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SOILS ISSUES

PHYSICAL MANAGEMENT OF SOILS OF THE TROPICS: PRIORITIES FOR THE 21ST CENTURY

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Increasing agronomic productivity and improving the quality of the environment are among the important goals of soil physical management in the tropics. Several perceptions, created by insufficient scientific data and misunderstanding of the basic processes, are being resolved by an improved data base and better understanding of the dynamics of soil physical properties and processes. Principal issues in the tropics for the 21st century include: (i) achieving food security; (ii) curtailing soil degradation and restoring degraded soils; and (iii) improving environment quality. These issues can be addressed by identifying and prioritizing research needs in soil physical management. Important among these are: (i) assessing soil physical constraints at farm scale; (ii) managing soil structure and tilth to minimize the risks of crusting, compaction, and hard-setting; (iii) quantifying and controlling soil erosion by water and wind, developing a cause-effect relationship between soil and climate factors, and evaluating the effects on productivity; (iv) managing soil-water, controlling soil salinity in irrigated agriculture, and developing water harvesting techniques in rain-fed agricultural systems; (v) studying the dynamics of soil physical properties in puddled soils of rice-based cropping systems; (vi) developing conservation tillage and residue management methods to improve soil tilth; (vii) understanding soil moisture retention characteristics in relation to plant available water capacity; and (viii) developing indicators of soil physical quality. Important environmental issues relevant to soil physical management are transport of agricultural chemicals into surface and ground waters, emission of greenhouse gases from soils to the atmosphere, and disposal of urban and industrial wastes. Soil physical management in the tropics must be based on a holistic approach to solve practical problems. It is also important to make the public aware of the contributions of soil science to society's well-being. In addition to enhancing food production, soil physical management needs to address environmental, engineering, social, legal, and archeological issues. Achieving these goals necessitates soil scientists working in close collaboration with engineers, climatologists, geologists, biologists, and specialists in GIS and geostatistics. (Soil Science 2000;165:191–207)

Key words: Food security, soil erosion, conservation tillage, soil salinity, soil structure, soil diversity, tropical soils, soil physical constraints.

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TROPICAL ecoregions are located between 23° 27′ north and south of the Equator, lying between the Tropic of Cancer and the Tropic of Capricorn or within the Torrid zone. These regions cover approximately 40% of the world's land area, 5.4 billion ha of the total land area of 13 billion ha. Subtropical regions are located between 23° 27′ and 30° N and S of the Equator. Combined tropics and subtropics cover an area of about 8 billion ha. These regions are home to a large portion of the world's population and to most of the world's poor, undernourished, and deprived inhabitants. These are also the regions where the population is increasing rapidly, the per capita arable land area is decreasing as a result of the increasing population and conversion to nonagricultural uses plus severe soil degradation, and the demand on soil resources for food and other basic necessities is escalating (Lal 2000). Because of the continuously widening gap between food supply and demand for some areas and the severe problems of soil and environmental degradation in others, the capacity of soil and water resources of the tropics to support present and future populations is being questioned. Is wide spread poverty in the regions caused by inadequate soil and other natural resources and harsh climate, unfavorable socioeconomic and political conditions, or both? Are perpetually low crop yields attributable to poor soil quality or to low rate of adoption or lack of improved technology to alleviate soil and environmental constraints to crop and animal production? A principal concern is the sustainability of soil management systems that can meet the demands of the rapidly increasing population without jeopardizing the quality of soil resources that are already under severe stress. Answers to these important questions require a critical and objective evaluation of the soil resources of the tropics, assessment of their potential and constraints, review of the prevalent management practices, and identification of research and development needs for sustainable management of soil resources.

Soils of the tropics are defined as those that occur in the geographic tropics. These soils have an "iso" soil temperature regime characterized by a difference between mean summer and mean winter soil temperature of 5° C or less (Soil Survey Staff 1997). As seen in *Soil Taxonomy,* predominant soils of the tropics include Oxisols, Aridisols, Alfisols, Ultisols, Inceptisols, Entisols, and others (Buringh 1979; Van Wambeke 1992; Lal 2000). Soils of tropical uplands, developed *in situ* over old land surfaces, are largely Oxisols, Ultisols, and Alfisols (together occupying about 45% of the tropics) and are highly weathered. Consequently, they contain predominantly low activity clays, have low cation exchange capacity, low nutrient reserves, low plant-available water holding capacity, and are prone to soil compaction and accelerated erosion under mechanized farm operations. Some of these highly weathered soils contain plinthite, which, on exposure, is hardened irreversibly. In contrast to highly weathered soils, Inceptisols and Entisols are young soils of recent origin, with no clear-cut genetic horizon and with little profile development. Young soils have generally high inherent fertility. Aridisols, predominant soils of the arid and, to some extent, the semiarid tropics, are severely constrained by drought stress. In Aridisols, water is held at a tension below -1.5 MPa for more than 9 months a year. Aridisols contain high concentrations of $CaCO_3$, $CaSO_4$, and other salts, and some are susceptible to wind erosion. Vertisols are clayey soils containing high activity clays, have high swell-shrink capacity, and develop large and deep cracks during the dry season. Soils with high native soil fertility and good soil physical properties include Histosols, Mollisols, and Andisols. Together, these soils cover only 143 Mha or <3% of the tropics, but they support dense population in places such as in Java, Central America, and western Cameroon.

The data in Table 1 show the extent of land area of major soil groups per FAO classification. As this system indicates, predominant soils of the tropics and subtropics are Leptosols > Cambisols > Arenosols > Acrisols > Ferralsols > Calcisols. Together, these six soil orders occupy 5.3 billion ha of the total land are of 8.2 billion ha.

Although there are no real differences in principal soil orders and the processes involved in their formation between soils of the tropics and those of the temperate zone (Eswaran et al. 1992), continuously high temperatures along with high and intense rains (in the humid and subhumid tropics) have caused extreme weathering and leaching of soils developed on geomorphically stable land surfaces. Therefore, management of these soils requires special attention due to the inherent constraints in soil and the prevailing harsh climate. The latter, characterized by intense summer rains and high evaporative demand, leads to rapid degradation of soil quality when converted from natural to agricultural ecosystems (Alegre and Cassel 1986; Alegre et al. 1991; Lal 1996). Consequently, vast tracts of once productive soils are now barren, covered by *Imperata cylindrica,* severely compacted and eroded, or salinized (Lal 1995).

