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Soil Management and Sustainable Agriculture in the Developing World

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Abstract

World population is projected to increase from 5.4 bi. in 1990 to 8.5 bi. by the year 2025. The developing world is expected to account for 84% of this population growth. It is only recently that policy makers have accepted that the 60-70% needed increase in food production plus demands for fiber, fuel and construction materials must come from already exploited soil resources of which 88% possess one or more constraints to sustainable production. These population increases will place higher pressures on arable land resources from the present 3.57 persons ha^{-1} to 5.88 persons ha^{-1}. In Asia this is already at 11.1 persons ha^{-1}. It has only recently been accepted in policy groups that improved soil productivity for sustainable production is the foundation upon which these new demands must be met.

Results from the Global Assessment of Soil Degradation (GLASOD) study report that human induced degradation of our vegetated soils has increased from 6% in 1945 to 17% in 1990 and with our present stewardship policies could increase to 25% by 2025. All 11 taxonomic units and over 5.0 M series have been identified within the developing world. The dominant orders are: 23% Oxisols (oxic horizon); 20% Ultisols (< 35% base saturation); 16% Entisols (recent soils); 15% Alfisols (> 35% base saturation); and 14% Inceptisols (young soils). Major management constraints include: 41% physical constraints; 27% low nutrient reserves; 23% aluminum toxicity; and another 16% are acidic; 15% high P fixation, 26% low K reserves and 9% have low CEC. Over 60% have variable charge and 30% have mixed charges requiring special nutrient management.

Soil management research in this domain has been highly focused on: (1) soil characterization and inventories needed to guide research and planning; (2) physical properties and water dynamics; (3) managing the chemical deficiencies and imbalances; and (4) soil biology. The public policies driving this research has been to exploit the soil resources to achieve some degree of self-sufficiency in production of basic food requirements and to supply unprocessed commodities for export to earn hard currencies for industrial development. Such policies only offer short-term gains that result in long-term degradation of the soil resource base and often permanent destruction of the environment.

Briefly reviewed in this paper are examples of soil management research that offers: (1) options for sustainable agriculture production technologies that could reduce deforestation in the humid tropics; (2) management components that offer risk reduction and sustainability for some semi-arid domains; and (3) analysis with sustainability indicators (partial and total factor productivity analysis) of past successes and second generation challenges now facing rice farmers in the intensively managed systems in Asia. These examples support the need for: (1) improved capacity based inventories for our soil resources; (2)

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integrating production component research into conservation management systems; (3) sustainability indicators to monitor the impact of exploitation on the quality of soil resources; and (4) public policies focused on sustainability of soil resources and the institutional capacities to respond to changing demands and policy implementations.

Introduction

Soils are the natural resource foundation upon which countries in the developing world must build their economies. Sustainable agriculture is highly dependent upon the successful management of these resources to produce this generations' food, fiber, fuel and construction materials requirements without compromising the ability of future generations to meet their own needs. The developing world includes those countries lacking the industrial, financial or mineral base to purchase the basic needs that their agriculture is unable to produce on a sustainable basis. By this definition, many of these countries are located between the Tropic of Cancer and the Tropic of Capricorn, therefore, when we speak of soils in developing countries the reference is primarily Tropical Soils. Soils in the tropics denotes a difference between mean summer and mean winter temperature of 5°C or less, with mean annual temperature > 5°C, and temperature is not a constraint to year-around agriculture production (Eswaran et al 1992).

Historically, production agriculture has been considered sustainable because application of scientific technology and land exploitation were the means to meet increased production demand pressures. It has become readily apparent to scholars of the subject that sustainable agriculture for the future must take on new parameters for three basic reasons: (a) globally there is a relentless demand for more food, fiber, fuel and construction materials; (b) scarcity of lands for agriculture; and (c) land degradation is slowly being recognized as a worldwide problem (Bently 1991). This paper will summarize identified constraints to our soil resources, management challenges to overcome the loss of productive soils caused by human induced degradation, and present some examples of successful approaches to soil management and new challenges for sustainable agriculture confronting the developing world.

Overview of Soil Resources an Population Effects

Meeting basic human needs has taken on new dimensions since the world oil crises imitated in 1973. Agriculture research in the developing world before 1950 concentrated mainly on cash crops for exports such as cocoa, coffee, tobacco, cotton and rubber. Increased trends toward food self-sufficiency research initiated by the Rockefeller and Ford Foundations and subsequently through International Agriculture Research Centers (IARCs) in the Consultative Group of International Agriculture Research (CGIAR) initiated many changes in developing countries toward this emphasis on food production. Annual crops of world-wide importance, such as, wheat, rice and maize were clearly favored over regionally important crops such as yams, pulses, oil seeds, vegetables or perennial crops. With the emergence of agroforestry, an international focus has been given to other crops for the purposes of fuel wood, forages for animals and constructions materials supporting production systems that emphasize conservation technologies and policies. The first section of this paper reviews the increasing population demand and effects upon on finite world soil resources.

