Soil Resource Condition

Soil, the principal medium for plant growth, is a thin layer of biologically active material lying over inert rock below, the result of complex processes of geologic weathering, nutrient cycling, and biomass growth and decay. Soil is the primary environmental stock that supports agriculture. Thus, good soil condition is central in determining the current state and future productive capacity of agroecosystems. It also greatly influences the provision of environmental services, including water flow and quality, biodiversity, and carbon. We discuss these roles in subsequent sections.

Since the emergence of agriculture, soil management has challenged farmers. Where land was abundant, farmers selected the best soils for production and used long fallow periods to restore soil physical and chemical properties lost by cultivation. With increasing population density, permanent agriculture evolved and farmers developed numerous techniques to sustain soil fertility, control the movement of soil and water, and improve soil characteristics favorable to crop cultivation. For millennia, farmers have used field rotation, leguminous and green manures, inorganic materials (such as lime and loess), and animal manures to recycle or concentrate plant nutrients in arable fields. The large-scale introduction of fertilizers, especially nitrogen and phosphorus, from natural or industrial sources has been a major source of yield growth. However, provision of mineral nutrients furnishes only partial restoration of the soil qualities essential to its sustainable use as a plant growth medium. Farmers and scientists have learned that soil productivity depends upon a range of interrelated factors including: soil organic matter, nutrient availability (particularly nitrogen, phosphorus, and potassium, but also micronutrients), water-holding capacity, soil reaction (pH), soil depth, salinity, the richness of the soil biota, and such physical characteristics as soil structure and texture.

This section first reviews the global pattern of inherent soil constraints, which highlights the spatial variability in soil resource endowment. Global evidence on the status of soil degradation in agricultural land is then assessed, followed by a discussion of more specific indicators of soil quality: soil organic matter, and soil nutrient balances. We conclude with a brief review of the prospects for enhancing agricultural soil's capacity to provide a range of goods and services.

Global Patterns of Soil Constraints

We used the Fertility Capability Classification (FCC) approach (Sanchez et al. 1982; Smith 1989; Smith et al. 1997) to examine the inherent productive capacity of the world's soils. The approach interprets soil profile data to ascribe up to 20 "modi-

Table 15

Share of PAGE Agricultural Extent[a] Affected by Major Soil Constraints[b]

	Share of PAGE Agricultural Extent	Free of Constraints	Poor Drainage	Low CEC	Aluminum Toxicity	Acidity	High P-Fixation	Vertisol	Low K-Reserves	Alkaline	Salinity	Natric	Shallow or Gravelly	Organic	Low Moisture Holding Capacity
Region[c]															
North America	12.2	29.3	17.6	0.0	18.1	28.2	0.0	1.4	12.8	6.8	0.2	1.9	4.0	1.5	8.9
Latin America and the Caribbean	17.3	12.4	11.3	7.2	30.9	17.0	13.1	3.8	39.3	5.4	3.2	4.8	10.1	0.3	12.9
Europe	9.2	18.2	18.3	1.2	11.7	51.1	0.0	1.6	0.0	8.6	1.0	1.3	8.0	2.2	14.7
Former Soviet Union	15.8	23.3	15.2	0.0	1.6	13.2	0.0	0.0	0.0	24.3	3.4	17.8	7.1	2.4	7.8
West Asia/ North Africa	3.1	20.4	3.2	0.1	2.4	14.2	0.0	4.9	1.2	30.1	4.5	0.6	20.9	0.0	1.6
Sub-Saharan Africa	16.1	7.0	9.5	15.9	20.5	28.6	4.3	6.2	29.7	2.7	1.3	2.3	11.4	0.5	23.2
East Asia	10.5	15.7	19.9	0.1	21.1	14.3	16.4	1.6	19.8	6.7	6.1	0.2	19.8	0.1	1.8
South Asia	8.4	13.4	6.8	0.7	5.0	32.2	0.2	19.5	9.0	9.6	8.3	0.5	9.4	0.2	7.9
Southeast Asia	5.6	6.2	21.7	2.3	37.9	32.6	8.1	3.1	43.5	0.6	0.9	0.3	6.4	3.3	6.0
Oceania	1.9	14.0	18.4	3.5	8.8	17.3	1.1	8.2	6.8	12.7	1.2	33.0	9.2	0.4	23.9
Total	*100.0*	*16.2*	*14.0*	*4.2*	*17.2*	*24.6*	*5.2*	*4.3*	*18.6*	*9.5*	*3.0*	*5.1*	*10.0*	*1.1*	*11.3*
Agroclimatic Zone[d]															
Tropics/Arid and Semiarid	14.4	8.4	7.9	11.8	7.2	29.6	1.2	16.5	11.9	4.1	2.6	3.9	13.3	0.2	20.8
Tropics/Subhumid and Humid	23.5	5.5	13.1	8.9	41.5	25.5	13.0	2.9	52.0	1.0	0.6	0.9	7.1	1.2	12.8
Sub-tropics/ Arid and Semiarid	9.4	24.1	5.6	3.2	1.1	13.6	0.0	4.3	1.3	25.3	11.8	7.6	15.6	0.0	13.9
Sub-tropics/ Subhumid and Humid	13.8	14.6	14.7	0.2	25.3	25.2	14.3	5.3	25.6	3.8	0.9	3.3	14.3	0.4	4.5
Temperate/Arid and Semiarid	20.1	25.5	13.1	0.1	1.1	9.6	0.0	0.1	0.1	23.9	5.5	14.9	9.8	1.4	5.0
Temperate/ Subhumid and Humid	18.0	23.1	24.3	0.6	14.3	39.5	0.3	0.5	5.7	6.7	0.9	1.3	5.1	1.9	13.4
Boreal	0.8	31.6	33.9	0.0	13.9	38.4	0.0	0.0	0.0	0.0	0.0	0.0	9.2	11.6	6.9
Total	*100.0*	*16.2*	*14.0*	*4.2*	*17.2*	*24.6*	*5.2*	*4.3*	*18.6*	*9.5*	*3.0*	*5.1*	*10.0*	*1.1*	*11.3*

