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SOIL MANAGEMENT IN THE DEVELOPING COUNTRIES

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The present world population of 6 billion will reach 8 billion by 2020 and 9.4 billion by 2050. By then, the population will have increased by another 575 million in India, 300 million in China, 200 million in Nigeria, 200 million in Pakistan, and 140 million in Ethiopia. Of the total world population, 8.2 billion will live in developing countries, of which 3 billion will reside in arid and semiarid environments. Thus, soil management challenges for developing countries include achieving food security with minimal risks to environment given per capita land area decreasing to <0.1 ha and per capita irrigated land area to <0.04 ha, severe scarcity of renewable fresh water resources, high risks of soil degradation by a wide range of degradative processes, resource-poor farmers, and weak institutional support. Productivity loss attributable to erosion-caused soil degradation is estimated at 18 million Mg of food staples per year at the 1990 level of yields for subSaharan Africa and 272 million Mg for the world at the 1996 level of production. The productivity loss at a landscape level may range from 0 (or even positive effect) to total crop failure. In addition to enhancing productivity per unit area and per unit time, soil management technologies must also address pressing environmental issues, especially with regard to the greenhouse effect and air quality, water quality, and land application of industrial and urban wastes. Enhancing food production would necessitate adoption of land saving technologies through agricultural intensification on prime agricultural land, conversion of marginal lands to other appropriate land uses, and restoration of degraded lands and ecosystems. Soil-specific technologies for agricultural intensification will have to be developed, fine-tuned, and adopted. These technologies will address the issue of: (i) enhancing soil structure, (ii) increasing nutrient use efficiency through integrated nutrient management and strengthening nutrient recycling mechanisms, (iii) conserving soil and water through residue management and adoption of conservation tillage, (iv) improving water use efficiency through development and adoption of efficient methods of water harvesting, recycling and irrigation, and (v) increasing cropping intensity. Improvements in rainfed agriculture through water conservation and enhancing water and nutrient use efficiencies will be a major challenge in subSaharan Africa, India, Central Asian countries, northeastern Brazil, and other semiarid regions of the developing world. Preventing and restoring degraded soils, enhancing soil C sequestration to mitigate the greenhouse effect, and decreasing risks of eutrophication of surface water and contamination of ground water will be priority issues. Soil scientists will need to work closely with those in the basic sciences to address the environmental concerns of agricultural intensification. There is a strong need for high quality, credible, innovative, original, and demand-driven research in soil science in developing countries. Research managers can facilitate achievements of goals of high quality science by creating a conducive and trustworthy work atmosphere and by rewarding productivity and merit. (Soil Science 2000;165:57–72)

Key words: Soil degradation, soil quality, greenhouse effect, soil erosion, soil salinity, tropical ecosystems, food security.

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A WORLD population of 6 billion in 1998, increasing at the rate of 1.8% per year, is expected to reach 8 billion by the year 2025 and 9.4 billion by 2050 (Hulse 1995; Fisher and Helig 1997; Litvin 1998). Most of the increase in population will occur in developing countries where nearly 1 billion people are already underfed and malnourished. The global demand for food may double over the period 1990–2030, with an increase of 2.5 to 3 times in developing countries as a whole and as much as 5 times in countries of subSaharan Africa (SSA) (Daily et al. 1998). Although the carrying capacity of the land is estimated by some to be as much as 50 billion humans (Hulse 1995), such drastic increases in demand for food and other resources derived from soil over a short period necessitate careful appraisal of soil and water resources with regard to their potential, natural and anthropogenic constraints, and environmental consequences of agricultural intensification. The problems of imbalance between people and natural resources are especially critical in developing countries (in Asia, Africa, South and Central America and the Caribbean, and newly independent states of eastern Europe and central Asia), where soil resources are often limited in extent and depleted in inherent fertility, the climate is harsh with highly variable and erratic rainfall, and the institutions and infrastructure needed to manage soil, and environment-related constraints and to enhance productivity are weak and poorly developed.

Soil, or the pedosphere, is in dynamic equilibrium with the biosphere, hydrosphere, atmosphere, and lithosphere. Its interaction with the biosphere forms the basis of all terrestrial life, with the hydrosphere leads to filtration of natural and anthropogenic chemicals from the water, with the atmosphere leads to fluxes of radiatively active gases, and with the lithosphere initiates recycling of elements and formation of new soil through weathering. Human society depends on soil for growing its food, recycling its waste, building its structures, and purifying its water. Drastic anthropogenic perturbations in this delicate equilibrium can lead to severe degradation of soil and water qualities, decline in productivity, emissions of radiatively active gases to the atmosphere, poverty, malnutrition, hunger, and economic regression. Therefore, sustainable management of soil must form the basis of economic development in these countries.

The objective of this manuscript is to describe soil and water resources of the developing countries, assess the magnitude and severity of soil degradation, outline soil-related constraints to enhancing productivity, and identify research and development priorities to alleviate these constraints.

SOIL AND WATER RESOURCES

The prime agricultural soil resources are finite, nonrenewable over the human time frame, unequally distributed over the geographical regions, and prone to degradation by misuse and mismanagement. As a result of the rapidly increasing population and the finite extent of soil resources, the per capita arable land area in developing countries is declining rapidly (Table 1). Although the per capita land area varies widely, the rate of its decline is about the same among major geographical regions of the developing countries, except those in eastern Europe where the trends are toward increase in area over time (Fig. 1). By 2025, the per capita land area in China and India will be 0.05 and 0.07 ha, respectively. The decline in arable land area is exacerbated by conversion of agricultural land to other uses (i.e., urbanization, infrastructure development) and soil degradation. The finite nature of arable land resources implies that the increase in food production will have to continue to come from agricultural intensification and increases in crop and animal production per unit area and per unit time from land already in production.