Population growth and demands

World population has increased from 3.0 billion in 1960, to 5.3 billion in 1990 and is projected to nearly triple to 8.5 billion by the year 2025 (Table 1, World Resources Institute 1990). By the year 2025 it is projected that 84% of the global population will reside in the developing countries in Africa, Asia and Latin America. To provide the present per capita level of the basic food groups for this higher level of inhabitation the production of these key food groups will need to increase from 46 to 51% over the next

three decades (Table 2). Global human needs planners are also including future demands for fiber, fuel and construction materials in addition to food into the production demand pressures that will be placed upon our soil resources. This will require quite different thinking on how we must plan and use our finite soil resources.

Table 1. Projected size and growth in population.

Region	Year 1960	1990	2025
		millions	
Africa	281.1	647.5	1581.0
N. & C. America	269.5	427.2	594.9
S. America	146.8	296.8	498.4
Asia	1666.8	3108.5	4889.5
Europe	425.1	497.7	512.3
USSR	214.3	288.0	351.5
Oceania	15.8	26.5	39.0
Total	3014.4	5292.2	8466.5

Source: World Resources Institute 1990.

Table 2. Actual and potential needs of selected food sources based on 1991 per capita projections.

Food source	Actual[1] 1950	Actual[1] 1990	Demands[2] 1995	Demands[2] 2025	Increase 1995-2025
			Million tons		
Rice	168	490	537	785	46
Other grains	463	1255	1298	1920	51
Root crops	253	570	624	911	46
Oil crops	91	198	217	316	46
Pulses	26	56	61	90	48
Meat	46	171	185	272	47
Fish	22	97	103	151	48

Sources: 1. Brown et al 1992; Brown et al 1993; 2. Hanson et al 1993.

Pressure on soil resources

There are number of criteria used as measures of present and future land-use demand pressures. Present technologies using modest inputs require 0.5 ha per capita to provide basic needs. In actually, there is about 0.28 ha per capita (World Resources Institute, 1990), Which means we presently do not produce adequately to meet basic human needs. It would be well to review some distorted land-use demand assessments, and then review some examples for soil management for sustainable agriculture production.

When population pressure on soil resources is calculated on total land area the human demand pressure is very misleading (Table 3, World Resources Institute 1990). For example, demand on soil resources in Africa would be viewed as very low when total land area is used because of large areas of deserts, mountains and semi-arid lands. The Pacific Rim island countries would appear to be almost uninhabited because of a high percentage of forested lands. When population pressure on soil resources is rightfully calculated on the areas classified as cropland, or soils that could be farmed in a sustainable manner with adoption of appropriate technologies and policies, the land use pressure is more realistic (Table 4, World Resources Institute, 1990). Under this scenario, land-use pressures in Africa and the Pacific Rim countries would move near the top on basis of population pressure on available soil resources.

Studies in Africa reveal that populations have extended out and encroached onto traditional pastures and forest/woodlands, or the marginal lands, and true average human pressure on available soil resources is presented in Table 5 (Hanson et al 1993). There has been very little effort or even concern expressed in what are the true productive carrying capacities of these soil resources and what input-output cost and benefits might be needed for sustainability and equitability.

Table 3. Projected population demand pressure on total land area by region in developing world.

Region	Total land area (million ha)	Population density (per 1000 ha)			
		1950	1990	1995	2025
Africa	2964	75	217	252	539
Asia	2731	504	1140	1250	1799
C. America	299	182	506	560	882
S. America	1754	64	169	186	281
Pacific Rim	50	40	99	111	183

Source: Calculated from data from World Resources Institute 1992.

Table 4. Projected population demand pressure on cropland by region in the developing world based on 1990 cropland area.

Region	Cropland (million ha)	Population density (per 1000 ha)			
		1950	1990	1995	2025
Africa	186	1193	3452	4015	8585
Asia	454	3033	6856	7518	10820
C. America	38	1755	3987	4409	6943
S. America	142	786	2090	2293	3477
Pacific Rim	0.7	2871	7071	7900	13071

Source: World Resource Institute 1992.

Table 5. Projected population demand pressure on cropland, pasture and forest/woodland in the developing world.

Region	Total cropland, pasture and forest/woodland (million ha)	Population density (per 1000 ha)			
		1950	1990	1995	2025
Africa	1763	126	364	423	908
Asia	1688	816	1844	2022	2910
C. America	197	276	768	850	1339
S. America	1516	74	196	215	326
Pacific Rim	43	47	115	129	213

Source: Hanson, Bathrick, and Weber 1993.

Soil diversity and Inherent constraints

The major land resource systems in the tropics are presented in Table 6 (Eswaran, personal communications 1993). These six land resources systems cover about 61% of the tropics and about 20% of the global land area. Not included are deserts, mountains and much of the area above latitude 50° north and south. From the point of view of land resources in the developing countries in the tropics, approximately 25% are acid and non-acid savannas of South America and Africa and 21% the humid regions of Latin America, Africa and Asia. When land resources areas are classified and broken down by Soil Taxonomic units, (Table 7, Eswaran et al 1992) the magnitude of site specific soil management becomes overwhelming if all soil production constraints are to resolved at the series or phase level. This is why constraints that limit the soil systems' capacity to be continuously productive would best be determined on their inherent productive capacity and/or constraint so that as management technologies are developed these can be delineated to analogous soil systems based on a quantifiable capacity factor.