Source: IFPRI calculation based on: (a) GLCCD 1998; USGS EDC 1999, (b) the fertility capability classification (FCC) applied to FAO's digital Soil Map of the World (FAO 1995; Smith 1989; and Smith et al. 1997), (c) country boundaries from ESRI 1996, and (d) FAO/IIASA 1999.

fiers," indicating soil constraints from an agricultural use perspective. We generated FCC modifiers for each of the 4,931 mapping units using data and analysis software included in FAO's Digital Soil Map of the World (FAO 1995). The proportional area of each soil constraint was then assessed for each five minute grid cell (approximately 10km^2 at the equator) of the soil map.[15]

Map 10 indicates which of the FCC constraints, including no constraint, is dominant (occupies the greatest proportional area) at each location within the PAGE global agricultural extent. Table 15 summarizes the area within the PAGE agricultural extent affected by soil constraints.

Acidity, defined in the FCC as a soil pH between 5.0 and 6.0 (Sanchez et al. 1982 quoted in FAO 1995), is the most common global soil constraint, affecting a quarter of the PAGE agricultural extent. A soil pH of around 6.0-7.0 increases the availability of nutrients and promotes beneficial microbial activity. Acid soils tend to be saturated with exchangeable aluminum. In some 17 percent of the agricultural extent, aluminum saturation is so high as to be toxic to plants. These problems are particularly acute in the highly weathered soils of the humid tropics, but can also be induced by long-term use of ammonia-based fertilizers. Other constraints linked to acid soils include a high capacity to "fix" natural or applied phosphorus, making phosphorus unavailable to plants, as well as low reserves of other nutrients, such as potassium. Phosphorus fixation is prevalent in only 5 percent of agricultural lands, but is a serious concern in parts of Latin America, East Asia, Southeast Asia, and Sub-

Table 16

PAGE Agricultural Extent[a] by Major Climate,[b] Slope,[c] and Soil Constraints[d]

	0 to 8 Percent Slope[c]			8 to 30 Percent Slope[c]			Greater than 30 Percent Slope[c]		
	Occurrence of Soil Constraints[d]								
	Predominant	Moderate	Low	Predominant	Moderate	Low	Predominant	Moderate	Low
Major Climate[b]	**(>= 70%)**	**(30-70%)**	**(<30%)**	**(>= 70%)**	**(30-70%)**	**(<30%)**	**(>= 70%)**	**(30-70%)**	**(<30%)**
					(percentage)				
Tropics									
Arid/Semiarid	7.8	0.5	0.1	4.9	0.5	0.1	0.4	0.2	0.0
Subhumid/Humid	13.0	0.3	0.1	7.8	0.3	0.1	1.5	0.2	0.1
Subtropics									
Arid/Semiarid	3.9	0.7	0.9	2.2	0.4	0.2	0.8	0.3	0.0
Subhumid/Humid	4.0	0.6	0.7	4.7	0.5	0.3	2.7	0.2	0.1
Temperate									
Arid/Semiarid	8.7	0.9	2.2	4.3	1.4	1.2	0.8	0.6	0.1
Subhumid/Humid	7.2	1.2	1.9	5.6	0.8	0.5	0.7	0.2	0.0
Boreal	0.2	0.1	0.0	0.1	0.4	0.0	0.0	0.0	0.0
Total	44.7	4.2	6.1	29.6	4.2	2.3	6.9	1.7	0.3

Source: IFPRI calculation based on: (a) GLCCD 1998; USGS EDC 1999, (b) FAO/IIASA 1999, (c) FAO/IIASA 1999 based on USGS 1998, and (d) the fertility capability classification (FCC) applied to FAO's Digital Soil Map of the World (FAO 1995; Smith 1989; and Smith et al. 1997).

Saharan Africa. Low potassium reserves are often found in the same regions, but are more extensive, occupying some 19 percent of the agricultural extent.