There are also severe constraints on renewable fresh water resources in some countries of the developing world. The nonavailability of hygienically clean water to about 1 billion people is the cause of 2 million infant mortalities a year in

TABLE 1

Regression equations to predict temporal changes in per capita land area for principal regions of the third world (calculated from FAO 1996; Engelman and LeRoy 1995)

Region	Number of countries	Regression equation	R^2
South Asia	7	$A = 0.32e^{-0.01Y}$	0.88
Southeast Asia and China	9	$A = 0.31e^{-0.02Y}$	0.92
Middle East	10	$Y = 0.63e^{-0.02Y}$	0.98
Sub-Saharan Africa	26	$Y = 0.51e^{-0.02Y}$	0.99
Latin America	13	$Y = 0.41e^{-0.02Y}$	0.99
Eastern Europe	6	$Y = 0.47e^{-0.004Y}$	0.58

A = area in ha; Y = years between 1960 and 2025.

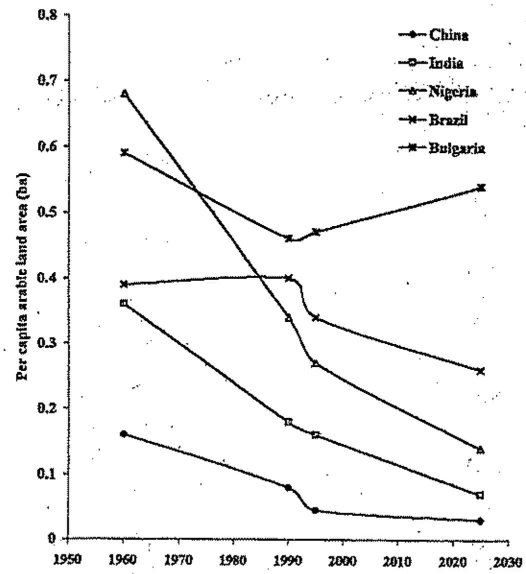

Fig. 1. Trends in per capita arable land area in some countries (replotted from FAO 1996; Engleman and Roy 1995).

developing countries (Litvin 1998). In many countries, there is also a severe shortage of renewable fresh water both for agricultural use and for human consumption. This shortage is bound to be exacerbated by the rising population. There are at least 30 populous countries that will face severe water shortage by 2025, and these include densely populated Egypt, India, and Nigeria (Table 2).

TABLE 2

Countries with per capita fresh renewable water less than 1700 m^3 by 2025 (adapted from Gardner-Outlaw and Engelman 1997).

Country	Per capita fresh water availability (m^3) by 2025
Afghanistan	1105
Algeria	313
Bahrain	104
Burkina Faso	1194
Burundi	292
Egypt	607
Eritrea	1256
Ethiopia	807
India	1567
Iran	916
Jordan	144
Kenya	602
Kuwait	55
Lebanon	1261
Lesotho	1290
Libya	47
Malawi	917
Morocco	751
Niger	1452
Nigeria	1175
Peru	1126
Poland	1406
Rwanda	485
Saudi Arabia	107
Somalia	570
South Africa	698
Tanzania	1425
Tunisia	288
Uganda	1467
Zimbabwe	1034

IRRIGATED AGRICULTURE

Of the 255 million ha (Mha) comprising the world's total irrigated land area in 1995 (Postel 1999), about 75%, or 190 Mha, is in developing countries (Table 3). The irrigated land area in the developing countries has increased by 60% since the early 1960s (Pinstrup-Anderson et al. 1997). It accounts for about 7.5% of all irrigated cropland and grazing land (World Bank 1997; Nelson et al. 1997), but it produces a large portion of the food, especially in developing countries of the arid regions such as the Central Asian Republics, Egypt, Pakistan, Iran. Throughout the world, about 17% of irrigated cropland produces 40% of the total food (Postel 1999). Irrigation is the basis of agriculture in Central Asian countries, and the per capita arable land area there ranges from 0.12 to 0.31 ha. Similar to the per capita cropland area, however, per capita irrigated land area—which in 1996 was barely 0.02 ha in Indonesia, 0.027 ha in Bangladesh, 0.04 ha in China and 0.05 ha in India (Table 3)—is also declining. Development of irrigated agriculture has lagged seriously behind the population growth and food demand in SSA. Consequently, the per capita irrigated land area in most countries of SSA is extremely small (Table 4).

SOIL-RELATED CONSTRAINTS TO CROP PRODUCTION

The principal soils of the developing countries of the tropics and subtropics are listed in Table 5. Predominant soils of the tropics include Oxisols, Ultisols, and Alfisols in the humid regions and Alfisols, Aridisols, Inceptisols, Entisols, and Vertisols in the dry regions. Some of these soils have severe inherent constraints to agricultural intensification (Stewart et al. 1991). The ease of achieving sustainable production in these soils decreases exponentially with increasing climatic aridity, which implies that achieving sustainable

TABLE 3
Total and per capita irrigated land area in some developing countries in 1996

Country	Irrigated land area (10^6 Ha)	Irrigated land damaged by salt (10^6 Ha)	Per capita irrigated land area (ha)
India	50.1	7.0	0.053
China	49.8	6.7	0.040
Pakistan	17.2	4.2	0.123
Iran	7.3	1.7	0.104
Mexico	6.1	1.6	0.065
Russia	5.4	NA	0.036
Thailand	5.0	1.5	0.085
Indonesia	4.6	NA	0.022
Turkey	4.2	NA	0.068
Uzbekistan	4.1	2.4	0.172
Iraq	3.5	NA	0.170
Egypt	3.3	0.9	0.052
Bangladesh	3.2	1.3	0.027
Brazil	3.2	NA	0.052
Romania	3.1	0.3	0.137
Afghanistan	2.8	1.3	0.134
Kazakhstan	2.4	NA	0.143
Azerbaidzhan	1.4	NA	0.184
Turkmenistan	1.3	1.1	0.312
Kyrgyzstan	1.1	NA	0.246
Tadzhikistan	0.7	0.3	0.118

FAO (1976, 1988, 1994, 1996); Ghassemi et al. (1995); Turnbull (1991); World Bank (1993a, b, c).
NA = data not available.

