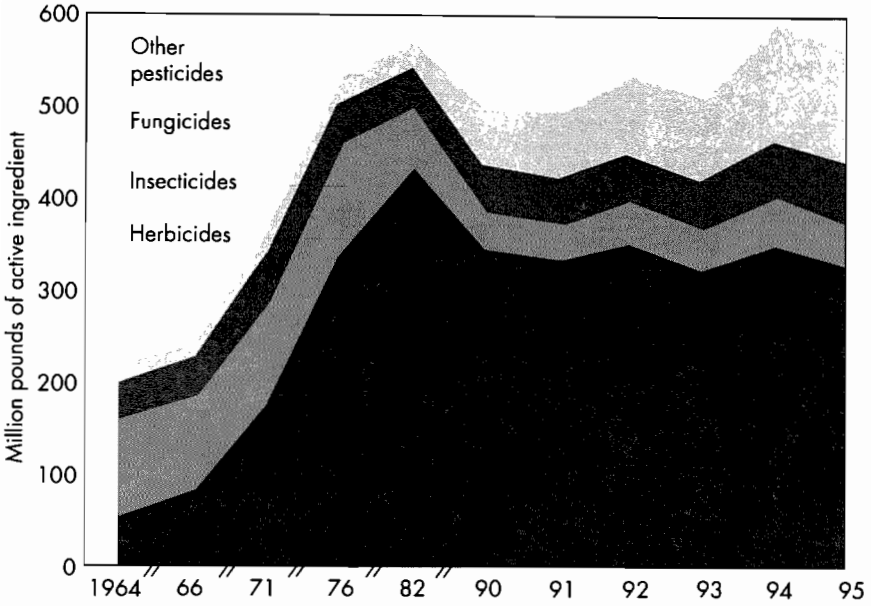
Nitrogen enters the soil from many different sources (fertilizers, biological fixation, animal manures, and rainwater) and leaves the root zone in many different ways (crop uptake, atmospheric volatilization, runoff, and leachate). Residual nitrogen—inputs minus outflows—may either go into soil storage or be lost to the external environment. As with water erosion, the fate of residual nitrogen depends both on management practices and the soil's inherent properties. Management practices that reduce residual nitrogen include the proper timing and placement of nitrogen fertilizer as well as utilizing cover crops, reduced tillage, crop rotations, and buffer strips. However, under similar management conditions, nitrogen leaching is reduced in soils with higher organic matter content, a higher clay content, or improved soil texture.[13] Additionally, high microbial activity increases immobilization of nitrogen and reduces leaching, at least temporarily.[14]

Like nitrogen, available phosphorus enters the soil through several direct (commercial fertilizers, phosphorus-bearing soil materials) and indirect (organic matter and manures broken down by microbes) sources and leaves in several ways (crop uptake, attachment to soil materials, leaching, erosion). Unlike nitrogen, phosphorus is tightly bound to the soil and only a small portion of the total phosphorus in the soil is available for crops.[15] In general, phosphorus that is lost through leaching to groundwater is not considered a problem.[16]

The majority of phosphorus loss from agricultural lands is through the surface flow of particulate phosphorus, tightly bound to eroded sediment particles. The two primary ways of reducing phosphorus loss, therefore, are to adopt practices that reduce the level of phosphorus applications and that reduce erosion and runoff from cropland. However, another way of reducing phosphorus runoff is by improving the efficiency of phosphorus uptake by crops. Phosphorus efficiency depends on the following soil properties: soil moisture, soil aeration, soil pH, soil type, clay content, microbial activity, and soil compaction.[17] In fact, the soil's bulk density is used to predict the concentration of soluble phosphorus in runoff.[18]

The major ways in which pesticides (Figure 4) enter the environment outside the soil are through atmospheric volatilization and aerial drift, runoff to surface water bodies in dissolved and particulate form, and leaching into groundwater.[19] Pesticides that strongly bind to soil clays and organic matter—including the banned organochlorine pesticides DDT and dieldrin—are subject to runoff and may collect in surface water or streambed sediments.[20] Pesticides with high water solubilities—including

FIGURE 4 Total pesticide use on major crops, 1964-1995



Source: U.S. Department of Agriculture, Economic Research Service, Natural Resources and Environmental Division. 1997. *Agricultural Resources and Environmental Indicators, 1996-97.* Agricultural Handbook No. 712. Washington, DC: U.S. Department of Agriculture. p. 117.

Includes uses on corn, cotton, soybeans, wheat, potatoes, other vegetables, citrus, apples, and other fruit (about 67 percent of U.S. cropland).

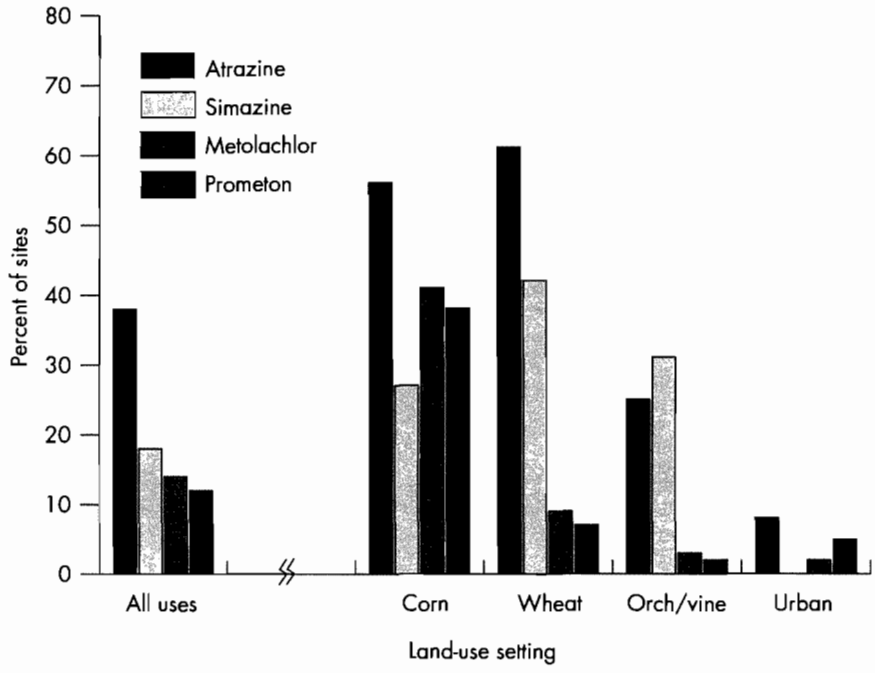
many herbicides—are likely to leach into groundwater. Three soil factors affect the movement of pesticides in groundwater (Figure 5):[21] (1) the pesticide degradation rate—determined by soil particle size, soil pH, organic matter content, microbial activity, and temperature; (2) water movement—indicated by the field capacity and the wilting point; and (3) the ability to resist water flows—determined by organic matter content and absorption rates.[22] The importance of organic matter in predicting pesticide leaching is clear in EPIC, where the prediction requires, among other factors, an organic carbon absorption coefficient.[23]