Poorly drained (hydromorphic) soils are found in about 14 percent of the agricultural extent largely in areas where physiography promotes flooding, high groundwater tables, or stagnant surface water. While problematic for many agricultural purposes, they are suited to rice cultivation and seasonal grazing (Bot and Nachtergaele 1999).

Although agricultural drylands are known to be underrepresented in the PAGE agricultural extent, constraints often related to drier environments feature significantly in Table 15. Saline soils—those with excess soluble salts—are found on around 3 percent of the agricultural extent, and natric (sodium rich) soils on around 5 percent of these lands, the latter particularly prevalent in Oceania and the Former Soviet Union. Although salinity presents problems of toxicity to most crops, sodicity inhibits infiltration and root development. Both salinity and sodicity are associated with dryer areas and more alkaline (basic) soils. Excessively alkaline soils, defined in the FCC schema as having a pH of greater than 7.3 (Sanchez et al. 1982 quoted in FAO 1995) occupy around 10 percent of the agricultural extent and, as with soil acidity, inhibit the availability of plant nutrients.

Focusing only on the proportion of PAGE agricultural extent free from soil constraints *(see Map 11)* provides another perspective on the spatial distribution of soil quality. Only 16 percent of agricultural soils are free from constraints. About 60 percent of those favored soils lie in temperate areas, particularly the midwestern United States, central western Canada, Russia, central Argentina, Uruguay, southern Brazil, northern India, and northeast China, while only 15 percent lie within the tropics.

To link soil constraints to broader climatic and physiographic factors, we defined three classes of constraints: predominantly constrained (over 70 percent of land having soil constraints), moderately constrained (30-70 percent with constraints), or relatively unconstrained (under 30 percent with constraints). We combined these extents with major climate, moisture availability and slope maps to assess the relative disposition of favored (flat, well-watered, fertile) compared to less-favored (sloping, drier, less fertile) lands within the PAGE agricultural extent. Table 16 summarizes this distribution.

Farmers generally prefer flatter lands without important soil quality constraints. Globally, in the semiarid, subhumid, and humid subtropics and the subhumid temperate zones, over three quarters of all available flat lands (defined as those with under 8 percent slope) without soil constraints (under 30 percent constrained) were found within the agricultural extent. However, large areas of steeper and soil-constrained land are also under cultivation. In some cases, these soils have positive attributes that make them preferred (for example, steeper slopes provide better drainage on heavier soils; vertisols are difficult to work manually but are quite fertile). For historical and political reasons, some ethnic groups are concentrated in regions with high soil constraints. In many cases, population growth and land scarcity in higher-quality agricultural regions have resulted in large groups of farmers migrating to regions having lower quality soils.

Soil Quality Status and Change

Natural weathering processes and human use have brought about continuous changes in soil quality. The deterioration over time of key soil attributes required for plant growth, or for providing environmental services, constitutes "degradation." The principal soil degradation processes are erosion by water or wind, salinization and waterlogging, compaction and hard setting, acidification, loss of soil organic matter, soil nutrient depletion, biological degradation, and soil pollution.

Climate plays a critical role in the degradation process. As temperatures increase, decay of organic matter is greatly accelerated, particularly in frequently tilled soils. Increased temperatures coupled with decreased precipitation tend to intensify degradation, making many soil-conservation practices less effective. Additionally, the potential for wind and water erosion is generally greater in warmer areas. Erosion is further increased in more arid areas because of lower inherent organic-matter levels and less natural vegetation. Retaining crop residues, a key feature in sustainable soil management, is much more difficult in hot and arid areas. In tropical areas, continuous cropping often results in quite rapid degradation and consequent productivity decline through increased chemical acidity, loss of essential plant nutrients, and structural collapse of the soil. Subsequently, the soil's capacity to form stable aggregates is reduced because soil organic matter, the binding material, has been lost (Stewart, Lal, and El-Swaify 1991).

Different land management practices are associated with different types and degrees of soil degradation. For example, salinization is linked with intensification on irrigated land and clearing of deep-rooted vegetation, compaction with mechanized farming in high-quality rainfed lands, nutrient depletion with intensification of marginal lands, water erosion with clearing and extensive management of marginal rainfed lands, and soil pollution with periurban agriculture (Scherr 1999b).

The diversity of causes, processes, and consequences of soil degradation presents challenges in defining useful indicators to describe its status. This section reports briefly on the only global attempt to define such indicators, the Global Assessment of Soil Degradation (GLASOD, Oldeman et al. 1991a) and interprets its findings within the PAGE agricultural extent.

For GLASOD, regional experts used a standardized assessment framework and regional (1:10M scale) maps to judge the prevalence of four types of human-induced degradation: water erosion, wind erosion, physical degradation, and chemical degradation. For each degradation type, the GLASOD experts assessed both the proportional area affected by degradation (*extent*) and the scale of degradation on affected areas (*degree*). In terms of degradation extent, the GLASOD results suggested that about 23 percent of all used land was degraded to some degree: 38 percent of cropland; 21 percent of permanent pasture; and 18 percent of forests. Of the degraded lands, about 38 percent was lightly degraded; 46 percent moderately degraded (suggesting significantly reduced agricultural productivity and partial destruction of original biotic functions); and 16 percent was strongly to extremely degraded, no longer suitable for agricultural use. The GLASOD analysis attributed around 35 percent of the extent of human-induced degradation to overgrazing and about 28 percent to other agricultural-related land management. About 29 percent was also attributed to deforestation (Oldeman 1994:111-116 and Oldeman et al. 1991b) and it is likely that a significant share of the cleared land was used for agricultural purposes.