agricultural production is more difficult in hot and dry than in cool and moist regions. Soil-related constraints to agricultural productivity are so severe that only a third of all rainfed cultivable area in developing countries (excluding China which has severe problems, but the statistics are not available) is free of major soil-related constraints (Table 6; Alexandratos 1995). Severe nutrient depletion in soils of SSA (Smaling and Oenema 1997; Stoorvogel et al. 1993), low inherent fertility in soils of the humid and subhumid tropics (Sanchez and Buol 1975; Greenland, 1975, 1981, 1991; Lal 1990b), and Al^{+} toxicity and P deficiency in soils of the acid tropical savannas in South America (Sanchez et al., 1982) are among principal soil chemical constraints to practicing agricultural intensification and obtaining high yields. There are also severe soil physical constraints, especially soil compaction and decline of soil structure, in soils of semiarid and subhumid regions (Lal 1987). Soil

TABLE 4
Per capita irrigated land area in some countries of subSaharan Africa in 1995 (FAO 1996)

Country	Irrigated land (10^3 ha)	Per capita irrigated land (ha)
Benin	7	0.0014
Burkina Faso	25	0.0031
Ethiopia	165	0.0030
Ghana	8	0.0005
Kenya	52	0.002
Mali	210	0.021
Niger	45	0.0053
Nigeria	880	0.0074
Senegal	180	0.023
Somalia	120	0.013
Sudan	1920	0.070
Tanzania	155	0.005
Uganda	9	0.0005

TABLE 5
Land area of predominant soil orders in the tropics (Buringh 1979; Van Wambeke 1991)

Soil order	World land area		Land area in the tropics	
	10^6 Ha	(%)	10^6 Ha	(%)
Alfisols	1730	13.1	800	16.2
Aridisols	2480	18.8	900	18.4
Entisols	1090	8.2	400	8.2
Histosols	120	0.9		
Inceptisols	1170	8.9	400	8.3
Mollisols	1130	8.6	50	1.0
Oxisols	1120	8.5	1100	22.5
Spodosols	560	4.3		
Ultisols	730	5.6	550	11.2
Vertisols	230	1.8	100	2.0
Highlands	2810	21.3	600	12.2
Total	13170	100.0	4900	100.0

TABLE 6

Estimates of rainfed cropland area prone to soil-related constraints to practicing intensive agriculture and obtaining high yields in developing countries (Modified from Alexandratos 1995; Scherr 1999)

Constraint	Sub-Saharan Africa	Latin America and the Caribbean	Near East/ North Africa	East Asia (excluding China)	South Asia	Developing countries
	%					
Low soil fertility	42	46	1	28	4	38
Sandy or stony soil	36	15	17	11	11	23
Poor soil drainage	15	28	2	26	11	20
Steep slopes	11	6	24	13	19	10
Total land with one or more constraints	72	72	43	63	42	67

physical constraints are particularly severe in Alfisols, Aridisols, and Inceptisols (Lal 1994). The data in Table 6 show the regional extent of soil-related constraints to rainfed agriculture in developing countries where the principal limitations are low inherent soil fertility and nutrient imbalance, sandy or stony soils with low available water capacity and susceptibility to drought, and poor soil drainage leading to anaerobiosis and steep slopes. Cultivation of steepland poses a major challenge in many regions of Central America, the Andes, the Himalayan-Tibetan ecoregions, southeast Asia, and the Pacific (Lal 1988b; Table 7). Although of relatively less extent, cultivation of steeplands is also an environmental hazard in eastern Europe (Nemeth et al. 1998). Alleviation of these constraints requires capital-intensive inputs that resource-poor farmers cannot afford. Further, institutional support and credit facilities are not available for ameliorative technologies that have proven successful on agricultural experiment stations and field plots.

HUMAN-INDUCED SOIL DEGRADATION

The adverse effects of inherent constraints on productivity and environment are exacerbated by land misuse, soil mismanagement, and subsistence farming by resource-poor farmers. The occurrence of widespread soil degradation in developing countries is attributed to cultivation of marginal lands (steep slopes, shallow soils) in harsh and highly variable climates. Cultivation of marginal lands is inevitable because of a shortage of prime agricultural land in some densely populated regions (Nelson et al. 1997). Soil degradation is especially severe in South and Southeast Asia (Sehgal and Abrol 1994; FAO 1994; Van Lynden and Oldeman 1998) and SSA (Lal 1988a; Steiner 1996), primarily because all inputs made to the soil are drastically lower than products harvested. Complete residue removal for fodder and fuel is a norm in these agroecosystems.

There are several qualitative estimates of the regional and global extent and the severity of soil degradation. The data in Table 8 show that 75% of the world's land area prone to water erosion, 83% prone to wind erosion, 90% prone to chemical degradation, and 60% prone to physical degradation occurs in developing countries. Of the world's total degraded land area, estimated at 1964 Mha, about 78% is in the developing countries. Soil nutrient depletion continues to be a major problem in Africa. Average annual nutrient loss on arable land in Africa in the early 1990s was estimated at 22 kg N/ha, 2.5 kg P/ha, and 15 kg K/ha. Consequently, the total nutrient loss in soils of Africa over the 30-year period is an equivalent of 1.4 Mg/ha of urea, 375 kg/ha of single superphosphate, and 900 kg/ha of muriate of potash (Stoorvogel et al. 1993).