Table 6. Major Land Resource Systems in the Tropics.

System	Area ($m.km^2$)	Percent Global (%)	Percent Tropical (%)
Savanna/acid	7.57	5.08	15.38
Savanna/non-acid	4.72	3.16	9.58
Desert Fringe	1.90	1.28	3.86
Humid	10.42	7.00	21.18
Steeplands	3.24	2.17	6.58
Wetlands	2.19	1.47	4.45

Source: Personal communications with Hari Eswaran

Utilizing data from the Food and Agricultural Organization of the United Nations (FAO) and the Fertility Classification Capacity (FCC) system developed by the Tropical Soils Management program at North Carolina State University, the World Resources Institute (World Resources Institute 1990) have assessed that 88% of soils in the tropics possess one or more physical and/or chemical constraint (Table 8a, 8b, World Resources Institute 1990). Inherent Soil characteristics are divided into physical (Table 8a) and chemical (Table 8b) constraints. For the major tropical land regions, the area with no inherent constraints

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Table 7. Estimates of number of soils in each category of the US system of soil taxonomy in the tropics.

Taxonomic level	Estimate of number of soils
Order	11
Suborder	45
Great Group	200
Subgroup	1,250
Farnily	1,000,000
Series	5,000,000
Phases of Series	10,000,000

Source: Eswaran, Kimble, Cook and Beinroth 1992.

Table 8a. Physical soil constraints by region in the developing world.

Region		Total Land Area	No Inherent Constraints	Physical constraints: Steep Slopes	Shallow Soils	Poor Drainage	Tillage Problems
Africa	(million ha)	3011	443	261	398	198	112
	%	-	14.7	8.7	13.2	6.6	3.7
C. America	(million ha)	274	58	69	44	15	19
	%	-	21.2	25.2	16.1	5.5	6.9
S. America	(million ha)	1898	208	329	193	213	27
	%	-	11.0	17.3	10.2	11.2	1.4
S.E. Asia	(million ha)	897	33	261	91	109	76
	%	-	3.7	29.1	10.1	12.2	8.5
S.W. Asia	(million ha)	678	46	161	174	6	6
	%	-	6.8	23.7	25.7	0.9	0.9

Source: World Resources Institute 1990.

are: Africa 14.7%, Central America 21.2%, South America, 11.0%, South East Asia 3.7% and S.W. Asia 6.8%. The dominate physical constraints are shallow soils and steep slopes (erosion susceptible), with the exception in South East Asia where land subject to poor drainage have been developed into highly productive rice soils. Chemical deficiencies are more inherent in soils of Africa, South America and South East Asia than physical limitations (Table 8b). Major limitations in Africa are Low K reserves, aluminum toxicity and low nutrient retention; South America, Low K reserves, aluminum toxicity and phosphorus fixation; and South East Asia, Low K reserves, aluminum toxicity and phosphorus fixation.

Status of world soil resources

Soil degradation and the on-site and off-site effects have long been observed in a number of countries, but has not been quantified as the impact on the global soil resources since 1945. The Global Assessment of Soil Degradation (GLASOD) study sponsored by the United Nations Environmental Program (UNEP) and

coordinated by the International Soil Reference and Information Centre (ISRIC) in the Netherlands reports global increase of 11% (from 6% to 17%) in human-induced soil degradation between 1945 to 1990 (World Resources Institute, 1992).

Table 8b. Chemical soil constraints by region in the developing world.

Region		Chemical constraints						
		Low nutrient retention	toxicity hazard	Al fixation hazard	P K reserves	Low soluble salts	Excess of Na	Sulfate acidity
Africa	(million ha)	397	508	205	615	51	4	4
	%	13.2	16.9	6.8	20.4	1.7	-	-
C. America	(million ha)	-	24	15	27	-	2	-
	% -	8.8	5.5	9.9	-	-	-	
S. America	(million ha)	117	842	600	913	24	25	2
	%	6.2	44.4	31.6	48.1	1.3	1.3	-
S.E. Asia	(million ha)	30	241	190	257	17	1	7
	%	3.3	26.9	21.1	28.9	1.9	-	-
S.W. Asia	(million ha)	37	4	2	4	49	0	0
	%	5.5	-	-	-	7.2	-	-

Source: World Resources Institute 1990.

GLASOD defines soil degradation as "a process that describes human-induced phenomena that lowers the current and/or future capacity of the soil to support human life". The primary casual factors to human-inducted soil degradation were from vegetation removal, fuelwood exploitation, overgrazing, agricultural activities and industrial and urban pollution (Table 9, World Resources Institute, 1992).

Globally, the order of importance of human induced soil degradation found overgrazing highest at 35%, followed closely by vegetative removal at 30% and agricultural activities 28%. Regional differences in causal factors will require different approaches in rejuvenation and preventive soil management practices. The four major types of soil degradation identified by GLASOD are water erosion, wind erosion, chemical degradation and physical degradation (Table 10, Worlds Resources Institute, 1992). Water erosion ranks first across all regions, with wind erosion ranking second with the exception of South America where chemical degradation ranks number two. These findings strongly support that future soil management technologies and public policies will need to change from the emphasis on exploitation to one of rejuvenation and preventive conservation if intergenerational equitability is to become a reality.

