A n appreciation of the dynamism of the links between soil resources and society provides a platform for examining food security over the next 50 years. Interventions to reverse declining trends in food security must recognize the variable resilience and sensitivity of major tropical soil types. In most agroecosystems, declining crop yield is exponentially related to loss of soil quality. For the majority smallholder (subsistence) farmers, investments to reverse degradation are primarily driven by private benefit, socially or financially. “Tragedy of the commons” scenarios can be averted by pragmatic local solutions that help farmers to help themselves.

The UN Food and Agriculture Organization (FAO) defines food security as “when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life” (1). Currently, more than a billion people have no food security. About 60 percent of rural communities in the tropics and subtropics are persistently affected by decline in household food production, with sub-Saharan Africa and parts of Latin America, the Caribbean, and Central Asia suffering worst (2–4). Technology, such as irrigation and improved crop varieties, has changed the situation for some people, but insecurity still prevails for the poorest and most vulnerable. The 1996 World Food Summit in Rome aimed to cut by half the number of undernourished people in the low-income food deficit countries (5). The target was reaffirmed in 2000 for achievement by 2015 in the Millennium Development Goals (6).

Reviews of techniques to improve soils through conservation and better management are common [e.g., in Central America (7)]. Food security requires policy adjustments in science,
organization of science, and engagement with farmers rather than revolutionary change (see Figure 5). The headline challenges for attaining global food security are political [e.g., conflict over land (8)], climatological [e.g., drought and global warming (9)], or epidemiological [e.g., impact of AIDS/HIV on farm labor (10)]. All too rarely is the underlying and changing quality of the natural resource base advanced as a key determinant of the increasing vulnerability of poor people to food insecurity. So what is the evidence that changing soil quality reduces food production? How may we better intervene to provide food security in the next 50 years?

Soil Quality

Soil quality is "the capacity of a soil to function within land use and ecosystem boundaries, to sustain biological productivity, maintain environmental quality and promote plant, animal and human health" (11, 12). As a concept, it differs from traditional technical approaches that focus solely on productive functions, including soil, water, and chemistry.

Instead, soil quality is a holistic concept that recognizes soil as part of a dynamic and diverse production system with biological, chemical, and physical attributes that relate to the demands of human society (13, 14). Society, in turn, actively adapts soil to its needs, mining it of its nutrients on demand and replenishing these nutrients in times of plenty.

Diverse interactions among soil, its productive output, and society are involved. These interactions include the outcomes of combinations of plant nutrients (15), the complex processes of change in capturing carbon (16),

![Graph showing erosion-yield relationships for a selection of tropical soils](image-url)
and the potential positive effects of soil amendments such as green manure on crop productivity (17, 18).

Assessing soil quality is a major challenge because quality varies spatially and temporally and is affected by management and the use of the soil resource. Integrated biological soil management is now recognized as essential, both for productive efficiency and for maintaining biodiversity (19). For example, traditional forms of conserving biodiversity in Ghana mean protecting at least 54 varieties of yam (Dioscorea spp.) while also managing the soil in sensitive ways that maintain soil-plant relationships. A product of this management is that the natural forest vegetation is kept to protect the climbing yams (20). Soil quality is a concept well understood by local farmers in this forest savanna zone, and new assessment methods stress the importance of adopting a strong farmer perspective (21).

Situations such as these are common throughout smallholder farming in the tropics [e.g., (22)]. Soil management is an intrinsic part of the overall management of biodiversity—now called agrodiversity (23)—and is therefore strategically a component of world development issues such as food security for growing populations and the provision of environmental services (24).

**The Evidence of Impact**

Depletion of soil nutrients—just one indicator of declining soil quality—is a major cause of low per capita food production, especially in Africa. Over the past 30 years, annual nutrient depletion rates for sub-Saharan Africa have amounted to a fertilizer equivalent value of US$4 billion (25). However, ascribing a decline in food production unambiguously to the effects of changing soil quality is difficult because of the complex interactions involved. Yields decline for many reasons, such as excessive off-take of nutrients in crops without replenishment, pests and diseases, weed infestations, and increasing prevalence of climate change–induced drought (26). There is an emerging understanding of the importance of microbial communities for soil health through the use of DNA and RNA methods to determine physical and chemical changes in soil (27). Many soil factors are involved, including soil depth and rooting, available water capacity, soil organic carbon, soil biodiversity, salinity and sodicity, aluminum toxicity, and general acidification.