Soil degradation, especially that attributable to pollution and contamination by disposal of urban and industrial wastes and salinization, is also

TABLE 7

Area of sloping land in some tropical regions (Adapted from Purnell 1986)

Slope %	% of land area					Total area	
	Africa	SW Asia	SE Asia	C. America	S. America	10^6 Ha	%
0–8	58	45	40	35	52	3,340	51
8–30	34	31	31	40	30	2,107	33
>30	8	24	29	25	18	1,048	16

TABLE 8

Soil degradation in third world countries (WRI 1992–93; Oldeman 1994)

Region	Water erosion	Wind erosion	Chemical degradation	Physical degradation	Total
	10^6 ha				
Africa	227.3	187.8	59.3	19.8	494.2
Asia	435.2	224.1	74.7	15.0	747.0
Central America & Mexico	46.5	4.4	6.9	5.0	62.8
South America	124.1	41.4	70.6	7.3	234.4
Total	831.1	457.7	211.5	47.1	1538.4
World total	1100.0	550.0	235.8	78.6	1964.4
% of the world total	75.6	83.2	89.7	59.9	78.3

severe in eastern Europe (Szabolcs 1997) and the newly independent countries of central Asia. About 1.5 billion Mg (10^9 Mg) of topsoil is washed away by water erosion annually in the former Soviet Union (Fireman 1991; Edwards 1993; Åhlander 1994; Allison 1996). The data in Table 9 show the percent of the land area affected by soil erosion in some east European countries, a serious problem in Serbia/Bosnia, Croatia, and Bulgaria (Németh et al., 1998). Transport of sediments and organic matter from intensively cultivated steeplands in the catchment has been a major cause of pollution of Lake Balatan in Hungary (Table 10). In Central Asia, Amu Darya and Syr Darya transport 270 million Mg (10^6 Mg) of sediments annually, along with a very high dissolved load of more than 7 mg/L (Kaser and Merhotra 1996). Ecological degradation in Central Asia, although less known, is similar to that in North Africa and SSA (Wolfson 1992). Vast amounts of sand and salt are blown out of the drying Aral Sea annually into the surrounding land. Central Asia's ambitious cotton production program has been an experiment in ecological disaster on a grand scale (Rumer 1991). Air pollution from industrial emissions is also a severe hazard in Central Asia (Åhlander 1994; Kaser and Merhotra 1996).

Soil degradation of drylands in arid and semiarid regions is called desertification and is a serious problem in developing countries of these regions (Dregne and Chou 1992; UNEP 1991). The data in Table 11 show that of the 3.6 billion ha of total land area subject to desertification, soil degradation accounts for 259 Mha, soil and vegetation 757 Mha, and vegetation of the rangeland 2576 Mha. The degradation in drylands is caused by water erosion on 478 Mha, wind erosion on 513 Mha, chemical processes on 111 Mha, and physical processes on 35 Mha (Oldeman and Van Lynden 1998). Dregne and Chou (1992) estimated that 71% of Asian drylands are prone to desertification, including 76% of rangelands, 56% of dry rainfed lands, and 35% of irrigated lands. Estimates of desertification in Africa show that 74% of rangeland, 61% of rainfed cropland, and 18% of irrigated lands are severely affected in 33 countries of the region (Dregne 1990; Dregne and Chou 1992). In Mexico and Central America, 75.4% of 570 Mha of drylands are degraded (Dregne and Chou 1992).

Degradation of irrigated land by salinization is a serious problem that needs careful planning for adoption of restorative measures. Irrigated land area affected by soil salinity is estimated at 14.0% of the total irrigated land area in India,

TABLE 9

Land use in East European countries and the magnitude of soil erosion (Adapted from Németh et al. 1998)

Country	Arable land (% of total)	Land affected by erosion (% of total)	Soil erosion (10^6 m^3/ha)
Bulgaria	34	64	136*
Croatia		90	
Czech Republic	40	17	
Hungary	51	25	80–100
Romania	41	31	126
Serbia, Bosnia etc.	32	89	73
Slovak Republic	31	11.5	

*10^6 mg/yr

TABLE 10

Annual transport of sediments and humus into Lake Balatan in Hungary (Toth and Fekete 1974)

Slope (%)	Catchment area (ha)	Soil erosion (Mg/ha)	Loss of soil humus (Mg/yr)
0–5	175	1030	23.7
5–12	164	2475	46.3
12–17	129	3603	86.2
17–25	169	8672	122.4
25–50	31	1764	21.2

13.5% in China, 24.4% in Pakistan, 26.2% in Mexico, 27.3% in Egypt, and 60.0% in Uzbekistan (Table 3). The problem of soil salinization is most severe in Central Asian countries, where irrigated cotton production has brought about ecological disaster. Irrigation is the predominant use of water in Central Asia, accounting for 90% of withdrawals, 95% of consumptive use, and 84% of return flows in 1980 (Pryde 1991). Irrigation is used in more than 90% of crop production. In Turkmenistan, 17.4 km^3 of the 19.8 km^3 available water in 1990 was used for irrigation, and 2.2 km^3 was used by industry, leaving 0.2 km^3 for household use. In Uzbekistan, 44.6 km^3 of the 5.24 km^3 was used by irrigation, 6.1 km^3 by industry, and 1.9 km^3 by households (Turnbull 1991). The Aral Sea basin contains about 97% of the irrigated area in Central Asia. The irrigation efficiency is very low, with 40% lost during conveyance (Pryde 1991).

As a result of the excessive water use and low irrigation efficiency, the Aral Sea has decreased in volume by 54%, the sea level has fallen by 25%, salinity has increased from 10 to 27 g/L, the shoreline has receded by 200,000 km^2, and about 75 million Mg of salt blows out of it annually onto the surrounding land (Kaser and Merhotra 1996). Consequently, the biological productivity of the ecosystem has declined by 30 to 50%. The desert lands of Central Asia, Kyzul-kum and Kara-kum, have increased in area from 22–24% to 35–40% during the 20th century (Wolfson 1992).

Faulty water application systems based on flood irrigation, high seepage losses from unlined canals, and excessive irrigation have led to problems of severe waterlogging and salt build-up in irrigated lands because of faulty policies regarding subsidizing irrigation water and power. It is estimated that 110 Mha of irrigated lands have been degraded to some extent over the past 300 years (Rozanov et al. 1990). With extremely low efficiency, even a small improvement in irrigation delivery and methods of application would lead to considerable savings in water, reduced risks of salinization, and aversion of ecological disasters.