Global climate change: Soils store atmospheric carbon

Soil is dark, crumbly, and spongy because of the carbon in humus—the decomposed part of organic matter. Worldwide, the amount of carbon in humus is two to three times the amount of carbon in atmospheric carbon dioxide (Figure 6). Soils serve as either a source or sink of carbon, depending on climatic conditions and how the soils are managed. Production practices that degrade soil by exhausting organic carbon are responsible for releasing carbon into the atmosphere. Lal and Pierce estimate that if 1 percent of the organic carbon stored in predominately tropical soils is decomposed by soil microorganisms each year, 141 billion tons of carbon

Source: Koplin, D.W., J.E. Barbash, and R.J. Gilliom. 1998. "Occurrence of Pesticides in Shallow Groundwater of the United States: Initial Results from the National Water-Quality Assessment Program." *Environmental Science & Technology* 32: 558-566.

FIGURE 5 Detection frequencies for four herbicides in shallow groundwater sites

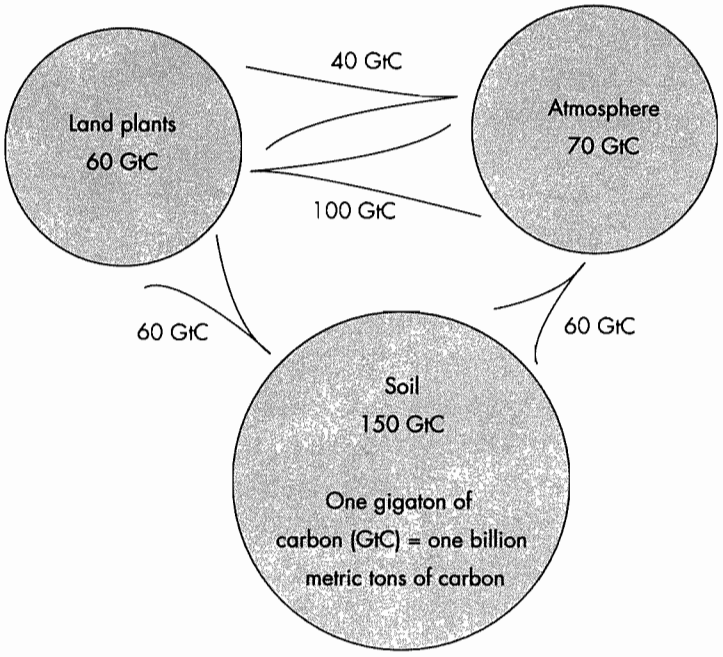


Abstract: Groundwater land-use studies, designed to sample recently recharged groundwater beneath specific land-use and hydrogeological settings, are a major part of the U.S. Geological Survey's National Water-Quality Assessment project. Pesticides were detected in 54.4 percent of the 1034 shallow groundwater sites sampled in agricultural and urban settings across the U.S. The compounds most frequently detected were the herbicides atrazine, simazine, metolachlor, and prometon, along with atrazine's degradation product, deethylatrazine. The above graph shows how often the herbicides were detected in all sampling sites, in sites devoted mostly to corn, wheat, orchards or vineyards, and in urban sites. Current research has yet to document the exact link between these findings and soil-quality attributes.

will be released into the atmosphere—a figure about 25 times greater than the 5.66 billion tons of carbon produced each year by the combustion of fossil fuels, or a hundred times greater than the 1 billion to 2 billion tons emitted from deforestation.[24] To make matters worse, potential global warming generated by greenhouse gases may accelerate the rate of carbon emissions from the soil. A 1 degree increase in temperature could increase carbon dioxide emissions from the soil by another billion tons per year.[25]

Public and private research has recently begun to document the links between soil quality, farming practices, and carbon retention in the soil. A recent economic study suggests that policies aimed at reducing erosion, rather than removing land from agricultural production, are the most effective means of preventing the loss of carbon from soil.[26] One Canadian energy and utility company, TransAlta Corporation, is promoting certain farming practices

FIGURE 6 Carbon flux and the soil



Source:
Volk, T. 1994.
"The Soil's Breath."
Natural History
103 (11): 48-54.

About 60 billion metric tons of carbon enter the soil every year, mostly in the form of fallen plant matter and photosynthesized "food" sent from the leaves of plants down to the roots. (A small influx from animals is omitted from the diagram.) An approximately equal amount exits annually in the form of carbon dioxide as soil organisms respire.

as part of its greenhouse gas offset program. TransAlta has established the Saskatchewan Soil Enhancement Project (SSEP), which promotes "low-disturbance direct seeding," a no-till practice that may improve farmers' productivity and lower input costs, while storing atmospheric carbon in the soil. TransAlta expects the SSEP to sequester up to 27 percent of its projected increase in carbon dioxide emissions through 2000.[27]