For mapping purposes GLASOD degradation extent and degree attributes were combined to form degradation *severity* classes (Oldeman et al. 1991a:15). We overlaid the GLASOD map of degradation severity with the PAGE agricultural extent map to obtain a spatial perspective of the correspondence of degradation and agriculture *(see Map 12)*. GLASOD mapping units falling within the PAGE agricultural extent tend to have higher severity classes than are found across all land use types (agriculture, grazing and forest land combined). The overlay reveals that 35 percent of the PAGE agricultural extent coincides with GLASOD mapping units classed as not degraded or as having low severity degradation, while over 40 percent of the agricultural extent coincides with mapping units whose degradation severity is high or very high.[15] This interpretation, however, gives an overly pessimistic view of soil degradation severity in agricultural lands. Both degradation and agriculture are defined as occupying only a proportion of any given area. In reality, the amount to which the degraded areas within GLASOD mapping units physically overlap agricultural areas within the PAGE agricultural extent, is unknown. For example, a degradation severity class of "very high" is assigned to an entire GLASOD mapping unit if as little as 10 percent of its *extent* has an extreme *degree* of erosion *(see legend of Map 12)*. Since the PAGE agricultural extent includes areas that are up to 70 percent non-agricultural *(see Map 1)*, it is quite conceivable that the 10 percent of the area degraded is non-agricultural and, consequently, that the agricultural area has no—rather than very high—degradation.

To avoid this bias, we characterized GLASOD degradation mapping units not by severity class but by their component extent and degree attributes. We then tabulated PAGE agricultural extent areas that coincided with different combinations of

Table 17

Distribution of PAGE Agricultural Extent by GLASOD Mapping Unit

Degradation Degree by GLASOD mapping unit	Degradation Extent (degraded share of GLASOD mapping unit) 0	1-5	6-10	11-25	26-50	>50	All
	(percent of agricultural extent)						
None	14.6						14.6
Light		12.2	8.2	10.1	2.6	0.3	33.5
Moderate		6.6	11.6	14.1	8.9	1.7	42.9
Strong		1.2	1.1	2.9	2.0	1.3	8.4
Extreme		0.2	0.0	0.3	0.0	0.0	0.5
All	14.6	20.2	20.9	27.4	13.4	3.4	100.0

Source: IFPRI calculation based on GLASOD (Oldeman et al. 1991a) and the PAGE agricultural extent (GLCCD 1998; USGS EDC 1999).
Notes: Relationships between the degradation of soil and its capacity to provide goods and services are complex. Depending on soil type, for example, a given depth of soil erosion could have negligible to very significant consequences for crop productivity.

degradation extent and degree from the GLASOD map. The results of this tabulation are shown in Table 17. In terms of degradation extent, around 35 percent of PAGE agricultural extent has 5 percent or less of its area degraded. About half of the PAGE agricultural extent corresponds with GLASOD mapping units that have 6 to 25 percent of their extent degraded. Less than 5 percent of the PAGE agricultural extent corresponds with degradation mapping units where more than half the area is degraded. In terms of degradation degree, about 48 percent of the agricultural extent is only lightly degraded or not degraded, while 9 percent is strongly or extremely degraded.

The consequences of different types and degrees of soil degradation on agricultural productivity and the provision of environmental services vary widely and are not always well understood. However, these global soil degradation estimates for agricultural lands are cause for significant concern. The picture they paint calls, at the very least, for a greater sense of urgency with regard to more reliable monitoring of the location, extent, degree, and impact of soil degradation. Such information is an essential prerequisite to assessing the priority and scale of appropriate remedial measures.

SOIL DEGRADATION IN SOUTH AND SOUTHEAST ASIA

The most comprehensive regional data on soil degradation is from the Assessment of Human-Induced Soil Degradation in South and Southeast Asia (ASSOD). The ASSOD study used a methodology similar to GLASOD, but was nationally representative (1:5M scale) and checked against available national data. The definition of "degradation" is different from GLASOD, as it represents expert assessment of the degree of yield loss associated with soil quality change. Thus, significant deterioration in key soil qualities that did not result in yield change was assessed as "no or negligible degradation" (van Lynden and Oldeman 1997).

ASSOD found that agricultural activity had led to degradation on 27 percent of all land, and deforestation on 11 percent since around the middle of the 20th century; overgrazing played a minor role. The more detailed ASSOD study showed more degraded land than the GLASOD study showed but, as in the case of erosion by water, often to a lesser degree. ASSOD did, however, show significantly greater extents of light to moderate loss of soil fertility, and strong and extreme terrain deformation by water and wind than did GLASOD *(see Table 18)*.