Technologies for Sustainable Production

Soil management research to develop technologies for sustainable agriculture must focus on major constraints within the specific agroecological domain that is being targeted. While scientific principals and approaches might have similarities across many domains, research must be targeted on the constraints within the given domain, to sort out what might be transferable from site specific data of other domains in order to prioritize the research need based on the technology gaps within a given domain. This section will review some examples of constraint driven research that were based on the identification of specific problems, the research tasks were then divided into components, and the technologies tested through the integration of the primary components. Examples will be drawn from the humid tropics, semi-arid Sahel and intensively managed rice soils in Southeast Asia.

Table 9. Causes of human-induced soil degradation by region.

Region		Total degraded area	Causal Factor				
			Vegetation removal	Fuelwood exploitation	Over-grazing	Agriculture activities	Industrial pollution
Africa	(million ha)	494	67	63	243	121	0
	%	-	14	13	49	24	0
N.&C. America	(million ha)	158	18	11	38	91	0
	%	-	11	7	24	57	0
S. America	(million ha)	243	100	12	68	64	0
	%	-	41	5	28	26	0
Asia	(million ha)	748	298	46	197	204	1
	%	-	40	6	26	27	0
Europe	(million ha)	219	84	1	50	64	21
	%	-	38	0	23	29	9
Oceania	(million ha)	103	12	0	83	8	0
	%	-	12	0	80	8	0
World	(million ha)	1964	579	133	679	552	23
	%	-	30	7	35	28	1

Source: World Resources Institute 1992.

Table 10. Increase by type of human-induced soil degradation 1945-1990.

Region		Total vegetated area	Total degraded area	Types of degradation			
				Water erosion	Wind erosion	Chemical degradation	Physical degradation
Africa	(million ha)	2234	494	227	187	61	19
	%	-	22	46	38	12	4
N.&C. America	(million ha)	2063	158	106	39	7	6
	%	-	8	67	25	4	4
S. America	(million ha)	1740	243	123	42	70	8
	%	-	14	51	17	29	3
Asia	(million ha)	3769	748	441	222	73	12
	%	-	20	59	30	10	2
Europe	(million ha)	949	219	115	42	26	36
	%	-	23	52	19	12	17
Oceania	(million ha)	787	103	84	16	1	2
	%	-	13	81	16	1	2
World	(million ha)	11542	1964	1094	548	239	83
	%	-	17	56	28	12	4

Source: World Resources Institute 1992.

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Alternatives to deforestation in the humid tropics

Deforestation in the humid tropics in South America is driven by complex biological, demographic, economic and social forces. Populations in these developing countries continue to grow. While much of the fertile and accessible lands are used intensively, government policies are seldom adequate to prevent migration to humid tropical regions and continuous deforestation. The traditional shifting cultivation of indigenous societies has been broken by exploitational policies of colonists resulting in various forms of unsustainable agriculture and continued deforestation. There are a number of land management strategies that can help mitigate tropical deforestation: (1) develop sustainable production systems for already cleared rain forest lands; (2) develop economic and equitable policies of land tenure for densely populated areas; (3) develop overall rain forest preservation and utilization programs for these remaining resources.

The approach was to develop options for acid, low-fertility soils that improve the economic status of subsistence farmers, maintain agriculture production on deforested lands, and recuperate productivity of degraded lands (Sanchez and Benites 1987). The integrated approach: (1) develops and applies sustainable management technologies; (2) establishes public policies to provide incentives to conserve existing rain forests, and (3) implement effective, economically sound environmental protection. The principal soil management options for sustainable production of the humid rain forest region of South America included: (1) paddy rice production for alluvial soils; (2) low-input cropping systems; (3) continuous cultivation; (4) legume-based pastures, and (5) agroforestry.

Paddy rice production. Alluvial soils, highly fertile and located near water supplies and river transportation account for 11% of the soils in the South American humid tropics (Sanchez. Palm and Smyth 1991). Research to adapt Asian rice technology developed the following technology: (1) land is cleared by slash and burn and leveled for flow irrigation; (2) supplement irrigation by gravity flow or pumping in addition to rainfall increased yields by 50%; (3) transplanting provided higher initial yields until paddies became established; (4) initial fertilizer responses were only to nitrogen; and (5) farmer yields often averaged 5.5 t ha^{-1} $crop^{-1}$. Yield from one ha of paddy rice is equal to 14 ha of upland rice under shifting cultivation.

Low input cropping. Low input are transitional systems developed to help poor farmers in more isolated rural areas make the transition from shifting cultivation into potentially more sustainable options. This system involves: (1) clearing secondary forests fallow by slash and burn; (2) work without fertilizers, lime, or external organic inputs; (3) plant acid-tolerant upland rice and cowpea cultivars in rotation, remove only the grain to minimize nutrient export; (4) establish a legume fallow when nutrient deficiencies and weeds make cropping unprofitable; and (5) after one year eliminate the legume fallow by slash-and-burn and shift to a more sustainable system, such as grass-legume pastures, agroforestry or high-input continuous system. A low input system is only transitional because nutrient depletion and weed encroachment eventually leaves the soils unproductive (Sanchez, Palm and Smyth 1991).