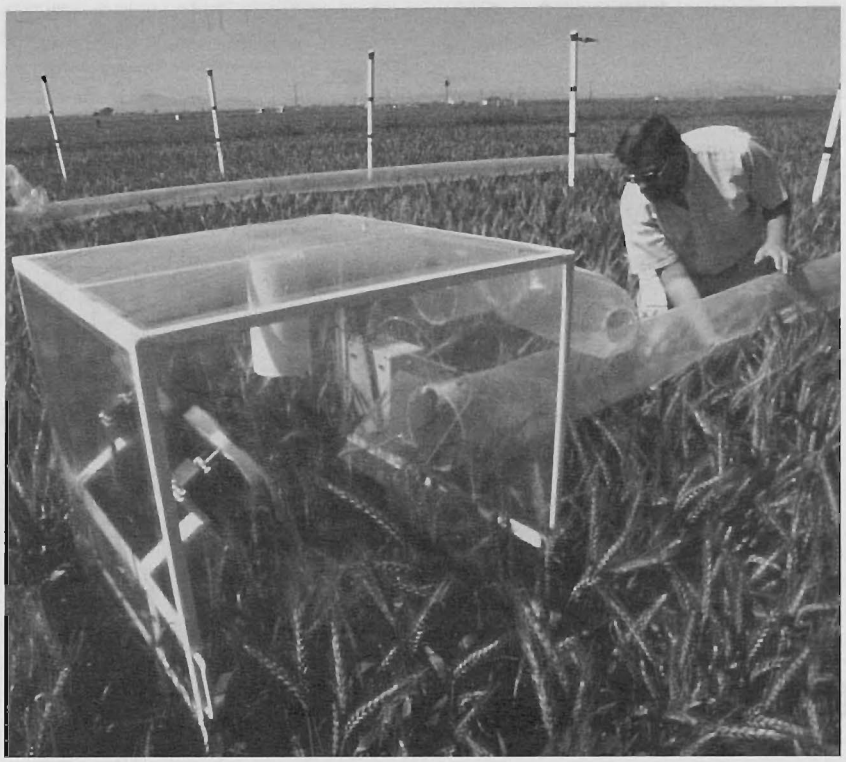
Researchers suggest that carbon sequestration may be particularly effective in tropical and sub-tropical soils.[28] Soils in these regions are somewhat degraded and, therefore, improved farming systems may lead to substantial increases in stored carbon. On the other hand, soils in the temperate zone—which includes most of the U.S.—are generally at or near their equilibrium values of organic carbon, so improved farming practices in this region may lead to smaller increases in stored carbon.[29] Nonetheless, research shows that tillage, cover cropping, and crop-residue practices can increase soil carbon even in temperate-zone soils, particularly in carbon-depleted soils.[30]

Air pollution: Soils as airborne particulates

Wind erosion problems, which are especially acute in arid regions, can cause severe air-quality problems. Blowing dust from fallow fields has

To see how crops will grow when carbon dioxide becomes more prevalent, scientists pump large quantities of carbon dioxide into field chambers like the one pictured above.

Photo courtesy of the Agricultural Research Service, USDA.



been identified as the cause of many respiratory problems.[31] In fact, the U.S. Environmental Protection Agency (EPA) has recently proposed new air-quality standards to regulate extra-small particulates emitted from industrial combustion and vehicle exhaust. These and coarser particulates, which can be the result of wind erosion from agricultural fields, are thought to aggravate asthma and similar ills.

Ever since the Dust Bowl smothered a four-state region in the mid-1930s, the U.S. Department of Agriculture (USDA) has been working with farmers to control wind erosion. Huge dust storms like those in the Dust Bowl may be a thing of the past, but according to the USDA, mini-dust storms occur regularly when the wind blows across the Great Plains and other scattered locations throughout the country.[32]

One observable link between agriculture and air quality can be found by examining the list of regions that fail to meet EPA's particulate matter air quality standards. As of May 9, 1997, four of the six areas that "seriously" failed to meet those standards are regions of large agricultural production in California or Washington State: the Columbia Basin in south-central Washington, and the Coachella, Owens, and San Joaquin valleys in California. Five other California areas, including the Imperial Valley and Sacramento County, are listed as areas that "moderately" failed to meet the particulate-matter standards.[33]

Management practices—including covering the soil with vegetation, reducing the intensity of tillage, and installing wind breaks—are the

On the Columbia Plateau, dust stirred up by field tillage shows the potential for wind-blown particulate emissions from dry, susceptible soils. Tillage dust generally is not considered as serious as wind erosion.

Photo courtesy of the Agricultural Research Service, USDA.

primary mechanisms for preventing wind erosion.[34] Nonetheless, organic matter content and other soil properties play a role, all else equal, in reducing wind erosion. Soil organic matter is crucial in binding soil particles into stable aggregates and therefore serves to keep the soil from being subjected to the eroding forces exerted by winds.[35] Moisture content is another soil property that affects wind erosion.[36] In short, a moist, well-aggregated soil is not easily eroded by wind.

Food safety: Healthy soils reduce the need for pesticides

Federal law regulates the levels of pesticide residues that are allowable in fresh and processed foods. The Food Quality Protection Act of 1996 placed very strict residue limits on pesticides in the diets of infants and children. Although the risks from exposure to pesticides may be greatest for the farm workers who must handle them, everyone eating food grown with chemical pesticides is potentially at risk. Residue limits may reduce some dietary risks; however, risks to the endocrine and immune systems, to particularly sensitive members of the population, and from chemical interactions and synergistic effects may not be addressed fully by current regulations.[37]

Soil can play two roles in reducing dietary risks from pesticides. First, it can act to filter harmful compounds. Although the soil's filtering may do little good if pesticides are sprayed directly on produce, it does help to keep pesticides out of groundwater. Second, farm practices that improve soil quality may reduce or eliminate the need for chemical pesticides by strengthening soil microbial communities, which in turn produce further benefits:[38]

At the Walnut Creek watershed in central Iowa, a technician samples surface runoff and water flowing out of tile lines under farm fields to measure pesticide and nitrate levels.

Photo courtesy of the Agricultural Research Service, USDA.

- healthy soil microbial communities can suppress root diseases;
- soil microbes in the root zone play a direct role in making soil phosphorus and other essential elements available to the roots;
- soil microbes can strengthen plant defense systems so plants can better withstand attacks from pests; and
- healthy soils allow certain beneficial insects, microbes, and other organisms to out-compete or attack pest organisms.