Soil physical management implies optimization of edaphological attributes of the root zone with regard to soil structure, porosity and pore size distribution, soil strength, infiltration rate, available water capacity, and soil temperature

TABLE 1

Extent of major soil groups by climatic zone in the tropics and subtropics (10^6 ha) (adapted from Lal 1997)

Soil order	Arid	Mountainous	Seasonally dry tropics and subtropics	Humid tropics and subtropics	Total
Histosols	3.4	0.8	12.2	32.4	48.8
Leptosols	419.5	544.3	198.3	66.7	1228.8
Vertisols	51.2	3.8	223.0	29.0	307.0
Fluvisols	90.1	4.4	84.4	66.2	245.1
Solonchaks	140.3	3.6	20.8	4.4	169.1
Gleysols	34.5	11.0	111.5	167.7	324.7
Andosols	9.4	20.7	18.4	20.7	69.2
Arenosols	395.9	7.0	320.1	127.3	850.3
Regosols	170.1	35.9	52.1	9.4	267.5
Podzols	1.4	3.2	13.5	11.3	29.4
Plinthisols	0.05	0.3	15.7	42.4	58.5
Ferralsols	0	4.0	231.3	507.2	742.5
Planosols	3.8	2.6	74.1	6.3	86.8
Solonetz	57.0	5.4	36.8	0.5	99.7
Greyzems	2.2	5.0	0	0	7.2
Chernozems	11.8	1.8	0	0	13.6
Kastanozems	143.5	17.6	44.7	0.5	206.3
Phaeozems	2.1	8.7	15.2	2.7	28.7
Podzoluvisols	0	17.4	0	0	17.4
Gypsisols	86.7	1.7	0.05	0	88.5
Calcisols	552.8	44.9	47.3	5.4	650.4
Nitisols	2.8	10.0	101.8	87.3	201.9
Acrisols	1.1	13.6	238.8	589.4	842.9
Luvisols	165.5	13.5	62.0	21.8	262.8
Lixisols	26.4	11.4	366.9	31.7	436.4
Cambisols	503.6	153.3	192.3	95.6	944.8
Total	2875.2	945.9	2481.3	1925.9	8228.3

regime. Management of these properties involves the choice of appropriate techniques of tillage and seedbed preparation, residue management, water conservation, and supplementary irrigation. Management of soil chemical and nutritional properties is also important to achieving and sustaining high yields and involves balancing the nutrient output for the desired yields with inputs through applications of chemical fertilizers and amendments. In contrast, a much more challenging task is that of maintaining favorable soil physical conditions so that nutrients and other inputs are utilized efficiently without leaking into the environment. Fertilizers alone or used in conjunction with improved crop varieties and measures to control pests and diseases cannot enhance and sustain productivity if strong and extreme deterioration of soil physical condition occurs. In contrast to the management of soil fertility, soil physical conditions cannot be managed by using inputs available in a bag. Further, once compacted and eroded, it is difficult, if not impossible, to replace the topsoil. Therefore, physical management of soils of the tropics is crucial to enhancing and sustaining high production with minimal risks to the environment. Physical management has, however, been neglected for too long, and at a very high economic and environmental cost.

This manuscript is about the identification and prioritization of research and development needs for physical management of soils of the tropics because of the rapid expansion of the human population in these regions. Emphasis is on physical rather than chemical and nutritional management because of the severe soil physical constraints affecting agronomic productivity and environment quality. An additional objective is to clarify some myths and common perceptions by highlighting factual characteristics of soils of these regions.

SIX COMMON PERCEPTIONS

The perpetual food deficit and persistent poverty in some regions of the tropics (e.g., South Asia, Sub-Saharan Africa, Central America) have created several perceptions of the soils of these regions. Some of these perceptions, supported neither by analytical data nor by experimental results, include:

Soils of the tropics are inherently infertile, highly fragile, and easily degraded: The soils in the tropics (Table 1) comprise 10 million phases, 5 million series, 1 million families, 1250 subgroups, 200 great groups, 45 suborders, and 11 orders (Eswaran et al. 1992). Although some soils are infertile and easily degraded, others are highly fertile and resilient. Widespread and severe problems of soil degradation in the tropics are not necessarily caused by soil characteristics *per se* and may be traced to land misuse and soil mismanagement, desperate attempts by resource-poor farmers to grow crops by mining soil fertility, human greed and shortsightedness, poor planning, and cutting corners for quick economic returns. Soil degradation in the tropics is most often caused by neglect and misuse of soil and other natural resources over a long period of time. Further, the available results of agricultural research have not been applied fully. Once the degradative process is set in motion by land misuse and soil mismanagement, it is exacerbated by unfavorable socioeconomic and political factors. Soil degradation is a physical process driven by social, economic, and political forces.

Ample water, abundant sunshine, and deeply weathered soils are conducive to intensive food production: Some classic failures of the large-scale development schemes in Africa and elsewhere in the tropics have been caused by this perception. The plant-available water capacity of the root zone and its management determine the magnitude and severity of the drought experienced by the shallow rooted annuals more than the mean annual rainfall. Further, biomass productivity of food crops in some regions of the humid and subhumid tropics is severely constrained by the lack of sunshine and the low level of net radiation received during the growing (rainy) season. Despite deep weathering, the effective root zone is limited by the edaphologically suboptimal quality of the subsoil horizon because of high mechanical strength, Al toxicity, P deficiency, and elemental imbalance.

There is a negligible level of organic matter content in soils of the tropics; humus as we know it is not formed in these soils, and the rate of oxidation at the prevailing temperature is so high that there is no point in trying to increase it: The level of soil organic matter content within the same soil order and with a similar history of management is comparable between soils in the tropical and temperate climates (Sanchez et al. 1982; Greenland et al. 1992). The soil organic carbon (SOC) pool of soils of the tropics, estimated at about 500 Pg per 1 m depth, is about 32% of the global soil pool (Kimble et al. 1990; Eswaran et al. 1993). Despite the high rate of decomposition (Jenkinson and Ayanaba 1977), the SOC content of these soils can be improved with proper land use and adoption of recommended management practices (RMPs). The low levels of SOC content observed are the result of no or little crop residue returned to the soil, no or little application of compost or farm yard manure, and wide prevalence of subsistence and exploitative systems often based on slash-and-burn agriculture (Sanchez and Logan 1992). Yet, management of soil organic matter content is crucial to sustaining productivity of upland production systems (Petchawee and Chaitep 1995).

Favorable soil temperatures throughout the year can facilitate multiple cropping: In contrast to wet and cold soils with suboptimal temperatures in northern latitudes, soils of the tropics are dry and hot in early spring (on-set of rains). Soil temperatures exceeding 50 °C at 1 to 5 cm depth in the afternoon are not uncommon (Lal, 1973; Prihar et al. 1979; Derpsch et al. 1985; Morote et al. 1990). However, the adverse effects of supraoptimal soil temperatures on seedling growth, crop yields, nutrient and water uptake, and fertilizer use efficiency have not been widely recognized. Consequently, the failure to adopt appropriate management systems has led to severe problems such as poor crop stand, low yields, low SOC content, lack of or low activity of soil fauna (e.g., earthworms), soil hardening, and numerous problems accentuated by a decline in soil structure as a result of continuously high soil temperatures.