ASSOD collaborators also provided data on types of farm management for nearly half of the degraded land. They found little association between land management and degradation: 38 percent of degraded lands were under a high level of management, 36 percent under medium management, and 25 percent under low management (defined as "traditional" systems existing for more than 25 years). In recent years, however, degradation had increased more often under low and medium management (van Lynden and Oldeman 1997:26-27).

Map 13 presents the ASSOD data on severity of soil degradation, within the PAGE agricultural extent. It highlights the geographic concentration of areas with the most serious degradation. The underlying data show the following: chemical deterioration and salinization are found in the same areas; fertility decline and water erosion are more widespread in China; and water erosion is widespread, especially in the agricultural areas of Thailand, India, and China.

Soil Organic Matter

The presence of soil organic matter (SOM), those parts of the soil that originated from plants and animals, is one of the single most important measures of soil quality and, hence, of agroecosystem condition. The beneficial attributes that SOM imparts include the following:

Table 18

Degraded Lands[a] within the PAGE Agricultural Extent[b] for South and Southeast Asia

Dominant Degradation Type	Impact			
	None/Low	Moderate	Strong	Extreme
	(percent of degraded PAGE agricultural land)			
Water Erosion[c]	16.2	17.4	20.1	9.1
Wind Erosion[d]	0.1	1.6	1.3	2.6
Chemical Degradation[e]	9.2	2.8	3.1	7.3
Physical Degradation[f]	0.4	3.0	5.4	0.4
Total	25.9	24.8	29.8	19.5

Source: IFPRI calculation based on: (a) the Assessment of the Status of Human-Induced Soil Degradation in South and Southeast Asia (ASSOD: van Lynden and Oldeman 1997), and (b) GLCCD 1998.
Notes: (c) Water erosion includes: loss of topsoil and terrain deformation; (d) wind erosion includes: loss of topsoil by wind action, terrain deformation, and overblowing; (e) chemical degradation includes: fertility decline and reduced organic matter content, salinization/alkalinization, dystrification/acidification, eutrophication, and pollution; (f) physical degradation includes: compaction, crusting and sealing, waterlogging, lowering of the soil's surface, loss of productive function, and aridification.

- ♦ stabilizes and holds together soil particles—thus reducing erosion;
- ♦ provides a source of carbon and energy for soil microbes;
- ♦ improves the soil's ability to store and transmit air and water;
- ♦ stores and supplies nutrients such as nitrogen, phosphorus, and sulphur;
- ♦ maintains soil in an uncompacted condition and makes the soil easier to work;
- ♦ retains carbon from the atmosphere and other sources;
- ♦ retains nutrients (e.g., calcium, magnesium, potassium) by providing ion exchange capacities; and,
- ♦ serves to reduce the negative environmental effects of pesticides and other pollutants.

Through such effects, soils rich in organic matter not only yield more food, because they are more productive, but also enhance soil biodiversity, store carbon, regulate surface water flows, and improve water quality—all key goods and services of relevance to this study. Factors influencing SOM formation in agroecosystems include crop type and rotation practices, crop residue availability, application of organic and inorganic nutrients, and the population and vigor of soil biota. Other conditions being equal, organic matter accumulates most at low temperatures in more acidic soils and under anaerobic conditions (Batjes 1999).

Land conversion into agriculture is a primary cause of SOM decline. SOM levels tend to fall as litter formation rates are decreased, organic matter is oxidized from increased tillage, and soil erosion increases. Good farming can slow the decline and can establish SOM formation and decomposition equilibrium rates that maintain long-term soil quality and productivity. This is, however, much more easily achieved in temperate rather than in tropical regions, where higher temperatures, and sometimes higher erosion and leaching rates, accelerate SOM loss. Tiessen et al. (1994:784) found that 65 years of cultivation of a Canadian prairie reduced the soil carbon content by almost 50 percent, while only 6 years of cultivation in a Brazilian semi-arid thorn forest reduced the soil carbon content by 40 percent, and just three years of slash-and-burn cultivation of a Venezuelan rain forest soil reduced litter layer carbon by around 80 percent and the soil carbon by around 30 percent. Ironically, SOM plays a critical role in the quality of highly-weathered tropical soils where the lack of inorganic nutrients, and the limited natural regeneration, place greater reliance on the decomposition of litter or of applied organic matter to enhance soil fertility. Simply applying more inorganic fertilizer in such situations is seldom effective as a minimum threshold amount of SOM is required to bind incoming inorganic nutrients.

The indicator of SOM used here is the organic carbon content of soil[16] to a depth of 100 centimeters. The data set used for this indicator, described in the Carbon Services section, combines carbon data from soil profiles (Batjes 1996; Batjes 2000) with maps of soil distribution (FAO 1995), in order to estimate the organic carbon storage of the world's soils. Table 19 summarizes the distribution of soil organic carbon storage by region and Table 26 shows the distribution by agroecological zone.[17] The data clearly demonstrates that soil carbon densities are significantly higher in temperate latitudes (except for those tropical areas, mainly in Southeast Asia, that contain peat soils).