Pesticide-free farming practices and soil-quality improvements may not completely reduce the dietary risks from pesticide exposure. A recent study on the sources of pesticide residues showed that current pesticide uses in farming production are only one of four sources of exposure.[39] The other three sources—pesticide residues on imported produce, pesticide residues from post-harvest chemicals, and persistent pesticides long since stopped or banned—make up a significant portion of exposure risks.

Biodiversity: Farm practices affect diversity on and off the farm

Agricultural practices can have a profound effect on biodiversity.[40] Intensive agricultural practices negatively affect biodiversity on and off the farm by disrupting soil structure, causing erosion, requiring high levels of chemical inputs, simplifying the landscape, or relying on monocultures. Alternative farming practices, on the other hand, can help maintain biodiversity by creating the proper conditions for beneficial organisms and natural enemies of pests to multiply. Less intensive practices also encourage the survival and proliferation of non-pest insects and organisms that would be killed by conventional methods. For example, no-till cropping has been shown to promote greater biodiversity of beneficial nematodes, mites, ground beetles, spiders, and earthworms.[41]

Alternative practices can also contribute to the conservation of nonagricultural biodiversity. For example, lower levels of pesticides reduce nonpoint-source pollution and its harmful downstream effects. Diverse crop rotations create diverse habitats for indigenous species. Crop covers and buffer and filter strips near waterways benefit riparian and aquatic ecosystems.

Despite these potential benefits, little research has been done to quantify the positive relationships among alternative practices, soil quality, and biodiversity. To date, biodiversity programs have centered on plants, animals, and insects, and little attention has been given to the beneficial or pathogenic organisms that live below ground.[42] Effective management of the biota of agro-ecosystems, which occupy about 30 percent of the earth's surface, is critical to the conservation and viability of our biosphere.

3 *What is Meant by the Term 'Soil Quality'?*

IN 1995, THE SOIL SCIENCE SOCIETY OF AMERICA adopted a new definition of soil quality. According to the Society:[43]

> *"Soil quality is the capacity of a soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation."*

Along these lines, soil quality can be conceptualized as integrating and balancing three major functional components of the soil: sustained biological productivity; environmental quality; and plant, animal, and human health.

Because soil quality is characterized by three main functions, the definition implies that soils do more than just promote plant growth. This definitional emphasis on the soil's multiple functions represents a big change in the thinking of soil scientists, who historically associated soil quality only with plant or crop production. The broadening of the definition highlights the emphasis that many scientists are now placing on the benefits of good soil quality off the farm, or "downstream."

Implicit in the definition is the notion of a package of benefits accruing from healthy soils. Accordingly, recent thinking about maintaining soil quality involves:

- promoting crop yields,
- reducing erosion,
- maintaining water quality,
- regulating water and air quantity and sediment runoff,
- buffering global climate changes by storing or "sequestering" carbon,
- stemming excessive air pollution,
- ensuring food safety, and
- enhancing biodiversity.

Accordingly, when soil quality is maintained, many soil scientists now believe that the public receives not just one but all of these benefits. If this hypothesis proves correct, it is this package of suggested key benefits that makes healthy soils such a potentially important resource in the environmental and food-safety policy arena. This hypothesis also implicitly increases the importance of understanding how agricultural practices affect soil quality.

Soil quality is linked with management practices

In *The Soul of Soil,* Grace Gershuny and Joseph Smillie describe the soil as a living system:[44]

> *"[T]o understand soil is to be aware of how everything affects and is affected by it. We are all part of the soil ecosystem."*

As the Gershuny and Smillie quote implies, the soil is the mediator among farming practices, agricultural chemicals, and the environment. The soil affects us by directly or indirectly affecting food production, human health, food safety, surface water and groundwater quality, global climate, air quality, and our ability to maintain biodiversity. We affect the soil by tillage, fertilizer, pesticide, and residue-management choices. In other words, we have a dual relationship with soil quality: both cause and effect.

This dual relationship creates at least one area of potential confusion: separating the ability of a soil to provide various functions from the role that agricultural management practices play in determining soil functions. Management practices such as no-till cropping directly affect soil quality; they also directly affect functional outcomes like crop growth or chemical runoff. The confusion, however, can be resolved if the dynamic relationship between management practices and soil quality is clearly spelled out.

Currently-measured soil quality (sq) is a function of past years' management practices (m), as well as soil parent material (p) and all past

years' weather (w). This relationship can be written symbolically with the following equation:

$$sq_t = f_t(m_{-t}, p, w_{-t}),$$

where $f_t(\,)$ is an abstract function representing current production of soil quality, sq subscripted by t represents soil quality at time t (the current time period), and m and w subscripted by $-t$ represent values of management and weather prior to time t. The parent material variable has no subscript because it is constant over time. If we look towards the future, tomorrow's soil quality is a function of today's management practices and weather, past management practices and weather, and parent material. This relationship can be written symbolically as:

$$sq_{t+1} = f_{t+1}(m_t, m_{-t}, w_t, w_{-t}, p),$$

where sq subscripted by $t+1$ represents future soil quality, and m and w subscripted by t now represent current values of management and weather. But notice that three of the variables—namely, m_{-t}, p, and w_{-t} —in the abstract function $f_{t+1}(\,)$ are the same as those in $f_t(\,)$ which defines sq_t. Therefore, we can replace these variables by sq_t and rewrite sq_{t+1} as:

$$sq_{t+1} = f'_{t+1}(sq_t, m_t, w_t).$$

This rewritten equation says that future soil quality is a function of present soil quality, present management practices, and present weather.

Another way of viewing this dynamic relationship between management practices and soil quality starts by considering soil outcomes, such as crop production (c) and chemical runoff (r). These outcomes are a function of three current inputs: current weather, current management practices, and current soil quality. Again these relationships can be written symbolically as:

$$c_{t+1} = g_{t+1}(sq_t, m_t, w_t), \text{ and}$$
$$r_{t+1} = h_{t+1}(sq_t, m_t, w_t),$$

where $g_{t+1}(\,)$ and $h_{t+1}(\,)$ are abstract functions representing the production of crops and chemical runoff.