Soils of the tropics are well aggregated, have stable structure that can withstand mechanical compaction caused by vehicular traffic, and resist the erosive forces of raindrop impact and flowing water: Some Oxisols and Andisols are highly aggregated and have stable structures, especially under natural conditions. Structural attributes of Alfisols, Ultisols, Inceptisols, Entisols, and other soils cannot withstand misuse and mismanagement. Similar to their counterparts in the temperate regions, these soils are highly prone to compaction by vehicular traffic at a soil moisture range that increases vulnerability to densification and to erosion by raindrop impact and overland flow without protective vegetal cover (Cassel and Lal 1992).

Low-input agricultural systems do not cause soil degradation and are environmentally compatible: Extensive and subsistence agricultural practices followed in these regions have perpetuated low yields, low income, malnutrition and hunger, poverty, and substandard living. Granted that air and water pollution are health hazards, hunger and malnutrition caused by low-yielding agricultural practices perpetuate miseries and are life threatening. A lack of investment in soil restoration has also created the problem of extreme and severe soil degradation by erosion (Lal 1994a) and nutrient depletion (Smaling 1993). It is also slash-and-burn agriculture that leads to emissions of CO_2 and other greenhouse gases from the soil and terrestrial ecosystems into the atmosphere. Lal and Logan (1995) estimated historic emission of 27 to 74 Pg C from soils attributable to agricultural activities in the tropics, and the emission of radiatively active gases from soils is exacerbated by soil degradation.

ISSUES OF THE 21ST CENTURY

Identifying and implementing strategies for the sustainable management of soil resources requires objective assessment of the issues that affect productivity and environment quality. Important among these are the following:

Food Security and Agricultural Intensification

Managing soils of the tropics for food security is and will remain a challenge for at least the first half of the 21st century. The ever-increasing demand for food production will intensify further the quest to enhance production per unit area on soils already under cultivation. It is estimated that as much as one-third of the population of Sub-Saharan Africa will remain food insecure by 2010, when the population of the region will be about 1 billion. About one-quarter of the children of the tropics may face malnutrition even by 2020. There has been at least a 32% increase in per capita food production in the developing countries of the tropics since 1970 (Conway 1997), but the production gains have not been realized in all regions, especially in Sub-Saharan Africa (Paarlberg 1996). For most of the tropics, the increase in food production per unit area and per unit time has to occur at a much higher rate than in the past and without jeopardizing the soil's productivity and its environment moderating/buffering capacity. There are numerous constraints to enhancing food supply (Döös 1994). Enhancing food production will require substantial input of energy, as has been the case in achieving high yields in Punjab, India (Fig. 1). Similarly high but judicious input of energy will be needed to bring about a quantum jump in crop yields in the impoverished soils of Sub-Saharan Africa and elsewhere in the tropics. There is no choice but to intensify agricultural production on prime soils of the tropics. Yet the riddle of increasing agricultural output per unit input will remain a challenge for several decades of the 21st century.

Soil Degradation

Soil degradation has plagued humankind for thousands of years (Olson 1981). However, the problem is more severe now than ever before because of the exponential growth in demands on finite and nonrenewable (over human rather than geologic time scale) soil resources. Despite the alarming statistics (Oldeman 1994), there is strong debate regarding the on-site impacts of soil degradation on productivity. One school argues that global food production, especially in South and Southeast Asia, experienced quantum

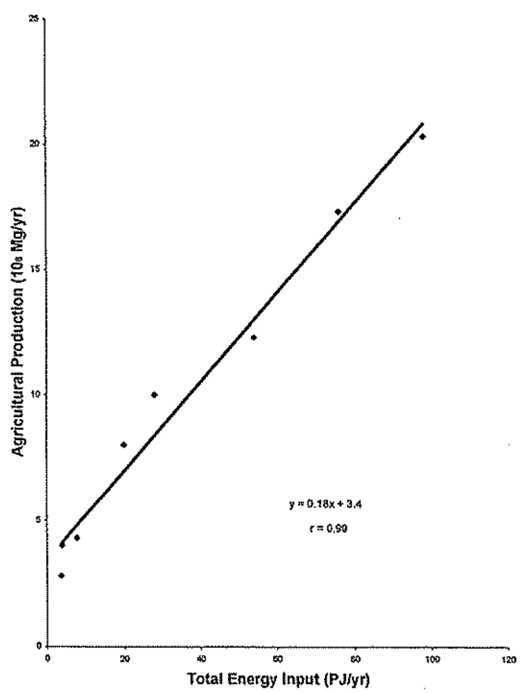

Fig. 1. Relation between energy input and agricultural production in Punjab, India, for the period 1955 to 1990 (redrawn and calculated from Panesar 1996).

leaps during the last 3 to 5 decades of the 20th century. They hypothesize that economic factors and market forces will force farmers to rectify the situation by adopting soil restorative measures (Crosson and Anderson 1999). They question the real threat of soil degradation and ask whether we are merely crying wolf and fussing over a tempest in a teacup? (Thomas 1993). The second school is equally vehement regarding the dire economic and environmental consequences of soil degradation (Lal 1989a; Dregne and Chou 1992; Kendall and Pimentel 1994; Pimentel et al. 1995; Oldeman 1998; Scherr 1999). Proponents of this school ask whether we are headed toward the same fate as some of the civilizations made extinct by soil degradation and whether the world is running out of good arable land. Oldeman (1998) estimated productivity losses caused by soil erosion on cropland since the second World War at 25% for Africa, 13% for Asia, 37% for Central America, and 13% for the world. Lal (1998) estimated the global yield reduction in 1995 due to soil erosion at 10% in cereals, 5% in soybeans and pulses, and 12% in root and tubers. Total production losses on a global scale were estimated at 272 $\times$ 10^6 Mg/yr comprising 190 $\times$ 10^6 Mg/yr for cereals, 6 $\times$ 10^6 Mg/yr for soybeans, 3 $\times$ 10^6 Mg/yr for pulses, and 73 $\times$ 10^6 Mg/yr for roots and tubers. These estimates of losses are drastically more than those reported by Crosson and Anderson. Alarming as the losses in food production calculated by Oldeman and Lal may be, these are mere estimates based on sketchy plot-scale data extrapolated to global scales.

