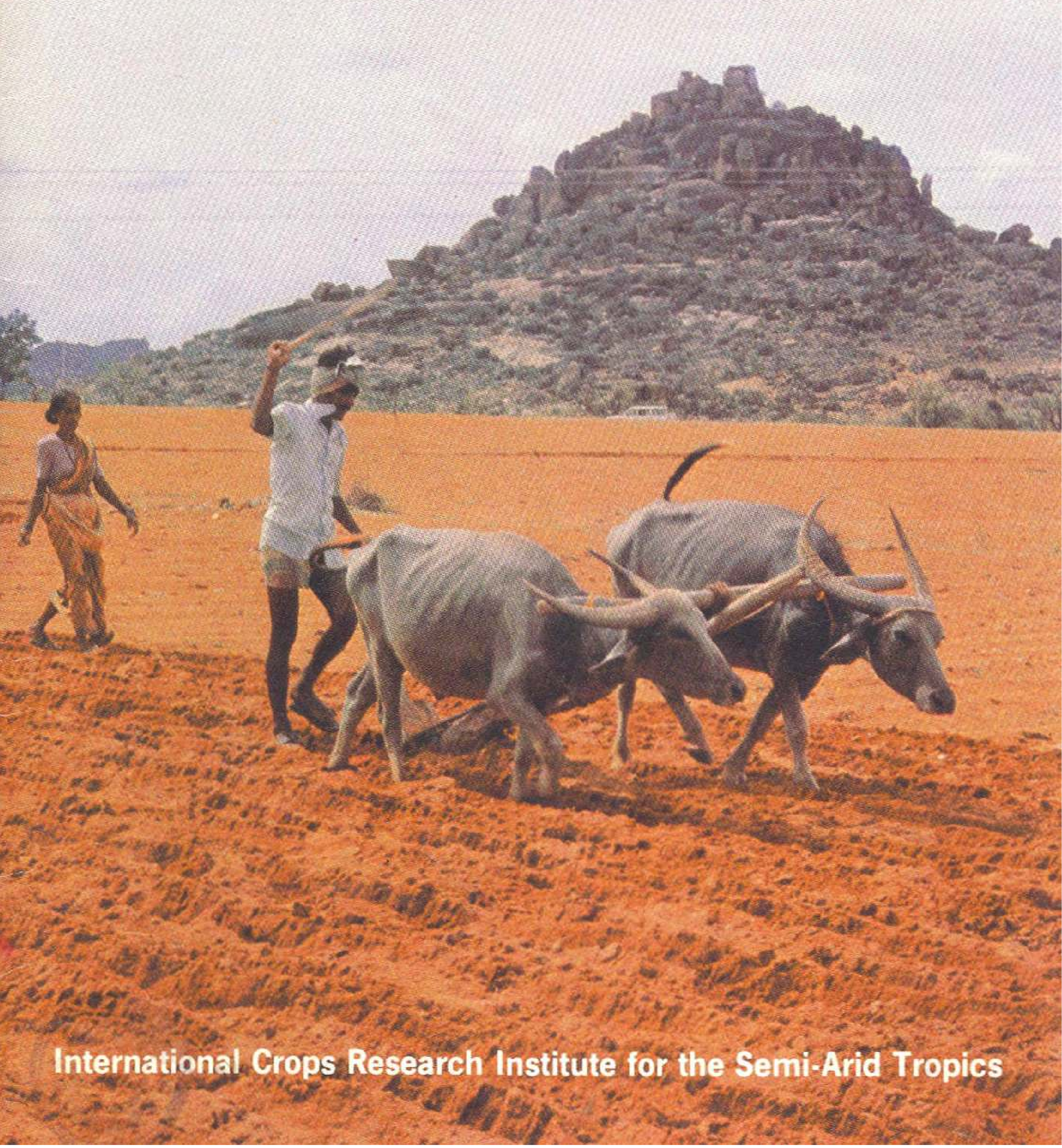
Dryland Management Alternatives and Research Needs for Alfisols in the Semi-Arid Tropics



International Crops Research Institute for the Semi-Arid Tropics

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The Authors

Dryland Management Alternatives and Research Needs for Alfisols in the Semi-Arid Tropics

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S.M. Virmani

An Interpretive Summary

of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils

held at

ICRISAT Center, India
1-3 December 1983

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Foreword

This publication summarizes the reports, conclusions, and recommendations of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils. The workshop was hosted by ICRISAT, 1-3 December 1983, and had the following objectives:

1. Review the important environmental, physical, chemical, and biological characteristics of SAT Alfisols and "related soils", and identify major constraints to their effective agricultural utilization.

2. Assess the current state of the art on effective management of SAT Alfisols under rainfed conditions with particular reference to the following.
   a. Soil and water conservation and management.
   b. Optimum requirements for effective crop establishment and growth.
   c. Water supply development and efficient use for supplemental irrigation.
   d. Fertility and nutritional requirements.
   e. Alternative cropping systems.

The full workshop proceedings are scheduled for publication in 1985. Meanwhile, we hope that the synthesized information included in this report will benefit farming systems researchers and practitioners working on these soils.

J.S. Kanwar
Director of Research

Synopsis

Alfisols and related soils constitute 71 % of the soil resources in the semi-arid tropics (SAT). Much of this region is under dryland cultivation. Unfortunately, conventional dryland cropping of these soils is characterized by extremely low productivity.

These soils have been subject to many investigations within and outside the SAT. But information available on them is still insufficient to clearly identify the technological options for optimizing their productivity. This workshop was sponsored by ICRISAT to assess the management of these soils under rainfed conditions in consultation with other researchers with relevant experience. Interest was especially on case studies for which long-term performance data, including data on soil, crop, and cultural management, were available.

Objectives

1. To review the environmental, physical, chemical, and biological characteristics of SAT Alfisols and "related soils", and to identify major constraints to their effective agricultural utilization.
2. To assess the current state of the art on effective management of SAT Alfisols under rainfed conditions.

Conclusions and Recommendations

1. Alfisols are so diverse that the constraints to crop production in various regions are often dissimilar, and no single strategy is likely to be universally successful in increasing their productivity. Nevertheless, there are certain constraints to production which these soils have in common. Component research is essential for an understanding of the general principles, and for indicating how location-specific land-use systems may be tailored to suit contrasting Alfisol regions.
2. In general, these soils are so poor in physical and chemical resources that there is less chance here of developing improved farming systems that "unlock" slack or unexploited resources than, for example, in the Vertisols of dependable rainfall regions where fallowing in the rainy season is common and double cropping is a natural target for improved utilization.
3. A systematic inventory of Alfisols and their agroenvironments is necessary to place the soils in an orderly classification, determine their capability for alternative land uses, identify the various constraints to crop production, achieve full understanding of existing and proposed management alternatives, and an objective projection of their range of applicability, to develop coordinated plans for needed network studies, and to select pertinent representative (benchmark) locations for such studies.
4. Securing systematic data on climatic parameters is a major requirement for establishing guidelines on potential cropping and relevant practices. Evaluating rainfall characteristics is critical also for soil- and water-conservation planning. Storm totals, peak intensities for different durations, and probability distribution (return periods and frequency) are the primary determinants of runoff, floods, and soil erosion by water. They also bear heavily on seal and crust formations, fertilizer-leaching hazard, pollen wash, grain mold incidence, etc. Data on the above parameters are lacking in SAT regions, particularly in Africa.