As an example, consider three implications from these dynamic relationships about promoting crop production and preventing chemical runoff, the two functional outcomes mentioned above:

1. Under identical management practices and weather, a high-quality soil achieves higher yields and prevents more runoff than a low-quality soil.
2. A low-quality soil could have higher yields and less runoff than a high-quality soil, depending on choice of management practices.
3. Soil quality can be improved over time with the appropriate choice of management practices.

These implications should make clear that soil quality and soil-management practices are inextricably linked, yet different concepts.

4 *What We Do and Don't Yet Know About Soil Quality*

IN 1957 SECRETARY OF AGRICULTURE Ezra Taft Benson wrote:[45]

> *"The management of soils is among the oldest of arts, but none is changing more rapidly than it. We know more about taking care of soil than our fathers and grandfathers did. There is much more that we should know."*

The same statement could easily be made today. We know a lot about soil fertility and soil productivity, and we know that agriculture inadvertently contributes to environmental-quality problems. Yet, we don't know how soil health is best measured. And we also don't know how changing levels of soil health are predictably related to changes in environmental quality.

What we know about soil quality

SOIL EROSION AND SOIL PRODUCTIVITY. First and foremost, we know how to manage the soil for high levels of crop production. We also know how to keep soil erosion from interfering with productivity. This is not to say, however, that management and technology improvements have made soil-erosion problems disappear. For instance, Walker and Young suggest that soil erosion may become an increasingly serious economic problem in the future if technological advances in agriculture fail to account

for erosion.[46] At present, however, the USDA estimates that the amount of cropland still requiring conservation treatment to maintain productivity declined by nearly 25 percent between 1982 and 1992.[47] Using well-established models such as EPIC (Endnote 9), we have a strong sense of what factors—e.g., soil conditions, weather, and management practices—influence soil erosion and soil productivity. In other words, we have developed a predictive ability relating soil erosion and productivity.

SOIL PROPERTIES. We also know how individual soil properties relate to overall soil health, thereby serving as crude indicators of soil quality. Several researchers have suggested that overall soil health cannot be accurately described without measuring a minimum number of specific individual soil properties.[48] Included in many researchers' lists are soil organic matter, aggregate stability, water-holding capacity, biological activity, bulk density, pH, aeration, and the water infiltration rate. Despite a lack of consensus on which individual soil properties must be included in this so-called minimum data set, or which soil properties are most important in describing soil health, there is strong consensus on how individual properties change under various farming practices. In other words, we know how management practices and weather alter individual soil properties.

What we don't know about soil quality

NATIONAL SOIL-QUALITY ASSESSMENT. Presently, scientists are not yet able to categorize the status of our nation's soil in terms of soil quality, broadly defined. Soil data collected by federal agencies such as the USDA's Natural Resources Conservation Service (formerly the Soil Conservation Service) pertain almost exclusively to soil erosion.[49] Indicators for soil quality and for the various production, ecosystem, and environmental effects that stem from soil quality have not been developed.[50] Instead, the National Resources Inventory covers, among other items, land use, conservation treatments needed, and erodibility.

A SCORECARD OR SOIL-QUALITY INDEX. Currently, scientists are attempting to quantify and monitor soil quality by integrating their knowledge of individual soil properties into a soil-quality index. But soil characteristics vary greatly from field to field and region to region, and they change over time as farming practices change. Capturing the temporal and spatial variability of the soil in an integrated index or scorecard that reflects the soil's inherent attributes and its capacity to perform, if feasible, will be a controversial and difficult task. Yet, several benefits could emerge (Box 3). Farmers could use a soil-quality index to evaluate the long-term effects of contemporary farming practices on the soil and, ultimately, to calculate the economic return from investing in soil quality. Researchers and policy

BOX 3 How soil-quality indicators or indices might be used

1. Assess the impact of management practices on soil degradation and soil conservation.
2. Assess the accrued benefits on highly erodible lands under the Conservation Reserve Program (CRP), first authorized by the 1985 Farm Bill.
3. Provide a basis for eligibility in the CRP and cost-sharing programs such as the Environmental Quality Incentives Program.
4. Establish the loan value and price of land.
5. Establish a more realistic base for tax assessment and tax credit.
6. Assess the impact of agricultural management practices on human and animal health.
7. Assess the impact of agricultural management practices on food safety and quality.
8. Assess the impact of agricultural management practices on water and air quality.
9. Provide information for simulating and predicting environmental change.
10. Provide an improved basis for land productivity and capability classification.

Source: Parr, J.F., R.I. Papendick, S.B. Hornick, and R.E. Meyer. 1992. "Soil Quality: Attributes and Relationship to Alternative and Sustainable Agriculture." *American Journal of Alternative Agriculture* 7 (1/2): 5-11.

makers could use this kind of index in setting research priorities. They could also use a soil-quality index to document changes in the soil resource base and to predict how soil-quality changes affect water and air quality, as well as food safety.

PREDICTABILITY. One of the most important priorities in erosion and soil conservation research was the development of a mathematical model for simulating erosion, crop production, and related processes. In 1981, a team from the USDA began developing EPIC, a physical process model that can simulate long-term erosion given inputs on weather, crops, tillage, and soil parameters. EPIC built upon previous models such as the universal soil loss equation (USLE), which was used for years to predict erosion and help estimate the impact of erosion on crop yields. In general, studies based on these models show that estimated yield losses from erosion in the U.S. would be less than 10 percent over the next 100 years.[51]

Although EPIC and other process models can sometimes help in predicting chemical runoff and leaching, their development was not based on broad notions of soil quality. Rather, they were developed with only one of the soil's functions in mind: promoting plant growth. The models do not provide information about soil microbial communities or the biological component of the soil, nor do they examine how other forms of soil degradation, such as soil compaction, might adversely affect crop productivity.[52] Given that process models such as EPIC cannot tell us how soil-quality improvements affect buffering capacity or air quality, and cannot examine

the impacts of a wide range of soil-quality changes on productivity, the need for models that reflect all of soil's functions is clear. Such models could provide key information that a farmer or policy maker could use for evaluating alternative farming practices and setting research and policy priorities.