The Soil Quality Institute has suggested several indicators that relate to yields (28), from which indexing approaches to measure soil quality have been devised (29). One of the main factors that integrate the effects of others is reduction in soil organic carbon (30). But these indicators do not offer a comprehensive measure of the spatial and temporal variability of soils, nor
of the dynamic relationships of soils and the people who work them (31). This lack has led to calls for interdisciplinary studies to understand how soil properties and processes interact within ecosystems (32); how economic utility is affected (33); and how society, culture, and local knowledge are influenced (34). Two topics that have attracted considerable attention for tropical agroecosystems are (i) the effect of declining soil quality on production, and (ii) the rationality and private benefit of farmers’ investments in soil conservation.

The cumulative loss of productivity from soil degradation of virgin land in all agroclimatic zones is estimated to be 5 percent (35). But this estimate hides large differences between zones and the vulnerabilities of some soils in the tropics (36). Since 1984, a series of experiments on major tropical soil types has attempted to determine the relationships between crop yield and cumulative soil loss (37). Results [e.g., (38, 39)] indicate that yield decline follows a curvilinear, negative exponential that holds true for most tropical and many temperate soils (Figure 6). Erosion selectively removes the finer and more fertile fraction, with enrichment ratios of eroded sediments being highest on virgin soil (40). As the soil progressively loses its quality, subsequent erosion has less proportional impact. Although productivity diminishes rapidly in the early stages of erosion, different soils show different degrees of impact after varying amounts of time and prior erosion (41).

Understanding these patterns of yield decline is crucial to determining the implications of changing soil quality on future yields and food security. But can tropical smallholder farmers access the resources to maintain soil quality in the face of these trends?

**Resilience and Sensitivity**

It is important to distinguish the intrinsic susceptibility of the soil to erosion (its *resilience*) from the variable impact of that erosion on yields (its *sensitivity*). These concepts for soil management combine through changing soil quality to affect actual production (Figure 7). Resilience includes the “strength” of the soil or its resistance to shocks such as severe rainstorm events. Sensitivity denotes its fragility or its susceptibility to decline in production per unit amount of degradation (42). Resilience is manifested through specific degradation or erosion rates on different soils subject to the same erosive conditions, whereas sensitivity is a measure of how far the
Change induced in soil quality affects the soil’s productive capability.

A simple matrix (Figure 7) illustrates the possible permutations of resilience and sensitivity for a few tropical soils. The management strategies adopted for different permutations of sensitivity and resilience can thus be related to the capacity of local smallholder farmers to take remedial action. For example, ferralsols (35 percent of the tropics and subtropics) and acrisols (28 percent), typical of humid rainforests and shifting cultivation, have low to very low resilience and moderate sensitivity. Once vegetation is removed, they degrade quickly and irreversibly through intense acidification, increasing free aluminum and phosphorus fixation. Combinations of structures such as terraces and biological measures such as intercropping are the most effective response. Mechanical structures require human and financial resources, especially labor and money, and are out of the reckoning of most subsistence farmers.

Nitosols (3 percent), by contrast, have moderate resilience and low sensitivity. They are typical of highland clay-rich areas, such as Ethiopia and Kenya, and are one of the safest and most fertile soils of the tropics and subtropics, with only minor problems of increased erodibility if organic matter declines.

Biological conservation methods are effective ways to address both erosion rate and fertility decline. They include a wide array of techniques to address both erosion rate and fertility decline. They include a wide array of techniques such as terraces and biological measures such as intercropping.

### Table: Resilience-Sensitivity Matrix for Tropical Soils

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>Resilience</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
<td>Resists erosion well but, if allowed to degrade through poor management, yields and soil quality rapidly decline. Nevertheless, capability can be restored by appropriate land management [Phaeozems]</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>Easy to degrade, with disastrous effects on production—loss of nutrients and plant-available water capacity. Difficult to restore, and should be kept under natural vegetation or forestry [Acrisols]</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
<td>Suffers considerable erosion and degradation without apparent influence on production or overall soil quality. Physical structures indicated to control off-site impacts [Ferrasols]</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
<td>Only suffers degradation under very poor management and persistent mismanagement. Biological conservation methods adequately maintain production and protect soil [Nitosols; Cambisols]</td>
</tr>
</tbody>
</table>