5. The high runoff-generation potential and erodibility, the susceptibility to seal and crust formation, poor water storage, profile-hardening tendency, and structural instability have been identified as the primary physical constraints to productivity in SAT Alfisols. Several knowledge gaps represent high priority areas for research aimed at a more systematic understanding and then amelioration of these constraints:
    a. Runoff and soil loss predictability.
    b. Optimized primary and secondary tillage.
    c. Improved soil structure.
    d. Sustained water supply for supplemental irrigation, including water harvesting.
6. While the importance of fertilizer use has been clearly established for Alfisols even under rainfed conditions, considerable gaps still exist in the following areas.
    a. Methods of enhancing and maintaining soil organic matter.
    b. Soil-water-fertility behavior under different agroclimatic conditions.
    c. Fertilizer requirements and management for alternative cropping systems.
7. Considering the diverse crop-producing capabilities of various Alfisols, a strong research emphasis should be placed on alternative agricultural land-use systems. Particular focus is needed on systems that are capable of sustaining some level of biological activity throughout the year by including an element of perennial vegetation, e.g., agroforestry and grass/legume ley farming. Crop rotations designed to maintain soil fertility rank high among conventional annual-cropping systems.
8. Implementation of all research recommendations requires a network-investigation approach because of the extreme diversity among Alfisols and their agroenvironments. Selection of locations for the network should be based on representative soils, climates, and land-use patterns. Hopefully, the selection requirements will be met by several of the existing experiment stations such as those operated by ICRISAT and the All India Coordinated Research Project for Dryland Agriculture (AICRPDA).

    It has been recommended that a committee be formed from among the workshop participants to engage in the deliberate designation of benchmark locations based on systematic criteria. Also, a standard set of procedures for formulating state-of-the-art plans for needed studies is called for. Component research as well as watershed-based integrated systems research should receive equal emphasis.

    Regular meetings involving contact personnel at the various locations should be held to review progress and formulate plans for continuing investigations.

Introduction

The diversity of soils in the semi-arid tropics (SAT) is indicated by the fact that eight of the ten orders in Soil Taxonomy (USDA 1975) are represented in the region. Of the total soil area in the SAT (21 mkm^2), nearly 33% are taken up by Alfisols. "Related" soils in the SAT are primarily the Entisols (13%) and Aridisols (25%), both often similar in characteristics and management requirements. Thus Alfisols and related soils constitute 71 % of the soil resources in the SAT.

The areas where these soils occur are now mostly under dryland cultivation. Unfortunately, as is widely recognized, conventional dryland cropping of these soils is characterized by extremely low productivity.

These soils have been subject to many investigations within and outside the semi-arid tropics. But information available on them is scattered and still too scant to decide on technological options for optimizing their productivity. Indeed, there have been few systematic efforts to inventory problems, document possible solutions, and identify immediate and long-term research needs for increased and sustained productivity of Alfisols.

This workshop was sponsored by ICRISAT to assess current knowledge on effective management of these soils under rainfed conditions. We were particularly interested in case studies for which long-term performance data, including data on soil, crop, and cultural management were available.

While this report is based primarily on papers presented at the workshop, we have drawn on other information sources, where available. It became quite clear at the outset that Alfisols—even when properly placed in the taxonomic heirarchy—are so diverse that the constraints to crop production in various regions are often dissimilar, and that no single strategy for increasing the productivity of these soils is likely to be universally successful. Nevertheless, there are some contraints to production common to all Alfisols and related soils. It was therefore assumed that certain common components for their successful management could be identified.

SAT Alfisols and their Agroenvironments

The Soils

Alfisols occur extensively in southern Asia, western and central Africa, and in many parts of South America, particularly northeast Brazil (Cocheme and Franquin 1967, Fig. 1). These soils are derived mostly from granites, gneisses, and schists, but occasionally also from sandstone, mica, acid trap, quartzite, and shale. Alfisols derived from rocks such as green chanockite and diorite are rich in clay-forming minerals like feldspar, mica, and hornblende; hence their fine texture. Lime concretions in the form of nodules or thick veins are also found in some Alfisols. Such formations are the result of weathering of feldspars containing lime (Digar and Barde 1982). Alternatively, these soils may contain distinct layers of gravel and weathered rock fragments at lower depths (often called "murrum"). SAT Alfisols are identified at the suborder level within the ustic moisture regime. This implies dryness during parts of the year, but presence of moisture when conditions are suitable for plant growth (USDA 1975). With additional specifications of the mean annual soil temperature and duration of the period in which the control section of the profile remains moist or goes dry, the ustic regime

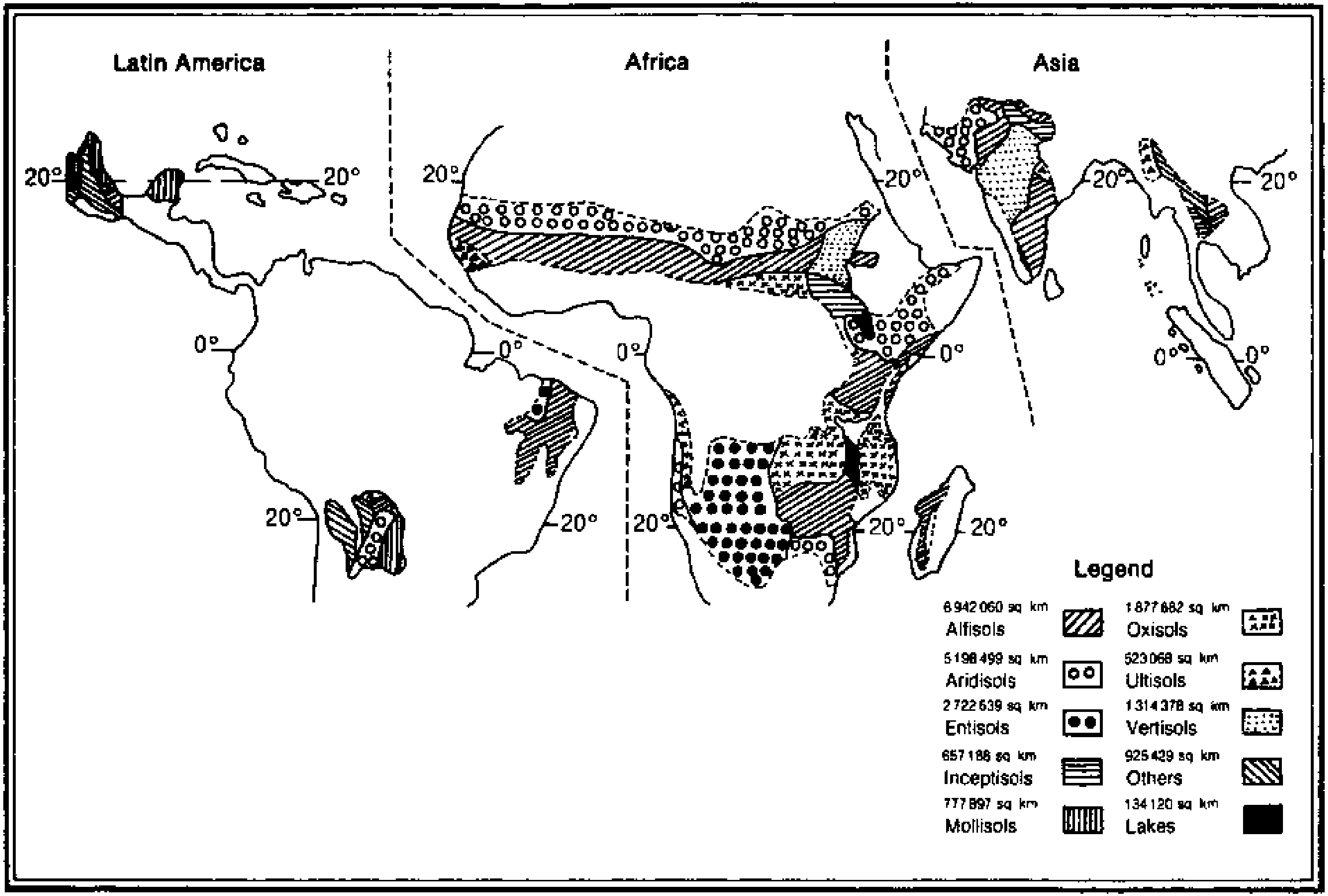

Figure 1. Soil classification in the semi-arid tropics.