There is only one way to resolve this important debate: separate emotions from facts. Casual statements such as "on the southern edge of the Sahara, some 250,000 square miles of once-productive land, an area of the size of Somalia, have become desert over the last 50 years (Paarlberg 1996)" will have to be replaced by precise statistics. That would entail: (i) generating a credible data bank on the extent and severity of soil degradation assessed by the use of internationally standardized methods, and (ii) establishing the cause-effect relationship between crop yield and severity of degradation for different levels of input. It is crucial that pedotransfer functions between soil properties and crop yield, similar to that shown in Fig. 2 between soil organic matter content and maize grain yield for a soil in Thailand, are established for key soil properties. In this case, maize grain yield declined at the rate of 2.9 Mg/ha for each 1% decrease in soil organic matter content. Similar soil-specific functions are needed that relate crop yields to available water capacity, rooting depth, water stable aggregation, etc. These and other important research initiatives need to be undertaken in the tropics, at national and international levels, by interdisciplinary teams involving soil scientists, climatologists, plant physiologists, agronomists, and economists. Establishing a credible data bank for soils of the tropics would require field assessment of soil degradation at subgroup (1250) or at least great group (200) level, including evaluation of degradation-induced changes in soil physical properties (e.g., rooting depth, available water capacity, infiltration rate, SOC pool, porosity, and pore size distribution) that affect productivity. Field assessment involving geoprocessing techniques (remote sensing, GIS, geostatistics) will need to be supported by detailed laboratory analyses to establish critical limits of soil properties in relation to productivity and environment-moderating capacity.

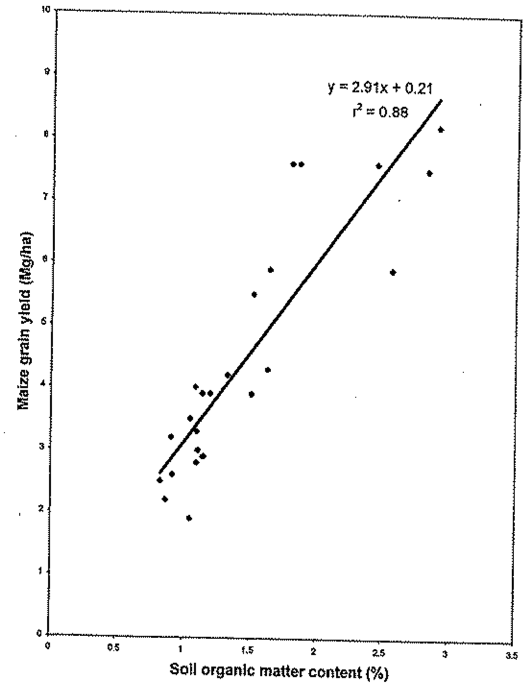

Fig. 2. Relation between soil organic matter content and maize grain yield in Thailand (redrawn from Petchawee and Chaitep 1995).

There is also the important issue of soil restoration. Rather than bring new land under cultivation through the deforestation of tropical rainforest and the conversion of tropical savannas to arable and pastoral land uses, degraded soils and ecosystems must be restored. Soil restoration requires understanding the soil's resilience characteristics and the impacts of exogenous and endogenous factors (Lal 1997; Seybold et al. 1999). The importance of physical management in soil restoration cannot be overemphasized.

Environment Quality

In addition to achieving food security, soil management options need to address environmental issues, especially with regard to water quality and the greenhouse effect. Intensive use of chemicals may exacerbate even the already serious water quality situation in the tropics, especially with regard to the nonpoint source pollution caused by transport of pesticides and fertilizers in the natural waters. There is also concern about the emission of radiatively active gases from the soil. Emissions of N_2O and NO_x are likely to increase with increases in application of fertilizers and biosolids. Thus, increasing fertilizer use efficiency is a major goal of soil physical management through optimization of soil moisture and temperature regimes and improvement of soil structure. Reducing CH_4 emissions from rice cultivation remains a challenge. There is, however, the strong possibility of SOC sequestration through adoption of RMPs and desertification control (Batjes and Sombroek 1997; Lal et al. 1999), and this must be explored in a systematic way.

RESEARCH PRIORITIES IN SOIL PHYSICAL MANAGEMENT FOR THE 21ST CENTURY

Both basic research leading to understanding the processes and mechanisms involved, and applied soil physical research to solve the practical problems, are important. The strategy is to solve the problem of the ever-increasing population of the tropics. Therefore, achieving food security and improving environment quality through sustainable physical management of soils will mean obtaining research information with regard to the following:

Assessment of Soil Physical Constraints

Although soil testing for fertilizer use is gaining momentum, there is no or minimal routine soil testing for assessment of soil physical constraints. Alleviation of soil physical constraints is, however, crucial to enhancing crop yields and minimizing risks of soil and environmental degradation. Crude and tentative as these statistics are, some estimates of soil physical degradation are available at global (Oldeman 1994) and regional (Van Lynden and Oldeman 1997) scales. Estimates of soil physical constraints at the state level, such as those shown in Table 2 for Haryana, India, are rare. What is needed is routine testing at the farm level for soil physical quality with regard to susceptibility to crusting or sealing, surface and subsoil compaction, infiltration rate for natural rains and irrigation (with regard to the impact of water quality), soil water holding capacity, and erodibility with regard to water and wind erosion. Development of routine field testing kits, along with information about sufficiency level of key soil properties by simple and affordable techniques, is a high priority. To be effective and of high quality, such a testing system may have to be privatized rather than managed through a government planning program.

Soil Structure and Tilth

Management of soil structure and tilth is still a mystery and a high priority (Cassel and Lal 1992). It is the decline of soil structure that leads to the onset of the degradative process, beginning with crusting, compaction, low infiltration rate, high runoff, accelerated soil erosion by water and wind, depletion of SOC and loss of clay contents, and decrease in productivity leading to exacerbation of soil degradation. This vicious cycle, decline in soil structure-low productivity-increase in soil degradation, has to be broken through adoption of appropriate systems of soil physical management. Why does the structure of many soils of the tropics deteriorate so rapidly, and how can this be prevented? How can the degraded soil structure be restored effectively and economically? What is the impact of soil structure on crop yield?