Although the soil organic carbon indicator is usable at multiple scales, routinely collected in soil surveys, and has standardized laboratory measuring techniques, there remain some practical questions over its use. One is the selection of soil depth over which the indicator is assessed. From a carbon sequestration and storage perspective (for which the indicator is used in

Table 19

Soil Organic Carbon Storage (0–100 centimeters soil depth) within the PAGE Agricultural Extent[a]

Region[c]	PAGE Agricultural Extent[a]		Total SOC[b]	SOC Density
	(m sq km)	*(% total)*	*(GtC)*	*(MtC/ha)*
North America	4.4	*12.2*	54	122
Latin America and the Caribbean	6.2	*17.3*	59	95
Europe	3.3	*9.2*	49	146
Former Soviet Union	5.7	*15.8*	66	116
West Asia/North Africa	1.1	*3.1*	8	71
Sub-Saharan Africa	5.8	*16.1*	42	77
East Asia	3.8	*10.5*	32	85
South Asia	3.0	*8.4*	25	83
Southeast Asia	2.0	*5.6*	26	126
Oceania	0.7	*1.9*	5	78
Total PAGE Agricultural Extent	36.2		369	102
Total Land Area[d]	130.4		1,555	
Agricultural Percentage of Total	*27.8*		*23.7*	

Source: IFPRI calculation based on: (a) GLCCD 1998; USGS EDC 1999, (b) FAO 1995, Batjes 1996 and Batjes 2000. *(see note)*, and (c) ESRI 1996. (d) FAOSTAT 1999.
Note: Batjes (1996) estimated the average soil organic carbon (SOC) content at a depth of 100cm by soil type based on over 4,000 individual soil profiles contained in the World Inventory of Soil Emission Potentials (WISE) database compiled by the International Soil Reference and Information Centre (Batjes and Bridges 1994). The authors calculated the global estimate of SOC storage by applying Batjes' (1996 and 2000) SOC content values by soil type to the soil type area share of each 5 x 5 minute unit of the Soil Map of the World (FAO 1995). SOC data for Greenland and Antarctica were largely incomplete and were excluded.

the section on Carbon Services), the goal is to assess total carbon within the entire soil profile because carbon found below the plow layer is more permanently stored. For agricultural productivity purposes, however, it is SOM dynamics in litter and the upper soil horizons (to 30cm) that are likely more critical. Furthermore, the underlying soil profile data is from various (often distant) points in time and may be unrepresentative of past and current land uses. The long-term monitoring of SOM is increasingly viewed as an important means of measuring progress toward achieving sustainable agriculture and of keeping abreast of degradation trends.

Soil Nutrient Dynamics

As production intensifies, so does the challenge of maintaining balanced soil nutrient conditions. Shorter fallow periods, greater planting densities, and higher grain yields place greater demands on soil nutrients. Net nutrient depletion ("mining") will occur if extraction rates consistently exceed replacement and regeneration rates. Conversely, if nutrients are applied in excess of requirements, residues often pass into surface- and groundwater resources *(see Box 4 in the section on Water Services)*. Nutrient mining directly affects soil productivity and, sooner or later, will require a change in management practices, such as fallow, increased nutrient inputs, less demanding cropping systems, or abandonment. Leaching of nutrient residuals is a production externality whose impacts are most apparent to downstream water users and to those concerned with the welfare of downstream aquatic ecosystems. The sign, size, and trend of annual nutrient balances can, thus, serve as an indicator of the changing productive capacity of agroecosystems (as well as for their nutrient leaching potential).

On behalf of the PAGE study, the International Fertilizer Development Center (IFDC) made a country- and crop-specific assessment of nutrient balances for Latin America and the Caribbean (Henao 1999). The analysis brought together data on inorganic fertilizer consumption, crop-specific fertilizer-application, organic-fertilizer use, and crop-residue recycling, as well as on nutrient extraction rates. Average annual nutrient balances were computed for two time periods, 1983-85 and 1993-95, as the difference between the sum of the nutrient inputs and outputs. Nutrient inputs comprised the following:

- Mineral fertilizer applied in kilograms of nitrogen (N), phosphorus (P_2O_5), and potassium (K_20) per hectare (together referred to as NPK);
- Organic fertilizer applied as manure or animal residue expressed as kilograms of NPK per hectare;
- NPK derived from crop residues left on the soil after harvest and estimated as kilograms of NPK per hectare; and
- Nitrogen fixation by soybeans and pulse crops, expressed in kilograms of NPK per hectare.