Source: USDA 1975.

typifies tropical regions with a monsoon climate that has at least one rainy season lasting 3 months or more in a year.

Alfisols usually possess an argillic horizon within the profile, which means that the clay content of these soils increases with depth. Shallow and gravelly Alfisols—a result of erosion—are also common. Such Alfisols are distinguished from Ultisols by the high base saturation of their control section (>35%). The enrichment of surface layers with coarse particles is assumed to be the result of clay migration with percolating water, termite activity, and/or selective removal of fine particles by erosion. Effective rooting depths of crops are limited either by the shallow soil depth down to the murrum layer, or by the compact agrillic horizon that may restrict water and root penetration.

The criteria for characterizing Alfisols are so flexible that many diverse soils are included in this taxonomic order. This is particularly true of the argillic horizon criterion (Naga Bhushana et al. 1983). The USDA (1975) lists three distinct ways (described below) of defining an argillic horizon, each depending on the clay content of the eluvial horizon.

a. If any part of the eluvial horizon has<15% total clay in the fine-earth fraction (< 2 mm), the argillic horizon must contain at least 3% more clay (13% vs 10%, for example). The ratio of fine clay to total clay is normally about one-third or more greater in the argillic horizon than in the overlying eluvial horizons, or in the underlying horizon.

b. If the eluvial horizon has >15% and<40% total clay in the fine-earth fraction, the ratio of clay in the argillic horizon to that in the eluvial horizon must be 1:2 or more. The ratio of fine clay to total clay in the argillic horizon is normally about one-third or more greater than in the eluvial horizon.

c. If the eluvial horizon has>40% total clay in the fine-earth fraction, the argillic horizon must contain at least 8% more clay; or, if the total clay content exceeds 60% in the eluvial horizon, the argillic horizon must contain 8% more fine clay (50% vs 42%, for example).

The definition of the eluvial horizon, diversity of parent materials, and the minerals, that prevail in the clay fraction are the major criteria for distinguishing between various Alfisols, as for instance those found in India and those occurring in West Africa (Naga Bhushana et al. 1983). Table 1 shows the major characteristics of a relatively fine-textured Udic Rhodustalf occurring in the Hyderabad area of the Deccan, India, and also found at ICRISAT Center (El-Swaify et al. 1983). Appendix A includes detailed description of a typical soil profile for this series. In contrast, Table 2 shows the major characteristics of a relatively coarse-textured Alfisol (Psammentic Paieustalf) at the ICRISAT Sahelian Center in Niamey, Niger. A major difference between Alfisols of West Africa and India appears to be the presence of more fine particles and 2:1 clays in Indian Alfisols. Apparently, Alfisols of West Africa are subject to considerable modification of their properties owing to their position with regard to the neighboring Entisols. Further, Stoop (1984) has described Alfisol-containing, laterite-overlying toposequences of soil formations that abound in western Africa's Sudanian zone where extreme variations in soils and production constraints are encountered. The lower positions in the landscape are occupied by relatively deeper, more fertile, finer-textured but poorly-drained soils. The shallower Alfisols occupy the plateau uplands, upper and middle slopes of these toposequences, with their gravel and sand contents decreasing and 2:1 clay contents increasing in that order. The generally lower overall clay activity in Alfisols of West Africa renders them relatively more "fragile" and therefore more susceptible than their Indian counterparts to the effects of degradation due to mismanagement.

Table 1. Major characteristics of the Patancheru soil series, a Udic Rhodustalf, at ICRISAT Center.

Horizon	Depth (cm)	Size class and particle diameter (mm): Sand (2.0-0.02)	Silt (0.02-0.002)	Clay (<0.002)	Coarse fragments >2 mm % of whole soil	Organic carbon (%)	pH (1:2.5) H_2O Suspension	E.C. (1:2.5) H_2O Suspension mm/nos/cm	Water retention 1/3-bar	15 bar
		---------- % of <2 mm ----------							Gravimetric %	
Ap	0-5	79.3	6.4	14.3	17	0.55	6.0	0.1	16.2	6.3
B t	5-18	66.7	5.5	27.8	17	0.52	6.9	0.1	20.0	12.4
B 21	18-36	41.6	6.8	51.6	36	0.63	6.9	0.1	21.9	13.9
B 22t	36-71	45.0	4.4	50.6	54	0.40	6.8	0.1	24.8	17.4
B 23t	71-112	54.1	7.4	38.5	50	0.10	6.5	0.1	23.6	16.2
B 3	112-140	70.6	4.1	25.3	63	0.18	6.2	0.2	18.7	11.5

Depth (cm)	Extractable bases: Ca	Mg	Na	K	Sum	CEC NH_4OAC	Base saturation %	CEC/clay ratio	Clay fraction mineralogy[1]: Am	KK	MI	SM	QZ	Sand fraction mineralogy[2]: QZ	FDM	FE	HE	FDP	Others
	---------- meg/100g ----------																		
0-5	2.6	0.5	-	0.4	3.5	4.8	74	0.34	11	37	12	17	17	35	25	10	10	5	15
5-18	3.8	0.9	-	0.5	5.2	8.2	64	0.29	12	37	10	19	14	45	20	5	5	10	15
18-36	5.8	3.8	-	0.6	10.2	14.8	69	0.29	14	37	10	23	13	40	30	10	-	10	10
36-71	7.9	3.1	-	0.6	11.6	14.1	82	0.28	12	38	11	20	16	30	30	5	5	15	15
71-112	5.4	2.5	0.3	0.4	8.6	9.8	88	0.25	12	44	8	18	16	40	20	5	-	10	25
112-140	5.7	1.9	0.5	0.3	8.4	9.1	92	0.36	10	39	8	21	16	35	25	5	-	15	20

1. Clay fraction mineralogy: Am = Amphibole; KK = Kaolinite; MI = Mica; SM = Smectite; QZ = Quartz.
2. Sand fraction mineralogy: QZ = Quartz; FDM = Feldspar-microline; FE = Magnetite; HE = Haematite; and FDP = Feldspar-plagioclase.

Table 2. Major characteristics of soil constituting Map Unit 3 (probably a Psammentic Paleustalf) at the ICRISAT Sahelian Center in Niamey, Niger.

Horizon	Depth (cm)	Particle size distribution (mm): Sand (2.0-0.05)	Silt (0.05-0.002)	Clay (<0.002)	Coarse frag-ments (%)	Texture class	pH (1:1) H_2O	NH_4OAC extra bases: Ca	Mg	Na	K	Total	CEC NaOAC	Base SAT	ESP
								---------- Meq/100 g				----------	--------- %		---------
A1	0-17	92.6	3.4	4.0	0.0	S	4.9	0.12	0.05	0.04	0.04	0.2	1.17	21	3
A2	17-32	88.3	4.5	7.3	0.0	LS	4.5	0.17	0.08	0.02	0.04	0.3	1.42	22	1
BT1	32-59	84.1	4.8	11.1	0.0	LS	4.6	0.19	0.11	0.03	0.04	0.4	1.54	24	2
BT2	59-85	83.5	5.7	10.8	0.0	LS	4.9	0.51	0.27	0.04	0.04	0.9	1.57	55	3
BT3	85-96	82.6	6.6	10.9	0.0	LS	5.2	0.56	0.34	0.04	0.04	1.0	1.55	63	3
BT3	96-126	46.5	7.8	12.5	0.0	FSL	5.1	0.75	0.48	0.21	0.05	1.5	1.63	91	13
2BT	126-176	80.9	6.7	12.4	80.2	SL	5.7	1.07	0.34	0.04	0.04	1.5	1.79	83	2
2BT	176-225	79.3	8.4	12.3	80.6	SL	4.8	0.57	0.24	0.05	0.04	0.9	1.77	51	3

Source: Soil Characterization Laboratory, Soil and Crop Sciences Department, Texas Agricultural Experiment Station, Texas A&M University, College Station, Texas 77843, USA.