There is a need to establish a relationship be-

TABLE 2

Soil physical constraints to crop production in Haryana, India (adapted from Agraval et al. 1995)

Soil physical constraint	% of net cultivated area
Excessive permeability	15
Crusting	43
Hard-setting	17
Mechanical impedance	2
Shallow rooting depth	5
Waterlogging	17
Wind erosion	26
Water erosion	2

Net cultivated area = 3.6 Mha.
Area under constraint is not additive because more than constraint may occur on the same land.

tween aggregation and other soil constituents. Similar to the empirical relationship established between soil organic matter content and mean weight diameter (MWD (mm) = 0.24% organic matter + 0.31, s = 0.86***, Chaney and Swift 1984) and % aggregation (Douglas and Goss 1982) for soils of the U.K. and Australia (Tisdall and Oades 1982), the cause-effect relationship needs to be established for soils of the tropics. For a Vertisol in India, Tyagi et al. (1982) observed a linear relationship (% aggregation > 0.25 mm = 158.9 SOC % − 9.5, r^2 = 0.87) between aggregation and SOC content. The interactive effect of SOC and polyvalent cations (Al, Mn, Fe, Ca) on aggregation needs to be studied. Both basic and applied research to improve soil aggregation and aggregate strength are needed to address the widespread problem of degradation of soil physical quality.

Although the importance of soil structure and tilth has long been recognized by soil scientists, quantification of these elusive properties remains a challenge. Quantification of pores and voids, their size distribution and continuity, and their dynamism and stability in relation to natural and anthropogenic perturbations are important structural attributes that need to be related to management systems on the one hand and productivity on the other. The data from western Nigeria in Table 3 are a relevant example, indicating the importance of macro- or transmission pores to a soil's infiltration capacity. The high equilibrium infiltration rate in the traditional system was related to relatively high macroporosity even though soil bulk density was high. Despite its importance, *in situ* measurement of pore size distribution and continuity remain major methodological challenge. Three important manifestations of soil structure and tilth are crusting, compaction, and hard-setting.

Crusting

In addition to decreasing crop stand and yield, surface crusting and seal formation also decrease infiltration, increase runoff of water and chemicals, and accelerate erosion. Crusting is caused by soil dispersion and slaking, followed by orientation of particles and ultradesiccation. Soils of low activity clays, high in silt and low in SOC content, are highly prone to crusting. Calcareous soils are also highly prone to crusting (Balba 1995). It is a major problem in many soils of tropical America (Roth 1992), Africa (Van der Watt and Valentin 1992), Australia (Chartes 1992), and Asia (IBSRAM, 1997). Use of soil conditioners has proven effective in some soils. The data in Table 4 from Israel show the beneficial impact of applying phosphogypsum to decrease runoff and erosion. Conservation tillage, residue management and mulching, and techniques to enhance SOC content are important to reducing crust formation. Understanding processes, critical limits of soil properties, and management systems to alleviate adverse effects of crusting are high priorities.

Soil Compaction

Soil compaction is a serious problem in the tropics, especially in soils containing predominantly low activity clays, high fine sand and silt content, and low levels of SOC. It can cause a drastic reduction in crop yield (Kayombo and Lal 1994). The problem of soil compaction is likely to exacerbate with increasing mechanization of farm operations. Some soils of tropical America, such as those in Bolivia, are naturally compacted, (Barber et al. 1989). There is a strong need to develop appropriate methods of characterizing soil compaction. Assessing soil bulk density is not a sensitive test, especially for heavy-textured soils.

TABLE 3

Effects of land clearance, tillage, and cropping systems on soil physical properties of an Alfisol in western Nigeria (adapted from Hulugalle 1994)

Treatment	Equilibrium infiltration rate (mm/min)	Bulk density (Mg/m³)	% macropores (> 14.4 μm)
Land clearance			
Manual	0.7 ± 0.2	1.38 ± 0.03	54.3 ± 2.2
Shear blade	0.5 ± 0.3	1.34 ± 0.03	47.8 ± 2.6
Tree pusher	0.7 ± 0.2	1.26 ± 0.03	53.5 ± 2.2
Traditional	3.3 ± 0.3	1.40 ± 0.03	56.3 ± 2.6
AOV	0.001	0.01	NS

AOV = one way analysis of variance expressed as probability level of F ratio.
NS = not significant.

TABLE 4

Effect of phosphogypsum on runoff, soil erosion, and wheat yield for 1980–1983 in the semi-arid region of Davir, Israel (adapted from Agassi et al. 1985)

Treatment	Runoff (mm)	Erosion (Mg/ha)	Wheat yield (Mg/ha)
Control	19.2 ± 17.6	0.6 ± 0.6	2.4 ± 1.8
Phosphogypsum 5 Mg/ha	3.8 ± 6.3	0.1 ± 0.1	2.6 ± 1.8
Phosphogypsum 10 Mg/ha	5.7	0.1	3.1

Evaluation of oxygen diffusion rate (ODR), macroporosity, and infiltration rate may be more appropriate than measuring the weight-volume relationship. The data in Table 5 for two soils from Papua New Guinea show small increases in soil bulk density as a result of conversion from natural grassland to sugarcane: an 11% increase in Fluvisol and 9% in Vertisol decreased the infiltration rate by 13.6 times in the Fluvisol and 20.6 times in the Vertisol. Infiltration rate is apparently a more sensitive indicator of soil compaction than soil bulk density. Similarly, Flowers and Lal (1998) observed that the ODR is a more appropriate measure of crop response to soil compaction on clayey soils than bulk density. Developing appropriate soil-specific systems of managing and alleviating compaction is an important topic. Managing traffic-induced soil compaction requires an interdisciplinary research team involving soil scientists, agricultural engineers, and agronomists. An integrated approach to soil compaction management involves the use of appropriate equipment, crop rotations and cropping systems (deep-rooted crops grown in rotation/association with shallow-rooted crops), and residue management techniques. The importance of soil fauna bioturbation due to earthworm and termite activity (Bond and Harris 1964; Lal 1991; Lavelle et al. 1992) in soil compaction management must be given the high priority it deserves. There is a need to establish critical limits of soil compaction by measuring ODR, soil strength, and least-limiting water range (da Silva et al. 1994; Kay 1998) in relation to root growth and crop yield.

TABLE 5

Effect of land use on soil bulk density (Mg/m^3) and infiltration of two soils in Papua New Guinea (adapted from Hartemink 1998)

Land use	Soil bulk density of 0–15 cm depth (Mg/m^3)		Infiltration rate at 30 min (mm/h)	
	Fluvisol	Vertisol	Fluvisol	Vertisol
Natural grassland	1.07	1.0	271	247
Sugarcane	1.19	1.09	20	12

Soils with high gravel or concretionary materials (30 to 70% by weight) in the subsoil horizon are common in the tropics and subtropics. Such soils have high mechanical strength, a rigid matrix, and low water and nutrient holding capacity. Root growth through such gravelly horizons is severely curtailed, even though the bulk density of intergravel material is low. There is a lack of understanding of soil physical processes (e.g., water movement, root penetration) affecting crop growth in soils with well defined gravelly horizons. Subsoiling and mechanical loosening are not effective in alleviating high soil strength. Bioremediation techniques are needed to create biopores through which crop roots can penetrate to explore nutrients and water in the horizon below. There is also a need to develop and standardize methods of assessing physical properties and processes of these soils.