Agroforestry. Agroforestry has become an popular management option for many humid tropical areas because it can be adapted to serve sustainability for a wide range of socioeconomic and soil-landscape communities. The soil management research on agroforestry has focused on: (1) selection of and management of acid-tolerant leguminous trees; 2) food crop-tree production systems; (3) managed fallow; (4) plantation crops-forage-small ruminant systems; (5) alley cropping or hedgerow system for soil and water conservation with much emphasis on nutrient cycling (Sanchez and Benites 1987; Sanchez, Palm and Smyth 1991). Alley cropping experiments have pointed out limitations on acid soils because nutrients are soon exhausted through food crop-tree competition on low-fertility soils. The potential options that can be developed from agroforestry systems appears to be nearly endless and especially suited to reclamation of soils formerly under rain forests. Because the time lag between the establishment of a agroforestry systems and economic return is much longer than for food or other cash crops careful economic planning is required at the individual farm level.

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Managing pastures and grazing lands. Poor management of tropical grasslands for animal production is a casual factor behind deforestation, soil degradation and land abandonment. Improved management includes the selection of acid-tolerant, persistent and compatible grass and legume ecotypes, addition of small quantities of needed nutrients and managed grazing. Long-term controlled trials near Pucallpa, Peru has shown that a mixture of *Brachiaria decumbens* with *Desmodium ovalifolim* could provide as much N to pasture biomass as 300 kg N ha^{-1} yr^{-1} of urea to pure grass confirmed by both cutting and grazing trials (Ara and Sanchez 1991). Of the animal intake about 33% of the N comes from the legume component and 67% contributed from the enhanced N content of the grass. About 10% of N transfer to the grass comes from legume litterfall and 90% recycled from animal excreta and root turnover. Under controlled grazing and careful management productive legume and grass mixtures have been maintained for over 12 years at Yurimaguas, Peru (Sanchez, Palm and Smyth 1991).

Continuous cropping with inputs. In humid tropic communities, farmers close to urban markets can also implement the option of continuous production with the use of external inputs because they are in a market driven economy, not a subsistence economy. To determine if a Ultisol in the humid tropics of Peru could be continuously cropped without degradation, the North Carolina State University TropSoils project undertook a long-term experiment comparing no-input with chemical correction and maintained application of nutrients (Alegre and Sanchez 1991). Sustained crop yields have been obtained with continuous cropping for 43 crops in 20 years. This continuous production was obtained with effective crop rotations, judicious application of lime and nutrients and improved crop management practices. Over time the soil's physical qualities did not deteriorate, organic carbon levels are maintained, and subsoil Al toxicity was greatly reduced improving the soil chemical quality indicators.

Potential for reducing deforestation. A major mission of soil management research in the humid tropics should be to reclaim deforested lands and save the pristine rain forest from unneeded destruction. The above discussed technologies have been evaluated for their potential to reduce the rate of destruction of tropical rain forests (Table 11). For every ha each farmer adopts one of these sustainable soil-management technologies onto traditional shifting cultivation there is the potential to reduce tropical deforestation by five to ten ha (Sanchez, Palm and Smyth 1991). These soil management technologies are especially applicable to secondary-forest fallow because such clearing of small biomasses contributes little to global climate change. To maximize benefits from these technologies effective public policies and institutional strengths are necessary.

Table 11. Potential for soil management technologies developed in Yurimaguas, Peru to reduce tropical depletions.

One hectare in sustainable management options	Potential area of tropical rain forest saved annually (ha)
Flooded rice	11.0
Low-input transitional cropping	4.6
High-input cropping	8.8
Legume-based improved pastures	10.5
Agroforestry systems	(not determined)

Source: Sanchez, Palm and Symth 1991.

Soil management technologies in the semi-arid tropics

While rainfall in semi-arid tropical Africa is limited, its variability and distribution are considered the major constraints to food security. Major soil limitations include low fertility, acidity, sandy texture, and low organic matter content and is subject to both wind and water erosion. The farmers in this region are well aware of these constraints and therefore this management strategy is to minimize risks. The mission of soil management research in the semi-arid tropics is to manipulate the soil-water-plant system to improve the economic production and to decrease year-to-year fluctuations by improving indigenous practices through the application of scientifically based soil and water conserving technologies. Research by the Texas A&M TropSoils program in Niger focused on the effects of crop residue and inorganic plant nutrients management on soil properties and risk reduction in the production of millet and other basic food crops.