While Alfisols are of many kinds, only three groups appear to be of major agricultural importance in the SAT. These are the Haplustalfs, Peleustalfs, and Rhodustalfs, which may be designated as generally thin, thick, and eutrophic (from basic parent material). Swindale (1982) has described the taxonomic distinctions among these soils and their relationships with other classification systems in common use.

In general, there is no direct correspondence between the orders listed in the U.S. Soil Taxonomy and the soil map units in the FAO/UNESCO soil maps of the world (FAO/UNESCO 1974-78). According to the latter, the major soil units relating to Alfisols in the SAT are the Luvisols, Nitosols, and Arenosols (Swindale 1982). Specifically, Alfisols in India appear to be more or less uniformly grouped around the Chromic Luvisols or Ferric Luvisols. West Africa's Alfisols, on the other hand, are more likely included under Luvic Arenosols or Ferralic Arenosols. In the French system of soil classification, Alfisols appear broadly to belong to the category of "Sols Ferrugineux."

Clearly, characterization and classification of Alfisols in the SAT are not sufficiently advanced to allow clear mapping and delineation. This is a high priority task and calls for establishment of systematic research networks for the understanding and transfer of appropriate improvements in technology.

Agroenvironment and Rainfall

Alfisols in SAT countries are distributed over a wide range of rainfall regimes. For instance, rainfall varies from less than 500 mm in Botswana to more than 1400 mm in Nigeria. In the SAT of West Africa, which accounts for 35% of the area under Alfisols in the world, mean annual rainfall varies between 400 and 1250 mm, with isohyets running parallel to the equator in bands or zones and southern bands or zones receiving more rain than northern ones.

Kowal and Knabe (1972) have shown that annual rainfall in the northern states of Nigeria decreases by 119 mm for each 1 degree of latitude. In Alfisols-dominated peninsular India, rainfall varies from 500 mm in a narrow zone covering southwestern Andhra Pradesh and eastern Karnataka to over 1000 mm in southwestern Tamil Nadu and Kerala; rainfall exceeds 1000 mm in eastern Madhya Pradesh and western Orissa. Sivakumar et al. (1983) observed from their study of long-term weather records in Africa and India that the coefficient of variation of annual rainfall varies from 9 to 45% and, as expected, the largest variations occur at locations with the lowest rainfall.

Rainfall concentration in most Alfisol regions of SAT Africa and India is restricted primarily to a short summer season. As shown in Table 3, over 80% of the annual rainfall is concentrated in the rainy season.

More important than the quantity of rainfall in a given season is the persistency in receiving a specified amount of rainfall over a short interval: for instance, one week. Sivakumar et al. (1983) have estimated the probabilities of receiving 10 mm of rainfall along with the weekly rainfall amounts for Alfisol zones in peninsular India. Their data show, for example, that while annual rainfall at Bangalore is higher and extends over a much longer period, it occurs at a lower probability than at Hyderabad. Further, locations farther south (e.g., Coimbatore) have a bimodal rainfall distribution, with two rainfall peaks separated by an 8-week period. The distinct rainfall distributions at the three locations suggest that cropping strategies for them should be tailored differently. Sivakumar et al. have shown that the weekly rainfall probabilities and totals in western Africa are more sharply defined than in India. For SAT locations in

Table 3. Seasonal distribution of rainfall (mm) for different stations in the Alfisol areas of India and Africa.[1]

Rainfall zone (mm)	Station	Country	Latitude °	Latitude ′	Prerainy season	Rainy season	Postrainy season	Dry season	Annual rainfall
500	Mahalapye	Botswana	23	04	38	395	68	3	494
500-600	Anantapur	India	14	41	34	502	33	22	591
	Birni N'Konni	Niger	13	48	30	507	10	18	565
	Coimbatore	India	11	00	18	197	64	323[2]	602
	Mourdiah	Mali	14	28	32	461	27	25	545
	Yelimane	Mali	15	07	15	516	24	17	571
600-800	Diema	Mali	14	33	19	584	31	18	652
	Cuddapah	India	14	29	57	634	37	23	752
	Fatick	Senegal	14	20	32	709	25	9	775
	Hyderabad	India	17	27	51	631	65	37	784
	Kayes	Mali	14	26	16	667	26	14	723
	Kurnool	India	15	50	47	517	34	32	630
	Kaya	Upper Volta	13	06	31	626	15	32	704
800-1000	Bangalore	India	12	58	22	755	27	27	831
	Foundiaugne	Senegal	14	07	46	752	24	13	835
	Gaya	Niger	11	59	32	768	15	21	836
	Kolokani	Mali	13	35	24	745	18	26	813
	Lilongwe	Malawi	13	57	32	785	45	18	880
	Madurai	India	9	55	213	590	46	34	883
	Salem	India	11	39	24	865	34	32	995
1000	Bougouni	Mali	11	25	0	1047	17	26	1090
	Gaoua	Upper Volta	10	20	60	1152	20	27	1259
	Bamako	Mali	12	38	32	933	32	25	1022
	Raipur	India	22	14	111	1174	33	19	1337

1. Adapted from Sivakumar et al. 1983
2. Because of the northeast monsoon, the rainfall pattern at Coimbatore shows a heavier precipitation compared with other locations during what is normally a dry season.

southern Africa, e.g., Lilongwe (Malawi) and Mahalapye (Botswana), the peak probabilities occur in December and January. At Mahalapye, the rainfall is less, the season shorter, and probabilities lower than at Lilongwe. Clearly, an understanding of seasonal trends in and probabilities of rainfall are critical for the timing of various planting and management operations in these climatic zones.

While there has been considerable research on rainfall amounts and distribution, little has been done to assess the characteristics of storms in the SAT. Data on important determinants of runoff, erosion, and surface stability, such as overall storm intensity, peak intensity, and kinetic energy are limited. All require the use of a recording rain gauge. Sivakumar et al. (1983) cite some research on overall intensities at Bambey (Senegal), where 75% of total rainfall is at an intensity below 8.6 mm/hr and 25% below 52 mm/hr. Similarly at Niono (Mali), 75% of received rain has intensities of 10 mm/hr or lower, while 25% has intensities of 58 mm/hr or lower. At ICRISAT Center, the overall rainfall intensities are lower than those reported for Africa; for example, 75% of the rainfall during the 1974,1975, and I976 seasons came in intensities below 6 mm/hr.

It is fair to state that for effective soil and water management and conservation planning, more elaborate long-term analyses of storm characteristics are required. Fortunately, recording rain-gauge charts showing historical data may already exist for many locations, and these can be used for this purpose.

Interpretation of rainfall data for planned effective utilization by crops have been discussed by Sivakumar et al. (1983), and for conservation planning by El-Swaify et al. (1982).

Constraints to Dryland Cropping and Effective Resource Utilization

The Alfisols of the Indian subcontinent possess a high potential for crop production under irrigation. Even with partial (supplemental) irrigation, grain yields exceeding 5 t/ha have been consistently reported for both sorghum and maize (Kanwar 1983, Vijaylakshmi and Sachan 1977).