Hard-setting, a process of slumping and compaction without the application of external load, is a major problem in several soils of Africa, Asia, and Australia (Mullins et al. 1990). Slumping is followed by a very sharp increase in the strength of soils upon drying over a short period of time. Some of these soils are called "lunch time soils," too wet to cultivate in the morning yet too dry and hard in the afternoon. Soil organic matter, the nature and amount of clay, and activity of soil fauna (earthworms, termites, ants) play an important role in management of these soils. It is important to recognize hard-setting as a condition distinct from soil compaction, understand processes and factors that cause it, and develop management options to minimize this problem.

Soil Erosion

Accelerated soil erosion is and will remain a serious problem in the tropics. Despite a considerable body of the literature (Oldeman 1994; Lal 1998), the available research information at plot and hillside scale remains ambiguous, incomplete, inconclusive, and incredible. The problems with the available data are: (i) a failure to adopt standardized methods in monitoring and evaluation (Lal 1994a and b; (ii) lack of basic information relating degree of soil erosion to changes in soil physical properties; and (iii) inadequate data to assess the on-site impact on agronomic productivity. Enrichment ratios of the eroded sediments (for nutrients, clay, and SOC contents), especially that of the wind-blown material (Zobeck and Fryrear 1986), are rarely determined. Further, most experiments are done on an *ad hoc* basis, for a short period, without collecting the supporting information on soil profile characteristics, rainfall and wind factors, soil surface properties, or the ground cover. It is not uncommon to find a footnote under a data table indicating that *x* number of rains were omitted because the storage tanks were too small to hold the runoff. With such sketchy and unreliable information, it is difficult to understand basic processes and establish the cause-effect relationship. It is not the quantity but the quality of the available data that is a major constraint to making progress in soil erosion management.

The Universal Soil Loss Equation (USLE and RUSLE) has been used widely in the tropics to assess potential soil erosion hazard, often without validating or measuring soil-specific properties (factor K) and rainfall factors (kinetic energy and drop size distribution in relation to intensity). The information generated can thus be erroneous, misleading, and counterproductive and represents misuse and abuse of the empirical equation. The data in Table 6 is a rare example of comparative assessment of measured and predicted soil erosion rates. Predicted soil erosion rates are 2.5 to 640 times more by USLE and 1.2 to 68 times more by RUSLE than the measured rates. One wonders how wasteful, misleading, and counterproductive information developed without validation has been in impoverished countries that can ill afford such data. Is some information, regardless of its accuracy, better than no information? A typical example is the development of national or regional isoerodent maps (Lal 1990, based on the EI_{30} index of the USLE) using rainfall intensity (Babu et al. 1978) or the mean monthly rainfall amount (FAO/UNEP/UNESCO 1979). Models are never a substitute for real field data, even under best of circumstances (Philip 1991), and practicing professionals should certainly not use them without field validation and proper calibration. While identifying a realistic design criteria for the conventional plot method of erosion assessment, there is also a need to develop new and innovative methods of erosion assessment, including remote sensing techniques (Gobin et al. 1999).

Recognizing the need for conducting more original and innovative research on soil erosion processes and control measures, it is even more important to apply what is already known and to find out the reasons for the low rate of adoption of proven technology. It is also relevant to establish the cause-effect relationship between erosion and productivity and pedological factors and the quantitative range of soil loss tolerance. Unless the relation between erosion and productivity is established, it will be difficult to plan development strategies and to choose among soil management options.

Water Management and Soil Salinity

Soil-water management is a crucial issue because it also affects the salt balance in the root zone. Soil salinity is a serious problem, especially in irrigated croplands. There are at least 316 Mha of salt-affected soils in developing countries of the tropics (Table 7). The problem is exacerbated by the excessive use of subsidized irrigation and by the use of poor quality irrigation water (Condom et al. 1999). Whereas the technology necessary to reclaim salt-affected soil is known (Gupta and Abrol 1990), use of this technology for reclaiming soils has not gained the desired momentum. Efforts to develop methods that improve water use efficiency beyond that of the widely used and wasteful flood irrigation system have also been few. The potential to develop irrigation in Sub-Saharan Africa is great. It is im-

TABLE 6
Discrepancies between actual and predicted soil erosion from steeplands in Los Espabales, Honduras (adapted from Throw 1999)

Watershed plot area (ha)	Slope (%)	Management	Soil erosion (Mg/ha)		
			Measured	USLE	RUSLE
0.27	63	Mulch	20	672	74
0.004	55	Mulch	0.5	294	34
0.12	57	Slash and burn	92	1019	112
0.16	55	Vetiver hedge	0.7	447	52
0.004	55	Bare fallow	761	1896	927

TABLE 7
Distribution of salt-affected soils
in arid tropics (recalculated from Balba 1995)

Region	Land area (10^6 Ha)
Mexico and Central America	2.0
South America	129.2
Africa	80.5
Southeast Asia	21.5
South and West Asia	83.6
Total	316.8

portant to learn from the mistakes made in South Asia and to develop small-scale irrigation programs (Vaishnav 1994). A principal issue, water table management, combines a combination of installing drainage systems, adopting judicious farming/cropping systems, and using appropriate irrigation methods (tubewells with drip or sprinkler irrigation). The potential of bioamelioration of salt-affected soils and establishing appropriate tree species in combination with agroforestry systems needs to be assessed.

Soil-water management also remains a crucial factor in rainfed agriculture in the tropics, where drought stress is the principal constraint to enhancing food production. Although the green revolution has increased food production in irrigated areas, gains in crop yields in areas of rainfed agriculture have been modest. Therefore, conserving soil water, decreasing losses by runoff and evaporation, and improving water use efficiency in rainfed agriculture will be important priorities for the 21st century. Soil physicists need to work closely with hydrologists and climatologists to develop efficient water harvesting and recycling techniques to minimize risks of recurring drought and to offer a buffer against the vagaries of the climate.