Soil degradation has brought about severe productivity losses. Salinity has also caused drastic reductions in the cotton yield of Central Asia. A yield reduction greater than 20% has been reported on 30% of the cotton-producing area in Kyrgyzstan, 35% in Tadjikistan, 89% in Turkmenistan, and 61% in Uzbekistan (World Bank 1993 a, b, and c). Productivity losses are also severe in regions of subsistence agriculture in Africa (Dregne 1990; Tengberg and Stocking 1997) and Asia (Dregne 1992), where farmers ei-

TABLE 11

Extent of desertification as estimated by UNEP (1991) and GLASOD (Oldeman and Van Lynden 1998)

UNEP (1991)		GLASOD (1998)	
Land type degraded	Area (10^6 Ha)	Type of soil degradation	Area (10^6 Ha)
Irrigated land	43	Water erosion	478
Rainfed cropland	216	Wind erosion	513
Rangeland (soil and vegetation)	757	Chemical degradation	111
Subtotal	1016	Physical degradation	35
Rangeland	3592	Total	1137
Total degraded land	5172		
% degraded	69.5	Light	489
		Moderate	509
		Severe	139
		Total	1137

ther do not use or are unable to use off-farm inputs. Lal (1995a) estimated continent-wide losses in agricultural productivity in Africa attributable to past (1960–1990) erosion. Crop yield losses caused by past erosion ranged from 2 to 40%, with a mean of 6.2% for SSA and 8.2% for the continent. If soils had not been degraded by accelerated erosion occurring since 1960, 3.6 million Mg more of cereals (8.2 million for the continent), 6.5 million Mg more of roots and tubers (9.2 million for the continent), and 0.4 million Mg more of pulses (0.6 million for the continent) would have been produced.

Productivity losses caused by soil degradation are also severe in Asia, especially in the seven countries of south Asia. As much as 20% loss in productivity has reportedly occurred as a result of soil degradation in parts of China, India, Iran, Israel, Jordan, Lebanon, Nepal, and Pakistan (Dregne 1992). Oldeman (1998) estimated that since World War II, soil degradation in Asia has led to cumulative losses in productivity of 12.8% in cropland and 4.7 to 8.9% in cropland and pasture together. There is a serious fertility decline in salt-affected soils (Van Lynden and Oldeman 1998), especially in Pakistan. Yield reductions caused by soil degradation in the 1980s may have been as much as 60% in many regions of China (Huang and Rozelle 1994, 1996). Sehgal and Abrol (1994) observed that soil degradation is a serious problem in India, where 57% of the land is undergoing degradation. To increase food production in India by 50% by the year 2025, careful planning will be needed to reverse these soil degradative trends.

In 1998, Lal estimated the loss in global food production caused by soil erosion. For the 1995 level of food production, erosion-caused productivity losses of 10% in cereals (190 million Mg), 5% in soybeans (6 million Mg), 5% in pulses (3 million Mg), and 12% in roots and tubers (73 million Mg). The total loss of 272 million Mg of food production constituted 31 million Mg in Africa, 187 million Mg in Asia, and 16 million Mg in South America (Lal 1998).

SOIL DEGRADATION AND THE GREENHOUSE EFFECT

Soil degradation is a principal contributor to the increasing concentrations of radiatively active gases (CO_2, CH_4, N_2O, NO_x) in the atmosphere. World soils and terrestrial ecosystems contribute to the atmosphere about 2 Pg/yr (1 Pg (petagram) = 10^{15} g = 1 billion ton) of C compared with 6.0 Pg/yr contributed by fossil fuel combustion (IPCC 1995). World soils have been a major source of atmospheric increase in CO_2 since the spread of civilization and the dawn of settled agriculture. Rozanov et al. (1990) estimated the loss of soil C (assuming that soil humus contains 58% C) at the rate of 14.7 Tg/yr (1 Tg (teragram) = 10^{12} g = 1 million ton) since agriculture began 10,000 years ago, 204 Tg/yr in the past 300 years, and 440 Tg/yr in the last 50 years. According to these estimates, historic C emission from soils to the atmosphere is about 230 Pg. The magnitude of C loss from soil to the atmosphere has been estimated at 150 Pg by Bohn (1978), 450 to 570 Pg by Buringh (1982), 450 Pg by Wallace (1994), 40 to 80 Pg by IPCC (1995), and 90 to 100 Pg by Lal (1999a). Development and identification of strategies for mitigating the greenhouse effect necessitate that reliable estimates be made of the historic loss of C from soil to the atmosphere.

Depletion of the soil organic carbon (SOC) pool is accentuated by soil degradative processes, including erosion, decline in soil structure, salinization, acidification, and reduction in activity and species diversity of soil fauna. Global emission of carbon from sediments displaced by water erosion is estimated at 1.14 Pg C/yr (Lal 1995b). It is difficult to estimate the historic loss of C caused by past erosion, but it may be substantial (Lal 1999 a and b). The loss of soil C caused by desertification in drylands may also be high. Lal et al. (1999a) estimated that soil erosion from drylands causes annual emissions of 0.23 to 0.29 Pg C/yr, which may be an underestimate because of the difficulty of computing the loss of soil inorganic carbon (SIC) caused by water and wind erosion (Lal et al. 1999b; Nordt et al. 1999). Lal and Logan (1995) estimated C emission from soils and ecosystems of the tropics. The rate of C emission may be 0.5 Pg/yr, with total historic cumulative emission of 45 Pg (Table 12).

The depletion of the SOC pool from the root zone, both as a result of cultivation and the attendant degradative processes, has severe adverse impacts on soil productivity and environmental quality. In addition to the release of radiatively active gases to the atmosphere, depletion of the SOC pool degrades soil structure and increases soil erodibility and transport of sediments and sediment-born pollutants to natural waters. Leaching losses of NO_3^- and other chemicals are also accentuated by depletion of SOC pool.