That irrigation enhances productivity in Alfisol regions is also confirmed by time-series data from village-level studies on yields in farmers' fields under existing levels of management (ICRISAT Annual Report 1982, p. 324). Paddy irrigated from tanks and wells yielded on average about 3 t/ha in the rainy and postrainy seasons. In contrast, yields of common dryland cropping systems averaged only about 350 kg/ha and rarely exceeded 1 t/ha.

Aside from agroclimatic and socioeconomic uncertainties, efficient and conservation-effective crop production on Alfisols is constrained by certain physical, chemical, and biological limitations. The soil-based constraints are reviewed briefly below.

Physical Constraints

The most important physical constraints to sustained cropping of SAT Alfisols and related soils are their low capacity for water storage, high erodibility and potential for excessive runoff, high susceptibility to formation of crusts and root-limiting layers due to extreme structural instability and, often, their abundant gravel content. The low clay contents (3-10% in the surface and more in the argillic horizons), the relative inactivity of the prevailing clay minerals (kaolins with small proportions of 2:1 clays and sesquioxides), and the low levels of soil organic matter are responsible for many of these constraints (El-Swaify et al. in press).

Plant-available water, reported as low as 0.03 cm/cm in sandy Alfisols, reaches 0.1 cm/cm or more in loamy soils. De facto extractable water, measured in the field, averaged 0.066 cm/cm for the fine-textured Alfisols at ICRISAT Center. The values lie near the acknowledged critical threshold value for available water capacity (0.03 cm/cm), and far below the acknowledged value for full sufficiency (0.2 cm/cm) (Pierce et al. 1983). These restrictions are often compounded by limited overall soil depth, thereby severely limiting the total storage capacity of the profile. A profile that is less than 50 cm deep is barely able to meet a crop's evapotranspirative activity for more than a few days in succession without water replenishment; the problem is more serious for crops whose root systems are unable to explore deeper soil layers.

There is considerable evidence that conventionally cropped SAT Alfisols generally experience excessive runoff and are highly susceptible to erosion. The "inert" mineral composition of the soils and subsequent lack of interparticle bonding and stable aggregation enhance the potential for soil-surface sealing, particularly early in the rainy season when crop stands are too sparse to adequately protect the soil surface. The high runoff potential (exceeding 40% of rainfall at Hyderabad during normal rainfall years) compounds the low water-storage capacity, thereby increasing the drought-proneness of these soils at the critical crop-establishment period. The moderate-to-high erodibility causes the soil to undergo high erosion and brings about a further reduction in its physical and nutritional crop-supporting qualities.

At relatively mild topographies, Alfisols at ICRISAT Center are estimated to possess a mean annual potential erosion hazard exceeding 40 t/ha. This explains the abundance of shallow Alfisols in the SAT. Such soils are nearly always marginal in terms of their use for conventional cropping. Normally accepted (tolerable) rates of erosion far exceed what can be considered as permissible for these marginal soils. Efforts to maximize infiltration of rainfall by installing land-surface configurations are often frustrated by serious breaching of these configurations due to structural instability and excessive concentration of runoff into rills or low-infiltration zones (e.g., furrows). With runoff concentrated in restricted parts of the land surface, the danger of gully formations gets substantially increased.

Surface seals—the result of early showers—are readily converted into hard crusts during dry periods between storms. Crust strength depends on the characteristics of the "sealing storm" and the duration and intensity of subsequent sunshine. An average of 3 days of "sun baking" is required to form a crust sufficiently strong (2-4 kg/cm^2) to inhibit emergence of millet and sorghum seedlings. These small-seeded crops are generally more inhibited by crust than crops with bolder seeds (e.g., groundnuts). The significance of crust formation in different soils and at various locations cannot be fully assessed without a quantitative evaluation of the probability of occurrence and durations of the requisite storms and dry periods.

The inherent structural instability of Alfisols is not restricted to the immediate surface but extends to the lower layers. Hence, their profiles are often prone to hardening (such Alfisols are called Hardvelds in southern Africa), slumping, and a number of other associated phenomena. Bulk densities as high as 1.9 g/cc have been reported for lower horizons. Alfisols are also quite prone to compaction when tilled in relatively wet conditions. Soil strength in the dry state is such that farm implements (such as those used for tillage) find penetration difficult, and crop roots do not proliferate easily. For the growing crops, this effect compounds the problems of water storage and availability. But for a few studies on bulk density-root density in western Africa (Nicou and Chopart 1979), there is no information available on the rheologic characteristics of these soils and their influence on the performance of crop roots. The restrictive role of gravel layers (murrum) in this respect—presumed to be very pronounced in shallow Alfisols—is also not understood in quantitative terms. There is qualitative evidence, however, that this layer is penetrable by the roots of certain crops; more so when the water regime is favorable.

Fertility Constraints

The textures and mineralogical makeup of the SAT Alfisols are generally responsible for their overall low ion-retention ability with the possible exception of P-fixation. A capacity for P-fixation as high as 312 ppm has been reported for India's Alfisols, whose native extractable P levels seldom exceed 13 ppm (El-Swaify et al. in press). In addition, the conventionally cropped soils being low in organic matter, have a limited ability to supply N adequately to support crop growth. It is presumed, however, that the small quantities of nitrogen mineralized seasonally may be significant, particularly during the early part of the growing (rainy) season (El-Swaify et al. in press). Therefore, N and P are the most limiting nutrients to effective cropping and should be provided in the form of fertilizer even under rainfed conditions.

In the case of K, the evidence is not so conclusive. Whether it limits crop production *or* not clearly depends on the sources of K within the soil, and on the management history and crop demand. In Alfisols it is presumed that K is mostly derived from primary minerals (feldspars) by dissolution, and from small quantities of illite. Illite is more prominent in India's Alfisols than in those of western Africa. Alfisols in western Africa, therefore, get more readily depleted of K under intensive cropping. What is often reported as "exchangeable" K in Alfisols is probably K that is slowly dissolved and thus inadvertently extracted from these minerals during the course of exchangeable ion determinations. Understanding native K sources is important for quantifying the potassium "retaining and buffering" capacities of Alfisols and their long-term ability to release this nutrient under various rainfall and management conditions to meet the requirements of crops, particularly cultivars in high demand. Deficiencies of Zn, S, and even Ca have been reported in locations with a long history of monocropping (Venkateswarlu 1983).

Because all Alfisols have usually high infiltration rates, leaching of readily soluble nutrients is a common threat; improving surface structure to reduce early-season runoff may accentuate the problem. For instance, urea was fully displaced from the upper 50 cm of a sorghum-cropped Alfisol at ICRISAT Center when a rainstorm of 50 mm was received within a few hours (too short for full hydrolysis to be completed) of its application (C.W. Hong, ICRISAT, personal communication, 1983). Such rainstorms and insufficient rainfall are important reasons for pronounced variation in responses to fertilization under rainfed conditions from year to year. The strategy for fertilizer application, in terms of sources, quantity, timing, and placement should take into account the crops requirements and such water influences. Management responses under rainfed conditions (adjustments) to climatic trends can be crucial for crop performance.

More recent evidence also shows that the soils position within the toposequence not only produces substantial variations in its properties but modifies the hydrologic and nutrient regimes of the soil profile as well (van Staveren and Stoop, ICRISAT journal article no.399).

Such soil formations, which appear more common in the SAT of western Africa than of India, dictate that management strategies for cropping be tailored to suit the requirements of specific locations in the sequence (van Staveren and Stoop, ICRISAT journal article no.399).