Physical Properties of Puddled Soil

Puddling, a tillage process to destroy soil aggregates and decrease infiltration rates when soil is near saturation, is widely practiced in rice-growing areas of South and Southeast Asia. Although the practice may be useful for growing rice, it can have drastic adverse effects on growth and yield of the following upland crops. The principal disadvantages of the system include: (i) high water requirement, (ii) decline of soil structure with adverse effects on the following upland crops, and (iii) poor root development throughout the "paddy profile" (Sharma and De Datta 1986). The declining productivity of the rice-wheat system in some regions of the Indo-Gangetic plains (Abrol et al. 1999) may be attributable to degradation of the soil structure as a result of puddling. However, puddling may be beneficial for leaching salts out the root zone in some specific situations (Häfele et al. 1999). It is, therefore, important to identify alternatives to puddling (e.g., dry sowing), especially in regions where water is a limiting factor and growth of the following upland crops is adversely affected. Studying the dynamics of soil structure in rice-based cropping systems, developing methods of ameliorating structural characteristics, and identifying management systems that are efficient alternatives to puddling are priority issues for regions growing paddy rice, such as the rice-wheat belt of the Indo-Gangetic plains. Rice paddies emit 30% of the global CH_4 emissions, and developing management systems that reduce emissions is a high priority.

Tillage Methods and Residue Management

Farmers in the tropics use several traditional methods of seedbed preparation, ranging from manual and animal driven to highly mechanized plowing systems (Lal 1995). Excessive tillage and vehicular traffic can cause severe adverse effects on soil by depleting the SOC pool and accelerating soil erosion. Similar to the puddling system, there is also a strong need to develop viable alternatives to the plow-based method of seedbed preparation. The advantages of weed suppression and temporary reduction of bulk density of the surface layer are accrued at the heavy price of increasing risks of soil erosion, increasing water losses due to evaporation and runoff, depletion of soil organic matter content, and overall degradation of soil quality. Although not universally applicable, there is potential for widespread applicability of conservation tillage in row crop production in diverse soils of the tropics (Lal 1989b, 1995). Aslam et al. (1993) reported that wheat in Pakistan can be grown successfully with zero tillage. The data in Table 8 from Punjab, Pakistan, show that zero tillage produced 11% more yield than conventional tillage over a 3-year period. Conservation tillage and mulch farming techniques have also proven useful in the highly erodible soils of the Loess Plateau of China (Zhiqiang et al. 1999). Keeping in mind both socioeconomic and biophysical factors, there is a need to develop conservation tillage systems for a wide range of crops, soils, and agroecological environments. Use of crop residue mulch and cover crop-based rotations is important to the development of soil-specific conservation tillage sys-

TABLE 8
Wheat grain yield in Punjab, Pakistan, with zero tillage and conventional plowing (adapted from Aslam et al. 1993; Hobbs et al. 1997)

Year	Number of locations	Grain yield (Mg/ha)		Number of locations
		Zero till	Conventional till	
1985–86	15	3.6	3.5	2.3
1986–87	13	3.8a	3.5b	8.6
1987–88	6	4.2a	3.6b	16.7
Combined data	34	3.9a	3.5b	11.1

tems in the upland soils of the tropics. Another important consideration in addition to soil and environmental concerns should be the human drudgery of mechanical seedbed preparation by manual or animal-driven equipment at 40 to 45° C ambient temperature and 90 to 100% relative humidity. Thus, there is a need to develop soil-based guidelines for conservation tillage methods that take into consideration soil and climatic constraints and crop requirements for producing high yields.

Soil Moisture Retention

There are several problems inherent to estimating the plant-available water capacity of the root zone, which is generally determined by the difference in moisture content at −0.03 MPa suction (taken as the field capacity) and −1.5 MPa suction (taken as the permanent wilting point). There is a strong need to determine field moisture capacity and the permanent wilting point under *in situ* field conditions. The latter has to be determined for specific crops of the tropics (e.g., cassava, yam, cowpeas, etc.). The field capacity for many coarse textured soils may occur at as high as −0.005 MPa suction, and the permanent wilting point may be at −0.1 MPa suction. Further, soil moisture retention characteristics need to be developed and assessed under *in situ* field conditions and related to soil constituents, i.e., SOC and clay contents.

Indicators of Soil Physical Quality

Soil quality refers to its ability to perform specific functions: food productivity and environmental buffering capacity (Lal 1999). For agronomic functions, soil quality is a measure of its capacity to meet a crop's requirements to produce the desired yield (Johnson et al. 1997). The usefulness of the concept of soil quality can be enhanced greatly by making it objective, quantitative, and precise through development of appropriate soil quality indices. Key soil properties can be used as indicators of sustainable soil management (Hartemink 1998). Soil physical properties relevant to soil quality include plant available water capacity, effective rooting depth, infiltration capacity, % aggregation, mean weight diameter, and clay content. Based on these determinants, it is important to develop soil-specific indices as follows:

$$S_q = f(AWC, i_c, R_d, Cl, MWD, WSA, EC, SOC)_t$$

Where S_q is soil quality index, AWC is available water capacity, i_c is infiltration capacity, R_d is rooting depth, Cl is clay content, MWD is mean weight diameter, WSA is water/wind stable aggregation, EC is electrical conductivity, SOC is soil organic C content, and t is time. The choice of appropriate properties is likely to differ among soils and ecoregions. The index thus developed reflects the dynamic nature of soil quality.

SOIL PHYSICAL MANAGEMENT IN ENVIRONMENTAL CONTEXT

Two of the principal goals of soil physical management are achieving food security and improving environmental quality. Although notable progress in achieving food security was made during the last three decades of the 20th century in some regions of the tropics, there continue to be severe problems with soil, water, and air pollution. Soil physical processes that impact environmental quality are: (i) erosion by water and wind, (ii) transport of pesticides, fertilizers, and their by-products into the surface and ground waters, and (iii) emission of radiatively-active gases from the soil to the atmosphere. The need to understand these processes, especially in relation to land use and management systems, is of primary importance at this time. It is necessary to identify key soil properties (e.g., soil structure, erodibility, hydraulic conductivity and intrinsic permeability, macropore flow, diffusion coefficient) and processes (e.g., erosion, compaction) that affect the fate of agricultural chemicals. As much as 55% of global emission of N_2O comes from agricultural activities and relates to the use of nitrogenous fertilizers. The use of nitrogenous fertilizers will increase in the tropics, where nitrogen use efficiency is extremely low (30 to 50%). Whatever is not absorbed by the plants is leaked into the environment through runoff, leaching, and volatilization, similar to fate of pesticides. Knowledge of the principles of saturated and unsaturated flow can be used to understand the transport of pollutants through soils and to alter the flow behavior to reduce the risks of water pollution. Poor quality surface and ground waters are major health hazards in the tropics that need to be addressed. Transport processes are understood better in the landscape and watershed context. Therefore, studying water, sediment, and pollutant transport over and through the landscape, and in relation to spatial variability in soil physical properties and processes, is a relevant strategy. In this regard, the development of close collaboration between soil physicists, hydrologists, and specialists in GIS and geostatistics is an important strategy.