Crop residue effects the on soil system. Because of shortages in building materials, fuel and animal fodder, millet stocks, leaves and other crop residues are seldom left in the field. This exposes the soil surface to wind erosion during the long rainless period and exacerbates water erosion by intensive rainfall during the rainy season resulting in extreme spacial variability and low productivity (Pfordresher et al 1991). Research in Niger has quantified that millet residue left on the surface manifested a number on beneficial productivity effects upon these sandy soils: (1) recycling of nutrient elements following termite and microbial decomposition; (2) entrapment of the higher nutrient content aeolian materials; (3) reduction in soil acidity; (4) decrease in P fixation; (5) improvement in moisture dynamics of the system. Research conducted by ICRISAT (Bationo et al 1990) found that three years of leaving millet residue on the soil surface resulted in 268% increase in stover yields. Nitrogen uptake was increased 288%, P 240%, K 311%, Ca 212% and Mg 260%. Surface mulched can entrap at least 2.0 Mg ha^{-1} of nutrient rich aeolian materials, 60% during the three months prior to the rainy season (Drees et al 1991).

Plant nutrient constraints. Spacial variability of farmers' fields in Niger seen with infrared video imagery revealed that unproductive areas ranged from 2 to 36% with over 50% of the sites studied having 22% of the field nonproductive (Pfordresher et al 1991). Planting pearl millet in such a field for two consecutive years indicated that the location of the areas of poor growth is a function of soil properties and does not change perceptibly between years, and the crops are more affected in low rainfall years than above normal rainfall years. Aluminum toxicity is suggested as a major causal factor to the variable nonproductive areas in these soils with Mn toxicity contributing as a secondary constraint. Major nutrient deficiencies were identified as to be N, P, K and Mg (Chase et al 1989). Phosphorus is most commonly found to be the most limiting nutrient in the sandy soils in Sahelian West Africa. Response to N is obtained only when P is adequate and the millet residue has an additive effect to fertilizer when soils are low in P (Geiger et al 1991). Implications of this combined research are that stabilization of the soil surface against high winds and erosive water is needed to regenerate and/or preserve native fertility and that soil testing is badly need to select needed nutrient inputs on soils with sustainable production potential.

Intensive rice production systems

Today, rice-based agricultural systems dominate in much of Asia where more the 90% of global rice supplies are produced and consumed, supplying 30-75% of dietary calories. Irrigated rice systems account for about 55% of total harvested rice area and 76% of global rice production (IRRI 1993). About 40 million ha of irrigated rice are harvested each year in tropical and subtropical Asia. Modern irrigated rice systems in Asia are the most intensive crop production systems in the world. Double and triple-crop rice systems are practiced on some 10 million ha in Asia where year-round irrigation is available. Based on IRRI projections, rice production must increase more the 60% in Asia between 1992 and 2020 to meet the growing demand (Table 12, IRRI 1993). Much of the increase in rice production is expected to come from irrigated production systems (higher yield per unit area) which have fewer constraints to increased

productivity than in rainfed rice ecosystems. However, one of the major issues is the capacity of the biophysical resource base to sustain the required increase in rice output.

Table 12. Rice area (10^6 ha), yield (t ha^{-1}), and total production (10^6t, rough rice) in 1990 and estimates for 2020 in developing countries of South, East and Southeast Asia[1].

Rice system	1990 Area	1990 Average yield	1990 Production	2020 Area	2020 Average yield	2020 Production
Irrigated	70.0	4.9	343.4	70.0	7.9	551.2
Rainfed lowland	37.6	2.1	77.2	37.6	3.3	123.9
Upland	11.5	1.1	12.3	10.0	1.1	11.1
Deepwater	8.7	1.5	13.0	7.0	1.5	10.5
Total	127.8		445.7	125.0		696.7

1. Includes China, India, Indonesia, Pakistan, Bangladesh, Vietnam, Philippines, Thailand, Myanmar, Nepal, Malaysia, Sri Lanka, Cambodia, and Laos.
Source: International Rice Research Institute 1993.

Although rice output and yield continue to increase throughout most of Asia, recent trends indicate yield stagnation and declining factor productivity. For instance, yield growth rates declined from 2.6% per annum in the 1970s to 1.5% in the 1980s (1981-1988) for Asia as a whole. Concurrent with the decrease in yield growth rate, aggregate data from some countries suggests declining partial factor productivity for certain inputs (Rosegrant and Pingali 1993). A typical example is Indonesia where total rice production increased 70% from 1976 to 1986. However, the amount of nitrogen (N) fertilizer applied to rice increased by 440% (IRRI 1991). Similarity, data from domains where intensive rice systems predominate in the Philippines and India indicate trends that are similar to the aggregate national trends in rice output and production efficiency, i.e.; (1) there was a dramatic increase in yields and factor productivity following the rapid adoption of modern rice varieties and management practices in the 1960s; (2) yields and factor productivity continued to increase in the second decade after adoption; and (3) stagnant or declining yield trends and factor productivity in the most recent decade (Cassman and Pingali 1993). Although yields were stagnant in the latest decade, fertilizer rates applied by farmers continue to increase.