Biological Constraints

Although levels of organic matter in "virgin" Alfisols can be quite high, they decline rapidly following initial land clearing. Consequently, conventionally (seasonally) cropped SAT Alfisols are usually deficient in organic matter. The increase inorganic-matter levels, attained by conversion to "permanent" vegetation, quickly reverts to the old (lower) levels on return to seasonal cropping. The commonly practiced or recommended sole-cropping systems, or even the intercropping of short-term cereals and longer-duration crops (including legumes) contribute little to the buildup of organic matter in these soil. Another negative feature of these systems is that residues are often removed and used as fodder or fuel by some farmers; others (as in western Africa) burn them in the fields. Village-level studies in Upper Volta showed that rates of manure application are extremely low, ranging from 200 to 500 kg/ha (Prudencio 1983). Availability and application of manure were greatest among households using animal traction for farm operations—nearly double the rate of nonequipped households. In the Indian SAT, animal manure is preferred more as fuel than fertilizer, further limiting the scope for increasing organic-matter content in Alfisols. Further, irrigated rice competes favorably with dryland-cropping systems for manure and other resources in Alfisols areas. Much more manure and inorganic fertilizers are applied to irrigated rice than to rainfed fields (ICRISAT Annual Report 1982, p. 316)

Where residues are applied to the soil surface, termite activity, in places, ensures their complete elimination in a very short span of time. While some researchers regard termite activity as undesirable (Hegde. 1983), others maintain that it benefits soil structure in a number of ways (Perrier 1983). It is important to recognize that the presence of even small amounts of organic matter can be significantly beneficial to nutrient characteristics, ion-retention capacities, and stable aggregate formations in these relatively "inert" soils.

Return of at least some residue to the soil, whether as mulch or by incorporation, appears desirable but raises certain concerns in addition to the issue of competitive uses referred to earlier. These concerns include planting techniques, nutrient imbalances, termite damage to crops, aeration in the root zone, proliferation of pests and diseases, and optimization of application methods. These possible constraints must be investigated before residue return is endorsed in a given situation.

Alternatives for Improved Management

Improved management practices have a good potential to enhance productivity on Alfisols. For instance, data from a field-scale, steps-in-technology experiment over 4 years (1976-79) at ICRISAT using several cropping systems show that improved seed, fertilizer, and soil and crop management increased average profits (as compared to profits derived from farmers' simulated practices) by about 500%, from Rs. 424 to Rs. 2625/ha (Swindale 1982). Improved soil- and crop-management treatment, that is, accurate and timely placement of seed and fertilizer, and efficient weed control individually contributed more to profitability than either fertilizer or improved cultivars.

Physical Elements

Effective management of physical and engineering properties is of prime importance in dryland cropping of Alfisols. The aim should be to enhance rainfall infiltration, reduce water losses due to runoff and evaporation, control soil loss, provide favorable early-season conditions for seed germination and emergence to ensure strong crop establishment, create a soil zone that hydrologically and rheologically favors prolific root growth, and establish provisions for capturing runoff and groundwater for judicious use in supplemental irrigation, when needed. Alfisols are generally well drained so that provision for improving internal drainage to overcome waterlogging are seldom necessary. Clearly, certain systems of land or soil manipulation that serve one of the above purposes can simultaneously affect the others. In addition, there are usually strong interactions between the physical and other elements of management (e.g., improved infiltration also accelerates fertilizer loss by leaching, and deep inversion tillage may bring about textural and nutrient redistributions in the root zone).

The most commonly investigated soil surface management (shaping) treatments for Alfisols include flat cultures with or without contour or graded bunds or border strips; flat cultures with subsequent ridging several weeks after planting; open-ridge-furrow systems (including wide beds); and tied-ridge-furrow systems (listing) and combinations thereof (El-Swaify et al. 1983, Hegde 1983, Perrier 1983, Singh and Das 1983, and Vijayalakshmi 1983). For disposal of excess surface runoff, treatments have been incorporated into catchment designs that provide for the use of interterrace waterways whose capacity, slope gradient, and slope lengths are adequate for prevailing rainfall characteristics and required catchment drainage. Primary and secondary tillage operations and residue management have often been combined with land treatments; and, frequently, they have been found to interact strongly in determining the ultimate crop response and the impact on soil and water conservation (El-Swaify et al. 1983, McCown 1983).

In India, results from ICRISAT and AICRPDA (All India Coordinated Research Project on Dryland Agriculture) experiments have shown that the performance of flat cultivation and variations thereof has been on par with other land-surface configurations with regard to crop yields, and generally superior to other configurations in controlling runoff and soil erosion. This inference could now be tested multilocationally on an operational scale. In soils that are generally well-drained internally, the concept of bedding or ridging loses its primary importance, i.e., to drain and dispose of excess water from the seed environment. Further, for Alfisols whose subsurface layers contain more finer particles, ridging exposes low permeability (high runoff potential) layers in furrows that take up a large proportion of the field surface. Should the finer particles brought to the surface from these layers get mixed with the sandy top soil in the ridge or bed, as often happens during inversion tillage, the potential for high runoff in the ridge or bed zone is increased. It is also essential to indicate that unless ridges or beds are stable in their installed configurations, they will do more harm than good as runoff and soil-loss control measures. Broadbed-and-furrow (BBF) systems, which are quite successful in certain Vertisols, break down in soils lacking structural stability, be they Vertisols or any other.

In western Africa, ridged systems yielded more than flat-planted systems only when no plowing was done to enhance rain water infiltration (Perrier 1983). Both the systems gave similar results with plowing; no runoff or soil-loss data were reported with these studies. Tied-ridging far outyielded open-ridge and flat systems, with the benefits particularly out-standing in the absence of plowing. It should, however, be noted that varied results have been reported for tied-ridging because of the wide differences in soils and rainfall patterns at locations where this technique was investigated (El-Swaify et al. in press). Clearly, a system that allows no runoff can be beneficial only if the soil's infiltration rate is low enough to generate runoff but high enough to prevent excessive long-term waterlogging and restricted aeration. Also, surface stability should be strong enough to withstand high-intensity storms without breaching of main ridges, and the subsequent rilling and gullying. This technique should be considered primarily for marginal (subrainfail) areas. It requires occasional maintenance during the rainy season to ensure that the design functions efficiently, and may necessitate the modification of other management inputs to ensure overall compatibility. For instance, the leaching of fertilizers by ponded water may necessitate more frequent fertilizer applications. In the presence of mulching, tied-ridging appeared to offer no advantage over flat-planting (Perrier 1983).

In general, therefore, available evidence indicates that flat culture is the logical central mode for intraterrace land-surface configurations in Alfisols. For runoff and soil-loss control, this system should be complemented with such measures as (subsequent) light ridging, installation of graded border strips, graded bunds, contour bunds or a similar measure that also includes provisions for eliminating ponding of lower-field sections (Pathak et al. 1983). The timing of installing these provisions and their design should take into account the prevailing topography, seasonal rainfall distribution and characteristics, existing and required waterways, and boundaries of farmers' fields. For instance, the slight rainfall hazard early in the season at Bangalore does not necessitate preplanting installation of ridges; it can be done at the last weeding several weeks after planting (Hegde 1983).

Intensive primary tillage has been shown to be necessary for effective management of Alfisols. The intensity, frequency, and type of operations required vary with soils and environments. But where residue management represents only a minor part of the cropping system, minimum tillage concepts are clearly at a disadvantage in dryland cropping of SAT Alfisols. This conclusion has been reached repeatedly by researchers in both Africa and in the Indian subcontinent (El-Swaify et al. in press). Aside from improving the rheological and pore-space characteristics of these hardening soils, primary and secondary tillage operations play a part in enhancing rainfall infiltration, increasing profile-water storage, and minimizing evaporation at the critical stage of crop establishment. Tillage, therefore, complements the land-shaping treatments imposed in determining the ultimate runoff and erosion characteristics of a given field. The major elements of tillage-management of Alfisols are primary tillage, secondary tillage, and off-season tillage.