Soils play an important role in the accelerated greenhouse effect, being a source or sink for CO_2, depending on the land use and soil management. There are two important researchable issues: (i) the possible impact of potential climate change on soil physical properties (e.g., structure) and processes (e.g., erosion, densification); and (ii) the effect of soil physical management on fluxes of radiatively active gases between soil and the atmosphere. Addressing these issues will require close collaboration between soil physicists, microbiologists, climatologists, and atmospheric chemists.

Waste disposal, both urban and industrial, will become an important issue in the tropics. Understanding reactions between compounds in the reactive constituents of waste and soil (clay and SOC fractions) will be necessary to develop appropriate strategies to minimize risks of environmental contamination. Learning more about the impact of soil physical management (e.g., tillage, mulching, irrigation, drainage) in regard to safe waste application is important.

SOIL SCIENCE AND SOCIETY

Soil science, in general and soil physics in particular have made significant and long lasting contributions to the welfare of human civilization. Important among these are the knowledge of (i) erosion processes and their control, (ii) water retention and movement for developing methods of irrigation and drainage, (iii) root growth and development in relation to tillage methods, (iv) soil temperature regime and mulch farming techniques, (v) soil air composition and aeration in relation to fluxes of greenhouse gases between the soil and the atmosphere, and (vi) retention and transport of pollutants in soil in relation to quality of surface and ground water. Yet society does not recognize that these contributions are as important as those of other branches of sciences (Simonson 1991; Greenland 1991; Singer and Warkentin 1996). The contribution of soil science to the green revolution in South Asia, and especially that of soil physics in terms of water management (irrigation, drainage, salinity control, erosion control) and soil surface management (tillage methods, residue management, soil temperature moderation) are significant. The credit, however, is given mostly to plant breeding and varietal improvement. Nevertheless, the genetic potential of an improved variety cannot be realized until soil quality is optimized through improved soil management. The observed decline in productivity of the rice-wheat system in South Asia during the 1990s was the result of soil degradation. Soil quality management is crucial to achieving and sustaining the yield potential of improved varieties and cropping systems.

Soil scientists need to alter their strategy to make their contributions known to society and to convince society of their future role in achieving food security and improving environment quality. Soil science has a pivotal role to play in enhancing food production in the tropics (Greenland 1991), and soil scientists must learn how to communicate with society about their past contributions and future priorities. Soil is a grossly undervalued component of the natural ecosystem (Bridges and Catizzone 1996). One possible strategy is to adopt a holistic approach to the study of soil. This approach involves studies of soil not only for productivity but also for environmental, engineering, social, legal, archaeological, and biological issues (Fig. 3). To achieve the desired recognition, soil scientists in the tropics, as elsewhere, must work in close cooperation with other disciplines. They must address problems of interdisciplinary importance (environmental issues, nonagricultural land uses, waste disposal etc.) and look beyond their own discipline to work with colleagues in other sciences.

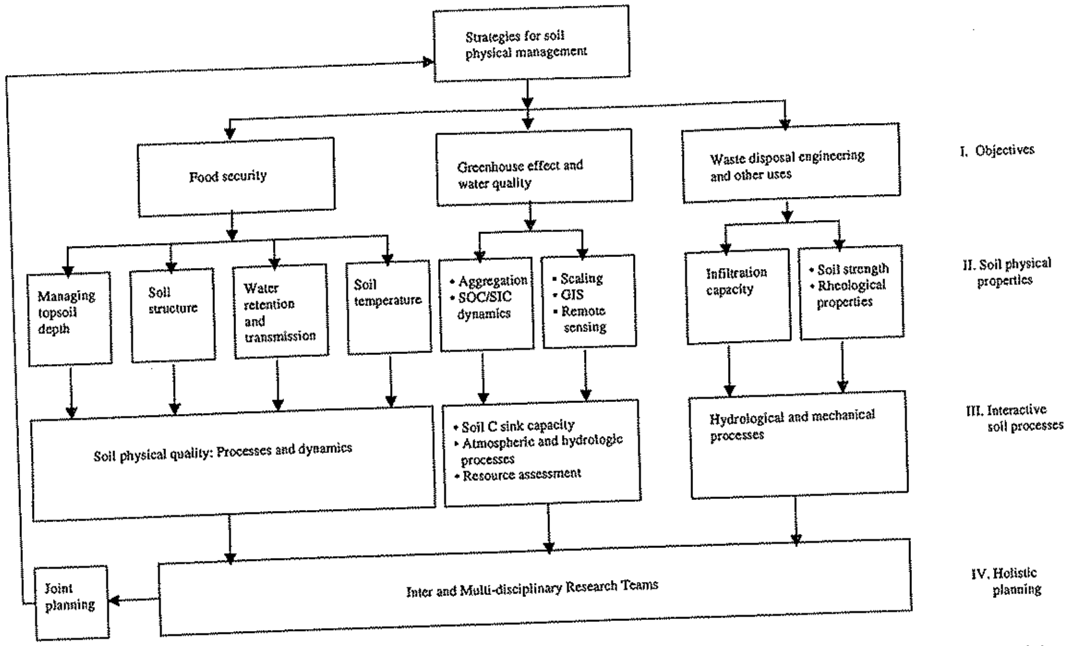

Fig. 3. A holistic approach to soil physical management based on inter- and multidisciplinary strategies involving collaboration between soil scientists, climatologists, hydrologists, civil engineers, geographers, specialists in geo-processing, economists, and other disciplines.

CONCLUSION

Soil physical management has and will continue to play a major role in achieving food security, a high priority in the tropics. Important soil physical processes affecting agronomic productivity are erosion, compaction and crusting, anaerobiosis, and drought. Key soil physical properties determining the rate and magnitude of these processes are % aggregation, MWD, infiltration rate, porosity and pore size distribution, and thermal conductivity. Determining interdependence among physical properties and processes for different land uses and soil management options is crucial to establishing the cause-effect relationship. Decline in soil structure sets in motion the degradative trends. Understanding dynamics of soil structure and developing systems of its management are crucial to sustainable management of soil and water resources of the tropics. Technological innovations are needed to develop conservation tillage methods, improve water use efficiency in irrigated and rainfed agriculture, control soil erosion and assess its economic impacts, reclaim salt-affected soils, manage soil structure, and regulate soil temperature. Soil physical properties also play an important role in water quality, gaseous emissions from soil to the atmosphere, and in identifying appropriate systems of waste disposal. To create a much needed awareness of the contributions of soil management to society's well-being, soil scientists need to adopt an holistic approach and work closely with scientists in ecological, biophysical, and engineering disciplines. The goals for the 21st century are to enhance food production on a declining soil resource base without jeopardizing environment quality. Soil physical management has a pivotal role to play in achieving these goals.

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