**Figure 7.** A resilience-sensitivity matrix for tropical soils (using FAO/UNESCO Soil Map of the World names), with indicated approaches to conservation. Under this schema, the top right cell represents the best soils and the bottom left the worst. Different management strategies for each of the four permutations are indicated, which in turn affect the extent to which smallholder farmers have the resources and understanding to cope with specific scenarios of soil degradation (61).
The rebel insurgency that toppled Haiti’s government in 2004 was, on the surface, simply the latest turn in a bloody cycle of repression and reaction. But deeper down, the uprising exposed a root cause of the country’s misery: some of the most denuded land on the planet. Only 3 percent of the once lushly forested terrain still has tree cover, and up to one-third, some 900,000 hectares, has lost so much topsoil that it is no longer arable, or barely so. Today the landscape is crisscrossed by gully-scarred, deforested hills and “rocks where there used to be dirt,” says Andy White, an economist at Forest Trends, a nonprofit organization in Washington, D.C. Erosion has brought the Caribbean country’s agriculture to its knees, he says, and that in turn “has driven rural poverty,” impelling desperate Haitians toward city slums where unrest continues to simmer.

The tremendous hemorrhaging of fertile soil makes Haiti one of the global hot spots for degradation, as illustrated on the preceding pages. For decades soil scientists have deplored the loss of land to erosion, nutrient depletion, salinization, and other insults. But policymakers have been slow to respond. One reason is that dire warnings in the 1980s that soil erosion would doom the world to chronic food shortages have failed to pan out.

But in the past few years, new studies have yielded better data linking soil degradation to a slump in the growth of global crop yields, uniting dueling camps. After years of “pecking away at this problem,” soil scientists, geographers, and economists “are coming toward the middle,” says Keith Wiebe, a resource economist at the U.S. Department of Agriculture (USDA). The bottom line: “As a global problem, soil loss is not likely to be a major constraint to food security,” says Stanley Wood, a senior scientist at the International Food Policy Research Institute in Washington, D.C. But as Haitians know all too well, degradation can be a severe and destabilizing threat in places where farmers are too poor to curb or overcome the damage.

Moreover, global warming is expected to exacerbate regional crises. As the ground heats up, organic matter decomposes more readily, reducing soil fertility and, asserts Duke University ecologist William Schlesinger, releasing carbon dioxide into the air to fuel warming. Deserts are also expected to expand and erosion worsen if violent storms occur more frequently. But there’s a flip side, says soil scientist Rattan Lal of Ohio State University, Columbus: “We can do something about it” by managing soils to stem erosion and retain more carbon.
involving the management of biomass: crop residues, green manures, and alley cropping, for example. The principal limitation here is the availability of organic resources and the human resources to manage them for effective soil protection. However, even at moderate levels of management such as those available in most smallholder farming households, nitosols can effectively continue to withstand degradation and produce indefinitely, at least for the next 50 years (43).

**Appropriate Responses to Changing Soil Quality**

Doomsday scenarios of increasing population and declining soil resource quality fail to capture the diversity of soils, while presenting the worst-case outliers as the typical situation. There are indeed some bad cases where degradation is rife and people are starving (44); these will continue to hold international attention for at least the next 50 years. International attention will also continue to be captured by global assessment initiatives such as the Millennium Ecosystem Assessment (45) that present pessimistic scenarios of the future, or initiatives to sequester more carbon into soils for gains in both global environmental benefits and food security, the “win-win” beloved of the World Bank (46). However, smallholder farmers in the tropics are the ultimate solution. They turn scenarios into futures. Their skills and social networks give us cause for optimism for future soil quality and food security. Many are already managing their soils sustainably and productively.

Although these smallholder farmers tend to be limited in labor resources (i.e., have low “human capital”), they compensate in forms of collective action and networking (i.e., “social capital”) (47, 48). This means that they adapt technologies to their local needs (using indigenous knowledge and innovation) and avoid labor-demanding and expensive practices. Interventions that use community-based approaches that empower farmers to manage their own situations therefore hold the greatest promise for maintaining soil quality and ensuring food security.

One of the most interesting recent developments in soil quality research, as reflected in the agendas of the major development agencies, is the recognition that farming practices do not merely extract soil nutrients, but they evolve in response to changing conditions over many years through informal experimentation and experience (49). Farmers may often make better decisions than the “experts,” not because of any greater analytical skills but because of the experience gained in integrating a vast array of local factors responsible for controlling production.