Off-season tillage serves several useful purposes (Vijaylakshmi 1983). It maximizes utilization of water from rainfall following the crop harvest, minimizes stored-water evaporation by a "mulching" effect, and allows the acceleration of planting operations (which must be conducted at the onset of the rainy season) thereby permitting earlier sowing and extension of the growing season.

Although intensive (deep) primary tillage for loosening the soil in the root zone generally aids root proliferation, improves profile wetting with rainfall, and increases crop yields, the rooting habits of the cropping systems and the rainfall pattern during the growing season determine the magnitude of these benefits. Only deep-rooted crops benefit from intensive tillage in years with above-normal rainfall. But what should be the frequency of intensive tillage remains to be determined. Plows that are capable of soil inversion (turning), such as the moldboard plow, have also not been compared adequately with implements that do not have this capability, e.g., chisel plows. The latter appear more beneficial in certain Alfisols, as suggested by the superior crop establishment, lower runoff and soil losses, and greater yield in an Alfisol with sand-enriched surface than a silt- or clay-enriched one (El-Swaify et al. 1983). But enrichment with sand may prove detrimental to germination and seedling emergence should temperatures in sandy layers reach suppressive levels. Although this was not found to be the case at ICRISAT Center, it may be a factor in other regions (McCown 1983).

The benefits attributed to tillage have not been determined for such possible interactions as water storage/nutrient/soil strength/root. The quality of tillage operations depends on timing and soil-water status, but no quantitative studies on tillage have so far been carried out on SAT Alfisols. Secondary shallow tillage is necessary for creating a seedbed of good quality, ensuring uniformity in planting depth and seed-soil contact, and for effective weed control and enhanced infiltration. Mulching has also proved beneficial, particularly in highly crusting soils. Primary tillage alone, especially if irregularly imposed (as often the case with conventional plows), or if it results in turning the field cloddy, can be quite harmful to crop establishment because it can lead to inadequate seed-soil contact and excessive drying due to rapid evaporation.

After rainstorms, Alfisols with surface unprotected by mulch or crop canopy seal rapidly and crust when they dry subsequently. Should crust formation be untimely for seedling emergence (occurs 3 or more days after sowing), mechanical devices are available for breaking crusts without damage to seedlings (Thierstein et al. 1983). Other methods for breaking crusts have been tried with some success. These include group-seeding and soaking of seeds before sowing (Sinclair 1983). Surface-sand enrichment and noninversion tillage also reduces crust strength. A long-term strategy for reducing the sealing and crusting tendencies of Alfisols is urgently called for.

Harnessing of runoff and/or development of other water sources for supplemental irrigation is necessary for optimizing the productivity of Alfisols since these soils have a limited capacity for water storage. Supplemental irrigation increases and stabilizes crop production on Alfisols even in dependable-rainfall areas (El-Swaify et al. in press, Vijayalakshmi 1983). The potential for delivering excess water to surface water-storage structures (tanks) or groundwater reserves is good since even improved cropping systems use only 30-45% of the seasonal rainfall. The remainder (55-70%) either runs off or drains to deeper layers. This water can be used for supplemental irrigation. When there is high rainfall, the runoff rates are also high in Alfisols during the early part of the rainy season; in other words, a dependable surface-water source is available throughout most of the season. But tank storage in these soils is often hampered by high seepage rates. Research is still in progress to determine the most feasible sealing materials and techniques (Maheshwari 1981). Research at ICRISAT Center has shown that tanks can be relied on to supply the water needed for supplemental irrigation when the average seepage rate is below 15 mm/day. A long-term probability analysis, using runoff modelling, showed that the potential for surface-water collection and storage in Alfisols at Hyderabad, India, was superior to that in Vertisols (Pathak 1980, Ryan and Krishnagopal 1981).

Two additional aspects of water supply development must be considered for Alfisols and related soils. For borderline rainfall situations prevalent apparently in drier SAT regions, effective methods are available for runoff inducement from designated catchments for direct use, or for storage for later use on limited land areas. A wide range of scales is available; donor "catchment" may refer to an area as small as one or two ridges or tilted beds, and the receiver area may be the furrow in which the crop is planted. In any case, the design must be such as to allow maximum benefits through the optimization of the ratio of catchment to receiver areas in view of the rainfall patterns and crop-water requirements (Frasier 1983).

A major point of emphasis when considering water supplies for Alfisols is the potential for sustained use of underground water resources. This water source is important and, in fact, is occasionally utilized at present. But its importance will increase when soil-management strategies are aimed at minimizing runoff, thereby enhancing infiltration and deep percolation. Since the capacity for water storage in the profile of Alfisols is limited, water moving beyond the root zone is lost to the crop unless it can be captured for reuse in supplemental irrigation (Englehardt 1983).

There has been little research on how efficiently available water (usually meager) can be used for supplemental irrigation, whether during the season or beyond. Striking benefits have been reported from even a few irrigations, called "life-saving" or "crop-saving" irrigation, at ICRISAT and elsewhere (Vijayalakshmi 1983). Maximization of benefits from supplemental irrigation complements effective control of rainfall-runoff relationships. Such maximization can be achieved through increased water-use efficiency, that is, by combined control of the timing, quantity, and method of irrigation. For instance, simple controls on water delivery from tanks permit expansion of the area irrigated at a reduced risk of crop failure. Also, a number of innovations have succeeded in increasing overall water-use efficiency in conjunctive dryland-irrigated systems in nontropical, semi-arid regions (Stewart and Musick 1982). Such innovations appear to have applicability in the SAT.

Fertility

Benefits of fertilization have been clearly documented for rainfed Alfisols, particularly with high-yielding cultivars, high planting densities, and/or improved management practices. But serious detrimental impacts of fertilization have also been documented, particularly with nitrogen fertilizer, when high rates were not accompained by adequate rain (ICRISAT Annual Report 1982). Also, in Alfisols with poor buffering capacity, soil acidification may be readily achieved when ammonium or urea salts are continually used as N fertilizer (van Staveren and Stoop, ICRISAT journal article no.399). In general, the strategy for N application is dictated by the high solubility of the common sources (e.g., urea). When rainfall received is significant, this compound becomes quite susceptible to leaching before it is hydrolyzed to ammonium. Such losses, which also occur with other soluble N sources and nitrification products, are particularly serious in the coarser-textured soils and early in the growing season when the crop is too young to efficiently capture the nutrient before it moves beyond the root zone. Hence, fertilizer banding and split applications are necessary on Alfisols. Recommendations range between 40 and 80 kg N/ha, with 50% as basal dose and the remainder as top dressing. In wet years, split-banding appears particularly superior to broadcasting or broadcast incorporation. Should there be flexibility in the selection of N fertilizer sources, ammoniacal or organic sources are preferable because they reduce leaching losses. Since use-efficiency of N fertilizer is intimately connected with rainfall amounts and characteristics, a "forecast" or "response" strategy is highly desirable for deciding fertilizer rates and application schemes in relation to rainfall patterns. Recent research seems to indicate that placing fertilizer directly below the seed aids better use-efficiency (C.W. Hong, ICRISAT, personal communication, 1983). But evidence in the literature is quite mixed on this subject, and results appear to depend on rainfall pattern and the sensitivity of seeds of specific crops to salt injury. Deep plowing of fertilizer with primary tillage is also reported to be beneficial (Venkateswarlu 1983). In deep Alfisols, good fertilizer recovery is generally observed as the losses, regardless of the application method, are very small. A major advantage of using organic-fertilizer sources, besides that of reducing the likehood of huge nutrient losses by leaching during high-rainfall periods, is that they aid structural development in these otherwise "inert" Alfisols. While fertilization of sole crops with N is relatively well understood, the same is not true of intercropping systems, particularly those involving legumes.