Long-Term Fertility Experiments (LTFEs) on continuous irrigated rice systems initiated by IRRI researchers and their colleagues in National Research Systems (NARS) over the past 25 years indicate similar yield trends (Flinn and De Datta 1984). Significant yield declines are evident at many of these sites specifically in treatments that receive complete nutrient inputs at rates that originally produced maximum yields. At two LTFE sites in the Philippines, negative yield trends appear to result from a decrease in the N supplying capacity of soil despite constant or increased soil organic matter and total N (Cassman et al 1994). Declining trends in soil N supply with continuous irrigated rice culture has also been reported by Japanese researchers (Saito 1991) and in Australia where continuous rice cropping resulted in the need for increasingly greater N fertilizer inputs to maintain yields (Beecher 1992).

A decline in the "effective" soil N supply with continuous rice appears to be a widespread but poorly understood phenomenon that is linked to decreasing yield and factor productivity of irrigated rice systems. In the IRRI Medium-Term Plan (1994-1998), efforts are directed towards understanding the soil properties and processes that govern N supplying capacity of lowland rice soils that are intensively cropped two or three times annually, and remain submerged for much of the year. The district farm, and experimental plot data suggest that declining partial factor productivity for fertilizer N, and possible fertilizer nutrients more

generally, can provide a focal point for research to quantify the magnitude of the problem. Monitoring both factor productivity (Lyman and Herdt 1989) and the output/input efficiency from applied nutrients (Cassman and Pingali 1993) provides a quantitative index by which the causal factors can be identified, their effects quantified, and remedial strategies tested. Moreover, this knowledge will help to develop management strategies to maximize the efficiency of nutrient use from endogenous soil reserves and from applied inputs, both of which are crucial to sustained yield growth and increased profit from irrigated rice farming.

Cropping systems performance. The impact of the green revolution on rice production was tremendous with regard to increases in yield. This success was based on straight forward "seed and fertilizer" technology recommendations that did not require much site-specific information. Improved modern varieties performed better than local landraces in nearly all irrigated environments, and accurate soil testing was not needed to recognize that these varieties responded to fertilizer, particularly N, at most locations. More recently, however, progress has been slow towards a more information-intensive crop management strategy that optimizes efficiency of all resources in the production system. Moreover, we have limited capacity to predict performance of cropping systems over the longer-term in relation to changes in the soil resource base caused by crop intensification. For instance, in the irrigated rice systems of Central Luzon, Philippines, fertilizer-N use efficiency achieved in farmers' fields is low because farmers do not adjust their N application (ranging from 25-250 kg N ha^{-1}) in relation to the native soil N supplying capacity of their soil which ranges from 35-100 kg N ha^{-1} crop uptake without fertilizer-N application (Cassman et al 1993a). Thus, the ability to predict soil N supplying capacity and the identification of causal factors for large differences among farmers' fields would greatly increase fertilizer-N use efficiency by farmers.

Applied and adaptive research on soil fertility management would be considerably more efficient if it targeted the capacity to: (1) predict the Soil Nutrient Supplying Capacity (SNSC) for major macronutrients; (2) quantify the relationship between grain yield and macronutrient uptake; and (3) develop improved soil test methods that predict the proportion of applied nutrient that is available for crop uptake; and (4) the increase in actual crop nutrient uptake from added nutrients.

New approaches for rice production research: looking forward. The approach IRRI proposes is based on four components: (1) the soil quality hypothesis; (2) more careful measurement of key variables; (3) extrapolation from long-term experiments to farmers' fields; and (4) integration of agronomic, soil, and social sciences in evaluating productivity trends and changes in the soil resource base.

The soil quality hypothesis. Recently C.T. de Witt (de Witt 1992) proposed that "Strategic research that is to serve both agriculture and the environment should not so much be directed towards the search for marginal returns of variable production resources, but towards the search for the minimum of each production resource that is needed to allow maximum utilization of all other resources of the farming system". This concept of resource use efficiency is well suited to irrigated rice systems because farmers attempt to optimize a large number of production factors including tillage operations, high labor requirements, high rates of nutrient inputs, and costs for irrigation, maintenance of irrigation infrastructure, and crop protection against weeds, diseases and insects. Production efficiency, therefore, reflects the technical efficiency of many practices and management decisions. Total Factor Productivity (TFP), which is a ratio of the value of all outputs compared to the costs of all inputs (including labor), provides an integrative value that quantifies the overall resource use efficiency of the cropping system.

On the other hand, soil quality can be defined by quantitative properties that contribute to crop growth, plant health, and yield development. In all cropping systems the inherent SNSC is one of the most important components of soil quality. When native soil fertility decreases due to cropping, greater inputs of nutrients from external sources are required to maintain yields. This trend would be reflected by a decrease in TFP. In fact, the inherent SNSC provides an integrative measure of soil quality because it is extremely sensitive to changes in the soil's physical, chemical, and biological properties that are both

directly and indirectly related to soil nutrient status. For instance, an increase in soil compaction can result in decreased root extension, which in turn results in a decrease in nutrient uptake from soil resources. Alleviating soil compaction through improved management would have the opposite effect. Likewise, root nematode or soil-borne disease problems would be manifested by a reduction in nutrient acquisition from native soil resources. Elimination of nematode or root disease problems would lead to greater nutrient uptake. These considerations lead us to the following hypotheses concerning soil quality: (1) measurement of the SNSC provides a practical and integrative measure of soil quality, particularly in irrigated rice systems where drought is not a constraint and soil physical properties such as aggregate stability, pore size, etc. are less important than in upland soil conditions; and (2) a decrease in the inherent SNSC will be manifested by a decrease in TFP unless farmers improve the agronomic efficiency (i.e., output per unit input) derived from applied nutrients inputs to offset the decrease in nutrients acquired from native soil resources. Based on these hypotheses, a major goal for future soil management research for sustainable production must include the soil quality parameter: the capability to predict the quantity of N, P, or K that the rice crop can obtain from indigenous soil resources (i.e., the SNSC) to allow recommendations for fertilizer-nutrient rates and timing that supply the minimum requirement for the targeted yield.