Farmers are unlikely to undertake practices that undermine the future and put household livelihood and food security at risk unless immediate survival is in question. They will invest in soil conservation if the private benefits—financial, social, and cultural—are greater than the costs.

The greatest damage to soils occurs where conditions are volatile with, for example, migrants and refugees. Here, local knowledge is poor and mining the soil of its nutrients is essential for sur-
vival, at least in the short term. The greatest threat to soil quality and food security occurs if the security of tenure for smallholders is made even more difficult by changing world conditions.

The future rests in managing changes in soil quality through working with local communities and rethinking how soils change local society (50). In semi-arid Benin, for example, *Mucuna pruriens* (velvetbean) is used as a green manure mulch and has become an accepted method for countering soil fertility decline.

From 15 original farmers involved in experimentation and adaptation in 1987, 100,000 were reported to have embraced this practice by 1996 (51). This is evidence of adaptability, flexibility, and responsiveness to techniques that bring private benefits to smallholders. In semi-arid Kenya, farmers choose “trashlines” (bands of uprooted weeds and crop residues) to intercept sediment and runoff, a technique never promoted by the advisory services. Yet when the marginal rates of return and net present values over 10 years are calculated, trashlines are almost always the only technique of soil quality maintenance that consistently benefits the farmers’ livelihoods (52).

Such findings point to some important, if uncomfortable, conclusions. Many farmers in the tropics are willing to invest in the future, protecting important public goods such as soils, and they are often the best arbiters of choice when it comes to technologies. Science does not always get it right and does not necessarily provide workable or acceptable solutions (53). Soil resources are not a static, homogenous medium; they are a dynamic element, responding to the demands placed on them by human beings and governing expectations of food security. If simple provisions — such as adequately resourced extension services and access to technologies — are made available, food production by smallholders can be transformed. The “tragedy of the commons” lies more in our simplistic, linear, disciplinary thinking than in reality. The challenge is to capture diversity by developing appropriate cross-disciplinary analytical methods and measures. A reinvigorated science and technology for agricultural development is necessary, but it is not sufficient. We must change mindsets that solutions are already available; the change is in how and to whom they are available. We must get closer to allaying the tragedy by providing realistic and accessible interventions for those who need it most — the poor, hungry, and disadvantaged, living on soils that are sensitive and lack resilience.

### References and Notes

5. See, for example, the World Food Programme’s goal for 2002–2005: “Excellence in providing food assistance that enables all... to survive and maintain healthy nutritional status, and enabling the social and economic development of at least 30 million hungry people every year” (www.wfp.org).
8. *The Daily News*, Harare, Zimbabwe, 17 June 2003 (http://allafrica.com/stories/200306170385.html). The article reports: “Food production in Zimbabwe has fallen by more than 50%, measured against a five-year average, due mostly to the current social, economic and political situation and the effects of the drought,” the UN agencies [WFP and FAO] said. The underlying cause was described as “unwise policies over land redistribution.”
9. “Global Warming Threatens Food Shortages in Developing Countries” [International Maize and Wheat Improvement Centre (CIMMYT), 2003] (www.cimmyt.cgiar.org/english/webp/support/n_release/warming/norelease_12May03.htm).

11. An alternative definition used by the USDA’s Natural Resources Conservation Service is, “SOIL QUALITY is how well soil does what we want it to do” (http://soils.usda.gov/sqi/soil_quality/what_is/index .html). The NRCS stresses that soil has both inherent and dynamic properties.


19. See UN/FAO’s Soil Biodiversity Portal on how soil biodiversity can be assessed with the aim of promoting more sustainable agriculture (www.fao.org/ ag/agl/agll/soilbiod/default.htm). The NRCS stresses that soil has both inherent and dynamic properties.


30. Agriculture has a potentially large role in the sequestration of carbon in soils; see (34).

31. “Soil science has been brilliantly informed by reductionist physics and chemistry, poorly informed by ecology and geography, and largely uninformed by social science.” Quote from M. J. Swift (15).


43. See the USDA-NRCS Web site World Soil Resources for links to most global soil resource sites and commentaries on soil management (www.nrcs.usda.gov/technical/worldsoils).


48. For further discussion on the capital assets framework and sustainable natural resource management, the Livelihoods Connect Web site (www .livelihoods.org) contains guidance sheets and a “sustainable livelihoods toolbox.”