Table 20

Nutrient Balances by Crop: Latin America and the Caribbean

Region[a]	Crop									
	Wheat	Rice	Maize	Sorghum	Potato	Cassava	Beans	Soybean	Other	All
	(kg NPK[b] per hectare per year)									
1983-85 Average										
Mesoamerica	-198	-89	-17	-120	15	-54	14	-88	-32	-39
Caribbean		-197	-70	-120	-67	-23	-11		-39	-67
Andean	-77	-110	-47	-32	-60	-63	-36	-114	-51	-57
Southern Cone	-101	-46	-89	-162	-77	-48	4	-27	-68	-65
LAC Average	*-111*	*-62*	*-61*	*-133*	*-60*	*-49*	*5*	*-30*	*-58*	*-59*
1993-95 Average										
Mesoamerica	-199	-105	-49	-111	-112	-126	4	-86	-11	-43
Caribbean		-170	-33	-85	12	-20	35		-10	-41
Andean	-79	-73	-37	-8	-6	-57	-47	-165	-28	-40
Southern Cone	-83	-72	-115	-161	-21	-31	7	-24	-50	-59
LAC Average	*-96*	*-77*	*-86*	*-108*	*-18*	*-35*	*4*	*-28*	*-37*	*-54*

Source: IFPRI calculation based on Henao 1999.
Notes: (a) Mesoamerica includes Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, and Panama. The Caribbean includes Cuba, Dominican Republic, Haiti, and others. Andean countries include Bolivia, Colombia, Ecuador, Peru, and Venezuela. The Southern Cone includes Argentina, Brazil, Chile, Paraguay, and Uruguay. (b) NPK: Nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O).

Nutrient outputs consisted of the following:

- Nutrient uptake in grain or main crop product in kilograms of NPK per hectare; and
- Nutrient uptake in main crop residue in kilograms of NPK per hectare. Depending on the crop and country, some proportion of this extraction was assigned for recycling *(see nutrient inputs)*.

The results of this analysis, summarized by subregion in Table 20, suggest that for most crops and cropping systems in Latin America and the Caribbean (LAC) the nutrient balance is significantly negative, although depletion rates appear, in general, to be declining. Across all crops, the nutrient stocks of the region's soils were being depleted by around 54 kg NPK ha^{-1}yr^{-1} in 1993-95. This rate was down 8 percent from 59 kg NPK ha^{-1}yr^{-1} in 1983-85. Stoorvogel and Smaling (1990) reported net losses of around 49 kg NPK ha^{-1}yr^{-1} for Sub-Saharan Africa where yields and nutrient application rates tend to be lower. Their estimates included such factors as erosion. Comparing LAC nutrient balances between 1984 and 1994 indicates that nutrient depletion under rice and maize is accelerating. On a subregional basis, the Andean, Caribbean, and Mesoamerica regions[18] had average depletion rates in 1994 of 40-43 kg ha^{-1}yr^{-1} and the Southern Cone countries 59 kg ha^{-1}yr^{-1}. These rates are 30, 39, 10, and 9 percent lower, respectively, compared to 1984.

In order to develop nutrient balance maps, we applied the nutrient balances for each of the major Latin America and the Caribbean cereals: wheat, rice, maize, and sorghum (which together account for around 36 percent of the arable crop area) onto maps of crop distribution for each cereal estimated by IFPRI (Sebastian and Wood 2000). The four resulting nutrient balance maps were aggregated to obtain a soil nutrient balance map for lands under cereals *(see Map 14a)*. The predominance of negative balances for the period 1993-95, particularly in Argentina, is clearly visible. Positive balances appear for Venezuela and Ecuador because of the positive nutrient balance assigned to maize in those countries. The major areas of significantly negative nutrient balance in cereal production are found in Buenos Aires province in Argentina, as well as in other parts of Argentina and in the Brazilian cerrados.

HOT SPOTS AND BRIGHT SPOTS IN LATIN AMERICA AND THE CARIBBEAN PRODUCTIVITY TRENDS

Information on cereal yield trends (1975-95) was combined with that of nutrient balances *(see Map 14b)*. Long-term cereal yield trends are positive in Argentina, Chile, much of southern Brazil, Uruguay, Venezuela, and much of Mexico. Cereal yields were stationary or decreasing in northeast Brazil, Paraguay, most parts of the Andean countries, and many Caribbean countries.

The superposition of yield trend and nutrient balance maps provides insights into the spatial pattern of agricultural productivity trends *(see Map 14c)*. Potential bright spots were defined as stable or increasing yields with positive or only marginally negative nutrient balances (0 to –25 kg/ha per year), noting that Latin America and the Caribbean fertilizer application rates are seldom sufficient to pose major water pollution threats. Potential hot spots were identified as areas in which yields are decreasing and the nutrient deficits are greater than 25 kg/ha per year, or where yields are stable but the nutrient deficit is greater than 100 kg/ha per year.

The mapped index draws attention to ongoing deterioration of the biophysical production capacity of agroecosystems, a situation that is not sustainable in the long term. At some time (unspecified here as we have insufficient data to assess the total nutrient stock of soils), land must either be abandoned, left as fallow to naturally restore its fertility, or additional investments must be incurred to replenish nutrient stocks.

Interpreting Regional and Global Soil Quality

For the foreseeable future, human food supply will continue to depend upon maintaining the productive potential of soil. Water and carbon cycles will depend on maintaining the ecosystem services of soils. It is difficult to relate the impacts of soil erosion and changing soil quality to agricultural supply, ecosystem condition and human welfare.