Extrapolation and magnitude of declining productivity. A yield decline ranging from 50 to 240 kg ha^{-1} yr^{-1} has been found in most of the long-term experiments with intensive, irrigated double- and triple-crop monoculture rice systems, and trends of stagnating TFP and decreasing N use efficiency are evident in farm monitoring studies (Cassman and Pingali 1993) A key issue is whether these two phenomenon are related, and the extent of such problems. Pivotal to this question is whether certain processes which occur in submerged soils, and are therefore inherent attributes of the irrigated rice ecosystem, contribute to both the yield decline in experimental fields and stagnating productivity in farmers' fields.

This issue provides an exciting opportunity for a new research approach that utilizes existing long-term experiments as dynamic references for the interpretation of farm monitoring data to quantify productivity and production constraints in relation to soil quality, crop management practices, and economic performance.

Conclusions

World population is projected to increase from 5.4 billion in 1990 to 8.5 billion by the year 2025. The developing countries are expected to account for 84% of this population growth. This will place extreme demands on the soil systems in Africa and Asia that already have high demand use pressures. In addition to the challenge to increase the production of basic food crops by 60-70%, many countries will also need to address the increased demands for fiber, fuel and construction materials. These demands must be met from present soil resources of which 88% possess one or more major constraint to sustainable production.

The recent GLASOD study, as reported by the Soil Resources Institute, reveals that human induced degradation of the global vegetated soils has increased from 6% to 17% between 1945 and 1990. Agriculture and harvests for human needs account for 99% of this degradation. This paper does not attempt to discuss all details of inherent constraints of global soils in developing countries, biophysical parameters of degradation and rejuvenation prescriptions, nor total review of research activities in soil management for sustainable agriculture. The objective is to present some future challenges that must be met by soil scientists, some ecosystem successes and second generation problems that have been quantified when high production systems are put under high production pressures.

Clearing of the Amazon rain forest is of major global concern because it is the last remaining large captured carbon and potential buffer zone. Options have been developed for the tropical rain forest of South America that offer high potential to reduce the rate of deforestation by enabling farmers practicing shifting cultivation to move to continuous managed production systems. Adoption of these technologies

offers the potential of saving from 5 to 10 ha of rain forest for each ha of new technology adopted annually. Many countries in the tropical rain forest agroecological zones possess other lands with high potential for sustainable production, but lack the public policies and institution systems that will maximize production on these more suitable lands. Soil management research in the uplands of the humid tropical agroecological zones has emphasized resource inventories, chemical limitations, physical attributes and water dynamics. Future research will need to focus on conservation driven sustainable use options compelled by social, market and public policy realities.

Soil management in the semi-arid tropical regions have focused on sustainability and risk reduction through maximum utilization of short and intensive rainfall periods. Many soils in this region are sandy textured, chemically deficient, low in organic matter and subject to wind and water erosion. Soil management research has focused on economic benefits to residue management, quantification of economic thresholds levels for nutrient inputs, evaluation of indigenous phosphate sources for direct application, water capture and water balance in specific management systems. Because sustainable productivity will be highly dependent upon control of wind erosion and water management to reduce erosion and increase moisture capture, more future emphasis will need to be within the context of interdisciplinary Land-Management-Units (LMU) and integrated watershed management to blend new technologies with the indigenous knowledge base.

More than 90% of all rice is produced and consumed in Asia, and it is estimated that global rice production must increase by 50-70% in the next 30 years. Past production increases resulted from area expansions and impacts of partial production factors from improved cultivars, plant nutrients, pest control and improved crop management. Most of the future increase must come from existing intensive, irrigated rice systems because there is little scope for an expansion of irrigated area. It was therefore crucial to assess present trends in yield growth at national, farm, and experimental levels in Asian rice production areas as a basis for targeting research and investment for rice-based agriculture. The evidence examined by IRRI does not provide an optimistic scenario. Yield growth at regional levels, total factor productivity at national, district and farm levels, and partial factor productivity from nutrient inputs in long-term experiments are decreasing where rice is cultivated continuously with irrigation. While there are many factors in both the socioeconomic and biophysical environment that may contribute to such trends, the key issue for future research is what are the underpinning processes responsible for the decrease in the productive capacity of the paddy environment as irrigated rice systems become more intensively managed.

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Sincerely,

Roger G. Hanson
Director

RGH:sm

Enclosures