RESEARCHABLE ISSUES IN SOIL MANAGEMENT

Sustainable management of soil and water resources will continue to play a major role in eco-

TABLE 12
C emissions from soils of the tropics (modified from Lal and Logan 1995)

Agricultural activity	Rate of emission (Tg/yr)	Historic/cumulative emission (Pg)
Deforestation and shifting cultivation	160 (93–227)	(2.3–3.2)
Arable land use	63 (38–92)	16.7 (10–24.5)
Pastures	92 (55–133)	24.5 (14.7–36.0)
Rice paddy	0.1 (0.05–0.13)	
Peat soils	2 (1.5–3.0)	0.4 (0.3–0.6)
Total	505 (300–732)	45 (27–74)

Figures in parenthesis are ranges.

nomic development of the developing countries. Principal issues that need to be addressed are food security, greenhouse effect, and water quality. In addition, there are some geographical regions in which the problems of soil management are more severe than in others, and there is a need for improvements in research quality and approaches to research management.

Food Security

The proportion of malnourished and underfed population may continue to grow in some regions of south Asia and SSA, not only because of the food deficit but also because of the poor accessibility and nonavailability of food to both rural and urban poor. While applications of soil science may not enhance accessibility, they can certainly increase the quantity or supply of agricultural products. In this regard, some important researchable issues include the following:

Agricultural intensification

With rapidly declining per capita land area, the principal strategy is to enhance food production per unit area and per unit time on existing agricultural land. While input-responsive and high yielding varieties are being developed by plant breeders and biotechnologists, it is important that increase in productivity is achieved without mining of the topsoil depth, depletion of the SOC pool, lowering of the water table, buildup of toxic levels of salts in the root zone, or impairment of other ecosystem services that maintain air and water qualities. The strategy is to improve soil productivity on a sustainable basis while improving soil and water quality. Control of severe erosion on steeplands (Moldenhauer and Hudson 1988) has to be achieved through integrated soil management based on the options discussed below:

Soil structure management Risks of decline in soil structure, stability, and continuity of pores to facilitate transport and retention of fluids and growth and proliferation of roots will have to be minimized. Although the deficiency of N (Cassman and Pingali 1995) and micronutrients cannot be overruled, decline in productivity of the rice-wheat belt of south Asia (Hobbs and Morris 1996) may be caused by decline in soil structure caused by puddling for rice cultivation. Decline in soil structure is exacerbated by complete removal of crop residue and other biomass from the soil for fodder and fuel. Decline in soil structure under continuous cropping also remains to be a challenge for soils of SSA, tropical America and Central Asia.

Integrated nutrient management Although fertilizer use has increased drastically in Asia, especially in China and India, it lags severely behind the production demand in SSA. If fertilizer use is not made at the optimum level, especially in SSA, the results will be damaging and counterproductive to human welfare. Indiscriminate use of fertilizers in Asia, with disregard of the need for application at a soil-specific rate and through appropriate formulations, has caused severe environmental hazards with regard to eutrophication of surface waters and contamination of ground water. Thus, fertilizer management must be based on a soil's capacity to supply nutrients at a time and rate required by crop growth. Rather than relying entirely on chemical fertilizers, it is important to strengthen nutrient recycling mechanisms. The latter include using farmyard manure and compost as a source of plant nutrients and for improving soil structure rather than using them as household fuel; enhancing biological nitrogen fixation (BNF) both in upland crops through rotation of cereals with legumes and in rice and other aquatic agroecosystems; and use of refined biosolids from urban and industrial by-products while minimizing the risks caused by contamination by heavy metals. Matching the nutrient demand from the crop with the nutrient supply from diverse sources (e.g., fertilizers, manure, BNF, nutrient recycling) is critical to improving nutrient use efficiency and minimizing leakage into the environment. The basic concept leading to soil-specific or precision farming technology will have to be developed to enhance the use efficiency of costly input.

Tillage methods Development of appropriate tillage systems and supporting equipment remains a high priority (Lal 1987). Merits and limitations of high intensity and frequency of plow-based tillage need to be addressed objectively in relation to soil and ecoregional attributes, crop root system, and socioeconomic and logistic constraints of the highly dynamic farming community. Despite the severe and widespread problems of accelerated soil erosion and adverse soil moisture and temperature regimes during the growing season caused by plowing, conservation tillage with crop residue mulch is not widely practiced in developing countries. Conservation tillage can be adapted even for wheat production in South Asia (Hobbs et al. 1998). Appropriate farming systems will have to be developed to reduce demands on crop residue and biomass for use as fodder and fuel. Most of the crop residue produced must be returned, directly as mulch or indirectly as compost, to the soil. In addition to returning crop residue as mulch, there is a strong need to develop appropriate seeding equipment for facilitating sowing in unplowed seedbed covered with crop residue and for controlling weeds with judicious use of herbicides. Adoption of appropriate conservation tillage methods necessitates development of a package of cultural practices specifically needed for successful adaptation of such a technology. Along with appropriate crop rotations and seeding equipment, soil-specific information is needed for rate and timing of fertilizer application, seeding rate, and integrated post control measures.

Water management Enhancing water use efficiency, both in rainfed and irrigated agriculture, is a high priority for agricultural improvement in developing countries. Although renewable fresh water resources are severely limited, current practices of flood irrigation and soil-water management are inefficient, wasteful, and harmful to the environment. Excessive runoff during the rainy season causes severe problems of erosion and sedimentation in some situations, ground water is being depleted in others, and the water table is rising too rapidly and bringing high concentration of soluble salts into the root zone in still others. The problem of water imbalance (especially in Central Asia and the Indian Punjab) has to be tackled through multidisciplinary and interinstitutional research involving soil scientists, agronomists, hydrologists, agricultural engineers, micrometeorologists, social scientists, economists, and policy makers. The wasteful and harmful system of flood irrigation practiced widely in South Asia must be replaced with furrow, drip, or subirrigation systems. Water harvesting and recycling technologies need to be adopted and used in arid and semiarid regions. There is a need to develop and use irrigation technology based on use of saline/brackish water. Halomorphic plants of industrial importance for pharmaceutical and biofuel purposes, as well as raw materials for other products, must be cultivated and supporting industry developed in arid regions. These income-generating technologies can alleviate poverty and create off-farm employment opportunities.