Rough estimates of agricultural productivity loss, based on GLASOD data, suggest cumulative productivity loss from soil degradation over the past 50 years to be about 13 percent for cropland and 4 percent for pastureland (Oldeman 1998:4). Crop loss yields in Africa from 1970-90 resulting from water erosion alone are estimated to be 8 percent (Lal 1995). The economic losses from soil degradation range from under 1 to 7 percent of agricultural gross domestic product (AGDP) in South and Southeast Asia (Young 1994), and under 1 to 9 percent of AGDP in eight African countries (Bøjö 1996). Unfortunately, most of these estimates are based on crude models using the areal extent of degradation, average aggregate rates of degradation extrapolated from experimental plots, and average values of lost yield. They fail to highlight the variations between regions or land use systems in soil conditions that are crucial to guiding policy and action.

Analyses at the subregional level are much more reliable, as they are able to take into account variations in soil, soil management, and farm economic conditions (for examples, see Ali and Byerlee forthcoming; Huang et al. 1996; Lindert forthcoming). Many farming communities have been successful in modifying their resource management practices in response to levels of degradation that might threaten their livelihoods or in response to new opportunities to capitalize the value of land improvements (Boserup 1965; Scherr 1999b). The indicators currently available, however, do not allow us to monitor such trends. Furthermore, data that would permit analysis of the capacity of different soils to recover from degradation, and hence the long-term risk to food security, is largely unavailable for many soil types.

Enhancing the Capacity of Soils to Provide Goods and Services

In considering the significance of soil constraints, it is important to recognize that many plants are adapted to tolerate some constraints if they are not too severe, even though higher yields are likely to be obtained in unconstrained soils. Irrigated paddy rice production systems create a unique flooded soil environment for the rice plant that overcomes many constraints inherent in the original soils. Tree and shrub species, such as *Atriplex*, grow in saline soils, *Eucalyptus* in poorly drained soils, *Tithonia* in phosphorus-deficient soils, tea in acid soils, and olives in dry soils. Crop-improvement programs around the world are actively seeking to develop germplasm that can produce acceptable yields, even with soil constraints such as moderate acidity and salinity. In many cases, farmers can grow crops in less hospitable environments by amending, draining, or specially preparing the soil. If land with better soils is unavailable, they may simply tolerate relatively low yields to obtain essential crop products.

Raising the productive capacity of soils, those inherently constrained as well as those whose capacity is being reduced by degradation, is an increasingly strategic area of agricultural research. On the one hand are the goals of arresting soil degradation; on the other is the growing belief that increased understanding of nutrient recycling, soil organic matter dynamics, and soil biology will help design of more efficient production systems that accentuate synergies between abiotic and biotic resources. Early efforts, that increasingly try to link scientific and local innovations, include greater use of nitrogen-fixing legume crops or trees; incorporation of crop residues, and animal and green manure, and soil treatments with locally available materials, such as leaf litter, lime, and rock phosphates. Researchers are developing lower-cost conservation practices, such as contour vegetative strips producing cash crops, that increase short-term productivity and income and, thus, encourage farmer adoption. Many "bright spots" where soil quality is improving have been identified (Scherr and Yadav 1995), and, in the past decade, public and NGO investment in agricultural land protection, rehabilitation, and improvement has increased significantly. Major multilateral efforts to develop and apply such integrated soil, water, and nutrient management approaches include the World Bank-coordinated Soil Fertility Initiative for Africa (SFI 2000) and the CGIAR's Soil, Water, and Nutrient Management Program (SWNM 2000). The Convention to Combat Desertification (UNCCD 2000) promotes dryland rehabilitation. There may be future avenues to mobilize private investment in land improvement for carbon emission offsets through the Kyoto Protocol of the Climate Change Convention (UN FCCC 2000). Ultimately, whether farmers invest to maintain and improve soil quality will depend on the economic prospects of agriculture, and the mobilization of investment resources.

Although such initiatives face significant challenges, the potential gains from improving soil quality are more far-reaching than the increased welfare of food producers and consumers. Improved soil quality will also enhance agroecosystem capacity to maintain water flow regulation, water quality, crop and soil biodiversity, and carbon storage services.

Summary of Indicators and Data

The analysis of inherent soil constraints presented a relatively static picture of soil resource quality domains within which various forms of degradation are occurring. Therefore, they are not indicators of soil capacity in and of themselves, but are useful to stratify observations of selected indicators such as SOM and nutrient balance, across broader, similar areas (using soil process or pedotransfer models). The SOM measure shown here was derived from the same type of soil survey data as the soil constraints analysis and, thus, is also static. The intent is that SOM monitoring would take place on a more frequent and spatially representative basis. Future indicators are likely to be developed by a more strategic monitoring of specific parameters such as SOM, soil acidity, salinity, and nutrient stocks, through a combination of remote sensing and community-level monitoring of variables of local interest.

The development of soil indicators is likely to demand and promote a two-way flow of information between communities and land management institutions. Researchers need to do much more work to develop indicators that relate soil quality changes to land use and management, and to their production, economic, and environmental impacts.