SPATIAL VARIABILITY. Models such as EPIC, for example, consider only a relatively small drainage area (one hectare), assume the land to have identical quality throughout the drainage area, and fail to include information on soil ecology. As new practitioners of precision agriculture are finding out, the land in even a single field is extremely heterogeneous—physically, chemically, or biologically. We need more information on what this spatial variability means regarding the design of sampling for soil-quality assessments. In its absence, we are unable to predict adequately how the adoption of farming practices designed to enhance soil health will affect crop growth and other soil functions.

SOIL ECOLOGY. Among soil quality's three components—chemical, physical, and biological—the biological component is the most difficult to quantify.[53] Microbial organisms are directly involved in nutrient cycling, maintenance of soil structure, and pest abatement, yet it has been difficult for scientists to relate particular species to particular soil functions.[54] The science of soil microbiology is often inexact, with many assumptions based on information derived from the aboveground ecology of plants and animals. In short, there has been little research done "to quantify the beneficial relationships between microbial diversity, soil functioning and plant quality, and ecosystem sustainability."[55]

OPTIMAL MANAGEMENT FOR SOIL QUALITY. One of the most important tasks yet to be accomplished with regard to soil quality is to differentiate empirically soil quality's impact on productivity from its impact on its other soil functions (such as regulating water and buffering environmental impacts). Throughout this paper is an underlying hypothesis: if soil quality is improved, substantial benefits accrue. This hypothesis assumes, however, that soil quality is not already at an optimal level—which in turn leads to the question of what an optimal level might be.

For some individual farmers, it is unlikely that soil quality is at an optimal level because they lack knowledge and resources, are uninformed about the most effective management practices for improving soil quality, or are constrained by short-term pressures such as lease agreements for rented land. But even if educational and other outreach policies helped these farmers to achieve soil quality that they would consider optimal, this "private" level of soil quality still might not be optimal for society at large—

BOX 4 Soil-quality success story: Stahlbush Island Farms

Bill and Karla Chambers
Corvallis, Oregon

Twelve years ago, Stahlbush Island Farms was a very conventional farm, using chemical-intensive production methods and producing only two crops. That's when Bill and Karla Chambers started working toward a new goal: to grow and process the highest quality food products available in the market place, while simultaneously improving their most important resources—soil and water. Today, after ten years of transition, the farm is highly diversified, uses only a few commercial chemicals, and does so sparingly. Perhaps most importantly, the farm is achieving higher yields, and has more than doubled in size.

The Chambers take full advantage of sustainable practices like diversified crop rotations and cover crops. No crop is grown on the same ground two years in a row and the rotation takes a minimum of seven years to complete. Cover crops (such as crimson clover, Austrian peas, fava beans, Micah barley, Manida oats, wheat, annual rye grass, and common vetch) are planted following harvest and worked back into the soil prior to planting spring row crops. The diverse rotation and cover crops help break disease and insect cycles, control weeds, generate soil nitrogen, and improve overall soil health. The basic tenet underlying the development of these practices is that the soil is far more complex than merely a medium for holding food nutrients just long enough for plants to take up these nutrients.

The next generation can expect undiminished and hopefully improved natural resources, thanks the Chambers' practices. They have done extensive work with Oregon State University to understand nitrogen movement in the soil. Their goal is to totally eliminate any nitrogen leaching into groundwater. They also have totally eliminated the use of herbicides, fungicides, and insecticides in growing sweet corn, squash, pumpkin, and green beans, and cut the use of pesticides by 85 percent on broccoli, strawberries, and spinach.

Of course, while the use of some inputs have decreased, others have increased. Labor, management, capital, and technology all are factors whose use increased as the shift took place from a conventional to a sustainable farming system. Stahlbush's experience may not be a complete recipe for farms operating under different conditions, but it may offer some glimpses of possibilities for the future.

Source: Bill and Karla Chambers, personal communication, October 3, 1997. See also http://www.stahlbush.com.

that is, the level of soil quality may not be high enough to generate certain desired levels of environmental and other societal benefits. However, the question of whether society actually wants a higher level of soil quality than does an individual farmer has not yet been answered.

The question can be rephrased as a comparison of empirically calculated soil-quality indexes: Should a soil-quality index, defined broadly, differ from a soil-quality index defined only in terms of productivity? If the two indexes do not differ, then the underlying soil attributes (such as organic matter or bulk density) equivalently characterize productivity and the other soil functions. If this were the case, then the level of soil quality chosen by the farmer (privately optimal) would be the same level of soil quality chosen by society (socially optimal). While we do not have

comprehensive evidence on this divergence, the presence of significant off-site costs (such as those from sediment) suggests a divergence would be expected in some instances at least. If the two indexes do differ, society may need to provide additional incentives to convince farmers to improve their soil quality. Scientists currently attempting to construct soil-quality indexes, therefore, must consider how their broad indexes differ from a standard soil-productivity index.

ASSESSMENT AND ECONOMIC ACCOUNTING OF SOIL QUALITY. One of the most important knowledge gaps is the economic valuation of improved soil quality and the costs of attaining it. To account for all possible costs and benefits, the economics of soil quality must be based on the soil's multiple roles in the entire ecosystem. Some costs and benefits are clear, but others are not, and many will prove difficult to quantify.

Perhaps the most obvious and easiest kind of economic benefit to quantify is an increase in productivity. This type of economic assessment has long been conducted for soil-erosion prevention, but a broader notion of soil quality may uncover productivity benefits that have previously been masked by efforts that focused only on topsoil depth and erosion. For instance, there appear to be productivity benefits from reduced compaction of soil or increased levels of organic matter over and above those from preventing soil erosion.[56] Insufficient knowledge of these relationships may have kept the costs of discovery high.