Prevention and restoration of soil and ecosystem degradation

Although adopting recommended/improved agricultural technology minimizes risks of soil degradation, it is equally important to develop cost-effective and efficient ways to restore degraded soils and ecosystems. There are vast areas of barren wastelands in the developing countries that can be restored through adoption of known and proven technology. Most prevalent forms of degradation include lands eroded by water and wind, ravines and gullied lands, salt-affected soils, crusted and compacted soils caused by overgrazing and overexploitation, soils with nutrient imbalance and low levels of plant-available nutrients, and soils contaminated with or polluted by industrial waste disposal. Problems of these degraded soils and ecosystems are accentuated by the "tragedy of the commons," and a lack of political will and institutional support to implement proven remedial technologies. The enhanced understanding of fundamental properties and processes governing soil resilience (Lal 1997; Blum 1997), factors affecting it, and technological options to accelerate restorative processes will be necessary to renew vast tracts of barren and unproductive wastelands. Developing and adopting strategies of biodegradation of agrichemicals, industrial pollutants and urban waste will need an interdisciplinary approach to address this major challenge. Through adoption of appropriate restorative measures, these soils could become a valuable resource for production of fodder and biofuel, timber and industrial raw material, and for cultivation of fruit trees and other perennial cultures and for farming C through its sequestration in biomass and in soil. In the process of being productive, these soils could become an effective repository of C through enhancement of the SOC pool and could increase formation of secondary carbonates. Restoring 2 billion ha of degraded soils that were once biologically productive could effectively mitigate the accelerated greenhouse effect if the improved land use system could sequester 1.5 Mg C/ha/yr in both soil and the above-ground biota. Thus, the importance of soil restoration in environmental enhancement cannot be over-emphasized. In addition, degraded soils could henceforth become centers of enhancing biodiversity and maintaining nature's reserves. Soil scientists can play a key role in developing a site-specific package of practices for soil restoration. Because of the vastness of the problem, however, coordinated efforts among researchers and policy makers is needed at local, regional, national, and international scales.

Improvement in rainfed agriculture

Developing countries that will experience the largest absolute growth in population by 2050 include India (575 million), China (300 million), Nigeria (200 million), Pakistan (200 million), and Ethiopia (140 million) (Fisher and Helig 1997). By that time, there will be only 1.2 billion people in the more developed countries compared with 8.2 billion in presently less developed countries. Most of the population will be concentrated in Asia and Africa, both regions with finite resources of soil and water and with harsh climates. Therefore, meeting basic demands of this unprecedented large population in developing countries will be a major challenge to soil scientists, land managers, and policy makers. Developing countries now have about half (52%) of the world arable land and 75% of the world population, and whereas the arable land may stay the same or decline, the population will increase to 90% of the world total. Further, at least 3 billion (about 30% of the population) people will live in arid and semiarid regions with severe water shortage problems (Falkenmark 1994) and desertification (UNEP 1991).

The green revolution of the 1960s was ushered in by agricultural intensification through growing input-responsive and high yielding varieties on irrigated lands. While sustaining productivity on irrigated land, future improvements in production have to come from agricultural intensification on rainfed cropland and grazing land. Multiple cropping, growing more than one crop per year on the same land, will necessitate increased efficiency of water and nutrient use. Greater nutrient input through fertilizers is inevitable, but crop yields will be severely constrained by water deficit and recurring droughts. The use of fertilizers and improved varieties is highly risky in environments with low, variable, and erratic rainfall. Therefore, water harvesting and recycling, development of small-scale irrigation technology, and water-saving irrigation methods (drip or subirrigation) combined with nutrient application will have to be developed. The strategy of agricultural intensification in rainfed ecoregions, called the brown revolution by Evans (1998), will depend on the development of technologies with unprecedented high water use efficiency. This will involve development of: (i) tillage methods that direct water runoff into the row zone, maximize infiltration capacity and minimize soil evaporation, and promote deep and prolific root system development; (ii) time, rate, and formulations of fertilizers used in conjunction with organic amendments that synchronize nutrient availability with crop demand; (iii) irrigation methods that deliver water directly to the root zone with minimal conveyance losses at a rate and time required for the optimum crop yield; (iv) cultural practices of integrated pest management that minimize the risks of soil-born pathogens (e.g., nematodes, stem borer etc.); and (v) systems that rejuvenate soil structure through bioturbation (soil fauna) even under intensive systems.

Soil Management and the Greenhouse Effect

In the past, soils in developing countries, especially those used for subsistence farming, have been a major source of radiatively-active gases (CO_2, CH_4, and N_2O). The potential threat of global warming, leading to a possible rise in temperature of 0.5 to 1.5 °C by 2050, and an increase in variability and frequency of extreme rainfall events may accentuate the risks of soil degradation, especially in subtropical regions of lower mid latitudes. Therefore, soil management systems need to be developed that minimize the degradative risks on one hand and lead to soil carbon sequestration and mitigating the accelerated greenhouse effect on the other. Nonagricultural land use and soil management systems need to be identified for marginal lands that lead to soil C sequestration. Over and above the enhancement of SOC, the processes and techniques that enhance formation of secondary carbonates (Nordt et al. 1999; Lal et al. 1999b) need to be identified and implemented in arid and semiarid regions. While enhancing nitrogen use efficiency, the emission of N_2O from soil has to be minimized through the judicious use of fertilizer and manures and the leguminous cover crops grown as green manures. Soil structural attributes must favor the oxidation of atmospheric methane and the management of crop residue and biosolids to enrich the SOC pool and stable microaggregation, especially in the subsoil below 30-cm depth (Lal 1999a). Rather than a cause improved agriculture and soil management practices can be an important solution to environmental problems.