Environmental benefits from improved soil quality will be much more difficult to measure in monetary terms. For example, a predictable link between soil quality and, say, surface-water quality has not been documented. And even if this link were documented, the value of improved surface-water quality depends on, among other factors, how it affects commercial and recreational fishing, commercial and recreational navigation, aquatic ecosystems, and municipal and industrial water treatment. The net value of improved drinking-water quality depends on the costs of getting clean water and the benefits of improved human health. The list goes on for improved air quality, improved flood control and erosion prevention, and mitigated climate change. Even if these benefits were documented in a predictable fashion, few of them are measured directly in the marketplace, and as a result we have no way of knowing if one individual places a higher value on some or all of these benefits than another might. The absence of market prices makes it very difficult to calculate the monetary benefits to society of the entire package of benefits. Fortunately, economists and others have made substantial progress in placing dollar amounts on these "non-market benefits." For example, preventing sediment damages could create annual benefits valued at $2 to $8 billion for users of the nation's waterways .[57]

Improving soil quality requires an increased understanding of the soil; unfortunately, this knowledge is not free. We might call this economic cost the price of investing in human capital. Building this human capital will require an immense technology transfer from scientists and government agencies to farmers. The Natural Resources Conservation Service may not be fully prepared for this transfer, but it has begun to position itself for this new emphasis. For instance, it has begun distributing one-page fact sheets that describe various aspects of soil quality. (The fact sheets are available on the Web at *www.statlab.iastate.edu/survey/SQI/sqiinfo.shtml.*) While these and more extensive attempts at educational outreach and technology transfer may appear expensive in the short run, they could lead to a more durable, low-cost, and long-term solution than current temporary cost-sharing plans for conservation practices or land retirements.

Another cost of emphasizing soil quality involves the transition period when the soil ecology is reacting to a change in management practices. During this period, farmers may have invested in costly technologies (such as planting grass waterways, installing windbreaks, shifting to minimum tillage and no-till, or planting winter cover crops), yet they may experience delays before the quality of their soil improves. If this is the case, the production and environmental benefits from improved soil quality will appear only well after the costs of these practices are incurred. For example, the time lag associated with the switch from conventional farming practices to more ecologically based farming practices, including organic agriculture, has been well documented.[58] Soil-quality policy, therefore, may require financial incentives to farmers as they move through the transition. Again, the necessary payments may yield a long-term stream of productivity and environmental improvements, yet the upfront costs may be significant.

5 *Are We Ready for Soil-Quality Policy?*

MANY SOIL SCIENTISTS, agronomists, and other scholars are convinced that our soils are a precious natural resource, just like the air we breathe and water we drink. Like clean air and water, improved soil quality is believed to carry direct benefits to the surrounding environment. Unlike air and water, however, we have no established consensus on how to predict these direct benefits or even how to measure soil-quality improvements (Box 5). Therefore, while the potential benefits of improved soil quality are enticing, these and other aspects of soil quality present formidable obstacles that make a soil-quality policy (similar to air- or water-quality policies) infeasible for now.

For instance, soil quality is not entirely equivalent to air and water quality. For human health, soil quality is an intermediate outcome, unlike ambient air and water quality. It is easier for scientists to establish ambient air- and water-quality standards because their impact on human health is direct; the impact of soil-quality standards on human health is indirect. While the soil affects our air, water, and food, it is one step removed from human health. Moreover, our science has not been able to establish predictable links between soil quality and human health.

Before soil quality can become a focus of national policy, research must address the needs of several key audiences. Farmers, for instance, will need to know how much return they can expect from investing in soil quality. Others will need to know the expected health and environmental benefits from enhanced soil quality. Policy makers, in particular, will need to know whether soil degradation is a social problem, and if it is, where

BOX 5 Strategies to promote soil quality

Although scientists do not yet agree on exactly how to quantify soil quality, they have a reasonably good idea of how soil quality can be improved. Nature itself provides a good model, experts suggest. Aspects of natural ecosystems that make them efficient at nutrient recycling and soil conservation include:*

- maintenance of year-round cover, which reduces water and wind erosion;
- some proportion of the plant population as perennials, which aid nutrient absorption by providing living roots year-round;
- soil nutrients associated with organic matter or soil biomass;
- gradual mixing of soil layers through the work of soil organisms; and
- high levels of plant and animal diversity, which lead to a greater resiliency during stress conditions.

Compared to natural ecosystems, agricultural systems appear to have several aspects that are antagonistic to maintaining soil quality. Nevertheless, practitioners generally agree that a number of practices can help maintain or improve soil quality, in part by mimicking natural systems:**

- crop-residue and organic-matter management,
- animal manure integration,
- cover cropping,
- crop rotations,
- reduced tillage or no-till,
- composts,
- erosion-prevention practices, and
- ecologically based integrated pest management.

Current economic research shows that these practices, under many circumstances, can improve farmers' net returns in addition to improving soil quality. As more research is devoted to soil quality, we can expect the profitability of these and other practices to improve.

Sources:
*Doran, J.W., M. Sarrantonio, and R. Janke. 1994. "Strategies to Promote Soil Quality and Health." In *Soil Biota: Management in Sustainable Farming Systems*. C.E. Parkhurst, B.M. Doube, V.V.S.R. Gupta, and P.R. Grace, eds. CSIRO, Australia.

**Magdoff, Fred. 1992. *Building Soils for Better Crops: Organic Matter Management*. Lincoln, NE: University of Nebraska Press.

and how to target policy. At this writing, further research into the measurement of the economic and environmental benefits from soil-quality improvements and the costs of such investments is key to providing a solid base for a public policy that addresses our soil resources.

Despite the knowledge gaps and other obstacles to a comprehensive soil-quality policy, it's not hard to identify policy areas where further soil-quality research could play an important role.

Policy requiring soil-quality research

IDENTIFY PROBLEM AREAS AND PROBLEM FARMS. The National Research Council and the Office of Technology Assessment have strongly

emphasized the importance of targeting regions where soil degradation and water pollution are most severe.[59] Federal, state, and local governments have already identified, at least implicitly, many priority areas. But these priority areas are identified for different purposes and under different programs. Some emphasize agricultural purposes; others emphasize environmental purposes. With a better understanding of soil quality and its potential for providing both agricultural and environmental benefits, the public sector could establish consistent targets by placing the emphasis squarely on soil quality.

LEVERAGE PRIVATE SECTOR APPROACHES FOR CARBON SEQUESTRATION. Many public utilities and energy companies are attempting to address problems of increased levels of atmospheric carbon by planting trees as part of their overall greenhouse-gas offset programs. At this writing, only one company—Canada's TransAlta Corporation—appears to have a project up and running that successfully promotes carbon sequestration in the soil. TransAlta's program should be evaluated and studied as a possible model for other energy companies.

INCLUDE SOIL QUALITY IN THE INITIATIVE FOR FUTURE AGRICULTURE AND FOOD SYSTEMS. Established by Congress in 1998, this new agricultural research program will direct additional federal funds to solve priority problems facing farmers and other participants in the food system. One of the areas cited by Congress for emphasis is natural resource management, including precision agriculture. Research to understand and measure the environmental and productivity benefits of improved soil quality falls squarely within the natural resources management area and also applies to improved long-term farm profitability, another program priority. To ensure that the Initiative considers the full spectrum of soil quality benefits, grant proposal reviewers should be briefed on the broad definitions of soil quality.

SET RESEARCH PRIORITIES. The National Research Council suggests that two types of research should be high priorities for USDA and EPA: (1) research on the development and implementation of cropping systems and other technologies designed both to be profitable and to protect and improve soil and water quality, and (2) research directed towards identifying factors that influence farmers' adoption of these technologies. Several technologies emerging on the horizon—such as precision agriculture, biotechnology, and no-till—have the potential to meet the dual objectives of enhancing both profitability and environmental quality. If broadly defined soil quality is not emphasized during the development of these technologies, they run the risk of improving only farmers' bottom

A technician measures the depth of a pool on the upstream side of a V-notch dam to determine streamflow, which is affected by soil infiltration and runoff.

Photo courtesy of the Agricultural Research Service, USDA.

lines in the short run, but not soil and environmental quality. One way of encouraging technologies that meet the dual objectives is to add society's preferences for environmental quality into the research and development process. Soil quality, broadly defined, provides a vehicle for this addition.

INCORPORATE SOIL QUALITY INTO EQIP. The Environmental Quality Incentives Program (EQIP) is basically a cost-sharing program that helps farmers offset the cost of environmental or conservation practices. Projects that potentially qualify under EQIP are evaluated on the basis of their costs and their benefits to the environment. If the links between soil quality and environmental quality were adequately quantified, soil-quality indicators could be incorporated into the EQIP project evaluation process.

INCORPORATE SOIL QUALITY INTO FARM PRESERVATION DECISIONS. Many states have programs that permanently preserve farmlands by paying farmers the difference between the market value and the agricultural value of their farms in exchange for any future development rights to the land. States facing a backlog in these programs often decide which farms successfully qualify, in part, on the basis of soil fertility. With a better understanding of soil quality, preservation decisions could be based on broadly defined soil quality, not narrowly defined soil fertility, if they are to generate the most benefits to society.

INCLUDE SOIL QUALITY IN THE CRP'S ENVIRONMENTAL BENEFITS INDEX. The Conservation Reserve Program (CRP) pays farmers to take environmentally sensitive land out of production, contingent on the estimated cost. Currently the land is evaluated using an "environmental benefits index," which rates the potential effect of "retiring" the land with regard to erosion, water quality, and other environmental aspects. It is not clear that the current environmental benefits index reflects the full range of benefits that accrue from healthy soils. Soil quality, adequately quantified, could be incorporated into the environmental benefits index to help prioritize land targeted for retirement under the CRP.

CONDUCT MORE R&D ON NO-CHEMICAL OR LOW-CHEMICAL NO-TILL TECHNOLOGIES. No-till technologies are promising in that they lower production costs, control erosion, and increase soil organic matter. However, adoption of no-till technologies often requires increased use of herbicides in the short run and rules out the need for crop rotations in the long run. No-till's long-term impact on soil quality, therefore, is ambiguous: the potentially adverse impacts of monoculture and herbicide use on soil ecology may offset some of the gains from low-disturbance cultivation. If research efforts were targeted to develop no-till techniques that involved crop rotations and decreased use of herbicides, these technologies could unambiguously provide economic and environmental benefits.

DEVELOP INSTITUTIONAL PROGRAMS TO REDUCE RISK WHILE INVESTING IN SOIL QUALITY. There is a widespread shortage of the expertise and general know-how required to profitably substitute improved soil quality for chemical inputs. If successful, farmers who improve their soils benefit themselves and the public who live in the same watershed or breathe the same air. It is difficult, however, to apply the expertise of these successful farmers to the vastly different situations faced by other farmers. Further, as noted previously, farmers who choose to invest in soil quality may not see an immediate payoff—there is likely to be a lag period while the soil goes through a transition. Long-term policy should address the risks incurred while investing in soil quality. One option is to structure "green payments"—financial incentives to promote environmentally friendly farming practices—as a way of offsetting some of this risk, especially during a transition period.

REWRITE K-12 AND COLLEGE EDUCATIONAL MATERIALS ON SOIL QUALITY. Much of the educational material currently available on soil quality deals with erosion and soil productivity. As previously discussed, soil quality encompasses much more than these two issues. The concept of

soil quality must include biological and ecological elements, not just physical and chemical ones. A scientific consensus is emerging that soil quality is a root element of air quality, water quality, and total environmental health. Teaching this broad concept of soil quality in primary and secondary schools, as well as in institutions of higher learning, would not only lead to a better understanding of society's environmental and public health problems, but would help build a broader constituency for soil quality.

CREATE A NATIONAL FUND FOR SOIL QUALITY RESEARCH TO UNDERWRITE LONG-TERM, MULTIDISCIPLINARY RESEARCH AND EDUCATION. Much research is needed to support effective and appropriate policy on soil quality. Given the current budgetary climate in the United States, one way of promoting soil quality research would be to create a separate national fund. Targeting research on soil quality would ensure that the needed research gets done. This research should bring together all relevant disciplines: physical, biological, ecological and social sciences. Ultimately, this type of research would place soil quality on the same footing as air and water quality.

At the root of all these suggestions are the notions—emphasized throughout this paper—that soil, air, and water quality are inextricably linked, and that effective environmental and public health policy should not ignore soil quality. Indeed, the broad definition of soil quality set forth by the Soil Science Society of America lays the foundation for these linkages. When backed by adequate research, the initiatives listed above may be considered possible first steps toward giving soil quality equal footing with air and water quality, and thereby fully integrating environmental policy.

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