Soil Management and Water Quality

Agricultural intensification, based on intensive use of fertilizer/manures and agricultural chemicals, will grossly exacerbate the risks of eutrophication of surface water and contamination of ground water. Interdisciplinary research teams (involving soil scientists, agricultural chemists, hydrologists, microbial ecologists, and crop physiologists) need to address the issue of water quality by developing technologies that minimize the risks of declining water quality. Surface runoff containing pesticides transported from agricultural lands has been a major health hazard to rural populations in south Asia and other developing countries. Watershed management systems that permit runoff flow through filter strips, riparian zones, or specifically created wetlands need to be developed to minimize the risks of water contamination.

Hot Spots of the Developing World

Soil management problems of the developing world, especially SSA, Central Asia, and South Asia, deserve very special attention by the world community. Sustainable management of soil and water resources of SSA will require special emphasis because this is the region with very serious problems of soil degradation, declining yield, and unprecedented rate of population growth (Lal 1990a). The current rate of fertilizer application to food crops is extremely low, and a large proportion of arable land is marginal. Drastic reduction in soil organic matter, depletion of plant nutrient reserves, and decline in soil structure leading to accelerated soil erosion with continuous cultivation will have to be arrested and reversed. In these soils, severity of drought stress may be linked closely with low inherent soil fertility, and the vicious cycle of declining yield-degrading soil-lower yield will have to be broken. Basic principles of improved technology for sustainable management of these fragile soils in harsh biophysical and socioeconomic environment may be easily adapted to other semiarid regions, e.g., south-central India and northeastern Brazil. Development of such technological innovations will require establishment of long-term soil management experiments on principal soils and agroecoregions (Greenland 1997).

Central Asia is another hot spot, with soil and environmental degradation problems of enormous proportions, scanty research knowledge, institutions that are weak, and information about the soil and environmental degradation is not well known to the outside world. Restoring the water balance of the Aral Sea basin, ameliorating salt-affected soils, diversifying cropping systems by replacing some area under cotton with other crops, restoring degraded and polluted soils, and improving water quality are important issues that need immediate attention. There is a need to establish long-term soil management experiments to study tillage and residue management techniques, irrigation methods, and diverse cropping systems.

South Asia, with one-fourth of the world population and home to most of the world's poor and malnourished people, is another global hot spot. The problem of soil and environmental degradation is severe despite relatively strong research information and functional institutions. This region, similar to SSA, suffers from the law of marginality. The law states that marginal soils cultivated with marginal inputs produce marginal yields and support marginal living. Furthermore, when people are poverty stricken and starving, they pass on their suffering to the land that is unable to support them. This vicious cycle, which has engulfed the rising tide of humanity in South Asia, has to be broken to free humanity from perpetual poverty, malnutrition and hunger, and subhuman living standards.

Research Quality and Its Management

The quality of soil research in developing countries holds great potential for improvement. Specific improvements are needed to identify the problem and conceptualize the approach to address it through interaction with the farmer. The research program must be relevant to the problems of the society, demand-driven, and original. There is an impressive cadre of highly trained and amply qualified soil scientists in most developing regions, including SSA. Yet, the quality of research output does not reflect the intellectual capacity of the scientific community. Part of the problem lies in research management and the lack of a conducive work atmosphere. Management of research must encourage originality. The top down approach, whereby research priorities and even experimental designs are decided by a central planning committee, often comprised of directors and department heads, puts scientists at the level of technicians. Young scientists must have the freedom to contribute to the research program at all stages of the planning process. There is a need to develop a transparent reward system based on productivity and merit. Soil science and agricultural professionals must be shown respect and be adequately rewarded so that they do not have to look for other jobs to feed their families.

CONCLUSIONS

The objectives of improved soil management technologies for the 21st century are to enhance agricultural productivity and improve environments, especially in rainfed cropland and grazing lands. The strategy is to apply basic principles of soil science to intensify agricultural production and address the issues of accelerated greenhouse effect and decline in water quality as well as other environmental problems arising from agricultural intensification.

Restoration of degraded soils and ecosystems will require thorough understanding of soil resilience characteristics, exogenous and endogenous factors affecting it, and technological options to restore soil's life-support processes. Studies of biodegradation of agricultural chemicals and industrial pollutants will form an important new paradigm of soil research in developing countries.

Enhancing agricultural production in rainfed agroecosystems will require greater emphasis on developing management systems that enhance water use efficiency and minimize the risks of drought through development of appropriate tillage methods and water harvesting technologies. Special emphasis will have to be placed on judicious management of the soils of SSA, Central Asia, South Asia, and other ecoregions with fragile soils and harsh climate.

A major shift in the paradigm for soil scientists of the developing countries is the enhancement of soil quality for diverse functions, including agricultural production, restoring degraded/polluted soils, mitigating the greenhouse effect, and decreasing the risks of eutrophication and contamination of natural waters.

Soil scientists will need to play a pivotal role in developing collaboration between farmers and biophysical and basic scientists. While addressing the problem of agricultural intensification needed to enhance production and meet the demands of unprecedented increases in the populations of developing countries, soil scientists will have to reach out to other disciplines (hydrology, climatology, ecology, geology, economics, political science) to address the increasing risks of soil, water, and air pollution. Soil scientists will need to identify themselves with other disciplines to broaden the scope of their research and to address environmental concerns effectively.

There is a strong need for innovative, original, high quality, credible, and demand-driven soil science research in developing countries. Although the availability of modern laboratory facilities and computers is helpful, the quality of research depends on originality, dedication, and the problem-solving skills of the scientist concerned. Scientific rigor and quality are always enhanced by bigger and tougher challenges, which are going to be in abundance for soil scientists working in developing countries. In this regard, research managers and administrators can also play a crucial role in creating the work atmosphere that: (i) rewards originality, creativity, and productivity, (ii) provides academic freedom, (iii) minimizes bureaucracy by removing bottlenecks and facilitating operations, (iv) encourages interdisciplinarity, and (v) creates trustworthy environments.

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