Phosphorus is the second most limiting nutrient in SAT Alfisols since they are invariably low in total (less than 200 ppm) and available P (less than 20 ppm). These soils generally have a high P-fixing capacity (312 ppm for the Patancheru series at ICRISAT Center). Cereals and pulses respond markedly to P fertilization in Alfisols. At ICRISAT Center, where the extractable (Olsen) P was less than 5 ppm, sorghum responded to applications of up to 10 kg P/ha in the form of water-soluble phosphates. While intercropped millet responded to levels of up to 5-10 kg P/ha, intercropped pigeonpea did not. Because of high fixation, banding of applied P fertilizer close to the crop is recommended for good response. Band application of 10-15 kg P/ha above the fixation capacity of the soil is generally recommended. But reports on such mycorrhizal crops as pigeonpea are conflicting, since their response to applied P is not consistent (R. Busch, ICRISAT, personal communication, 1983).

Most SAT Alfisols in India contain moderate levels of available potassium (around 125 ppm of extractable, including exchangeable, K) and high levels of total K (2 to 3% as K_2O). This is due to the abundance of K-bearing primary and secondary minerals in these soils. Therefore, responses to K fertilizer applications have seldom been obtained even with intensive cropping of high-yielding cereal varieties. Farmers in this region generally harvest and remove the cereal stalks for use as cattle feed; these stalks contain nearly 60-70% of the total K in harvested plants. With continuous cropping of high-yielding varieties, this practice is likely to result in significant mining of soil K, leading perhaps to its deficiency. A long-term experiment at ICRISAT has shown that sorghum and millet respond to K applications from the fourth year (El-Swaify et al. in press). In the light-textured and illite-deprived Alfisols such as those found in Africa, K-deficiency is reported to be a serious problem, making fertilization with K sources necessary.

Requirements for fertilization with secondary nutrients have been shown to depend on the location and cropping system (Venkateswarlu 1983). Responses to S have been reported at Bangalore, India, for groundnut, sunflower *{Helianthusannuus*), cowpea(\/igna *unguiculata* [L] Walp.), and black gram (Rao and Das 1982). The same crops responded to liming at Bangalore (Oxic Rhodustalfs), whereas groundnut responded to applied gypsum, maybe because of the crop's high specific requirements of Ca at pegging and podding (G. Rajendrudu and J.H. Williams, ICRISAT, personal communication, 1983).

Among micronutrients, Zn deficiency was noticed in Bangalore and Anantapur in groundnut, pearl millet, and maize. With improved cultivars and management (and the consequent high yields) these and other micronutrients will be mined at a faster rate, leading perhaps to more micronutrient deficiencies in Alfisols in the future.

Table 4 summarizes recommended fertilizer-management strategies for SAT Alfisols in India. Synergistic responses to multiple nutrient applications are a common phenomenon, although only one nutrient may appear to be limiting (Venkateswarlu 1983).

Table 4. Summary of recommended fertilization strategies for improved management of SAT Alfisols.[1]

Nitrogen

a. Short-term goal — Use of N fertilizer.
   Quantity—About 60-80 kg N/ha in average rainfall years;
   80-120 kg N/ha in above-average rainfall years; and
   40 kg N/ha in below-average rainfall years.
   Form — Ammoniacal form is preferred to nitrate or urea.
   Method — Banding.
   Time — Basal dose + two or more split applications of top dressing.

b. Long-term goal — Build-up of soil organic matter. Use of FYM and crop residues. Cereal/legume intercropping and, wherever possible, legume-cereal sequential cropping. Crop or cropping systems rotation involving ground cover, green manure, legume ley, or agroforestry applications.

Phosphorus

Quantity — About 10 kg/ha if soil P is 5-10 ppm as Olsen extractable P; 15 kg P/ha if <5 ppm.
Form — Water-soluble P.
Method — Band application.
Time — Basal.

Zinc

Quantity — 50 kg ZnS04 once in 3 to 4 years.

1. Source: El-Swaify et al. 1983, adopted from various sources.

Alternative Land Uses

The technical feasibility of alternative land-use systems for Alfisols in the SAT should be evaluated in terms of how effectively they surmount the physical, fertility, and biological constraints discussed *in* the previous section. More specifically, we expect that a land-use system will be technically feasible if it satisfies some of the following interrelated objectives: (1) improved water-use efficiency and access to available resources; (2) maintained or enhanced soil fertility; (3) improved soil aggregation and reduced surface sealing and crusting; (4) decreased runoff and soil erosion; (5) increased structural stability of the soil; and (6) reduced biological pest and disease incidence. Fulfilling these objectives should lead to better crop stands, more vigorous and stable crop growth, minimal resource-base losses, and sustained productivity.

How well a particular alternative land-use system satisfies these objectives on Alfisols in the SAT will depend on location-specific agroclimatic and edaphic conditions, and on farmers' past managerial practices. Nevertheless, we have drawn some general conclusions which are summarized in Table 5. We have evaluated land-use strategies according to their prominent vegetative components , as listed below.

1. Conventional Annual Cropping Systems

Conventional annual cropping, the land-use system most commonly practiced by farmers on SAT Alfisols, does not score high marks in terms of our six criteria. Of the conventional annual cropping systems, sequential and relay cropping appear to be technically unsound in

Table 5. Illustrative potential benefits of alternative land-use systems compared with conventional annual sole-cropped systems in SAT Alfisols.

Alternative land-use system	Potential benefits: Improved water-use efficiency and access to available resources	Maintained and enhanced soil fertility	Reduced surface sealing and crusting, and lowered soil temperature at sowing	Decreased runoff and soil erosion	Increased soil structural stability	Reduced pest and disease incidence
Conventional annual cropping systems						
• Sequential cropping	-	-	?	?	?	?
• Relay cropping	-	-	?	+	?	?
• Ratoon cropping	-	-	?	?	?	?
• Intercropping	+	?	?	+	?	+
Nonconventional annual cropping systems						
• Minimum tillage	+	+	+	+	+	-
• Intensive deep tillage	+	?	+	+	?	+
Agroforestry systems	+	+	+	+	+	+
Grass and legume ley farming	+	+	+	+	+	+

+ indicates that the alternative land-use system performs better than conventional annual sole cropping;
- indicates that the alternative land-use system is technically inferior to annual sole cropping;
? indicates that the impact of the alternative land-use system compared with that of annual sole cropping is not clearly known, but is probably not very different

typical dryland Alfisol environments. Sequential systems involving two full crops are seldom feasible unless one of the crops is a very short-season catch crop, which also means a crop with low yield potential. At ICRISAT Center it has been possible to grow a catch crop of horse gram after an early pearl millet, or a short-duration mung bean before a castor crop. But in both these systems, the additional returns compared with that from the sole crop were small (Willey et al. 1983). The same researchers also argue that while relay cropping, wherein the second crop is sown 2-3 weeks before the harvest of the first, may appear to improve the probability of producing two crops, in practice it is difficult to sow the second crop in the standing first crop, and to harvest the first crop while seedlings of the second crop are present. Ratoon crops of short-to-medium duration may also seem feasible, but here again on Alfisols at ICRISAT Center ratoon yields of sorghum—a likely candidate for ratoon cropping—were poor and erratic.

Although sequential, relay, and ratoon cropping do not appear technically attractive, there may be location-specific situations where they have some potential. For example, a cowpea-finger millet double crop has been recommended for Alfisols in the Bangalore region where distribution of the 870 mm mean annual rainfall is bimodal (Patil 1983). Double cropping is more labor intensive and requires more timely operations than sole cropping, which is what farmers do at present.

Conventional sole cropping systems have given fairly high yields on similar Alfisols (Udic Rhodustalfs) both at ICRISAT and AICRPDA in Hyderabad, India (Randhawa and Venkateswarlu 1980, ICRISAT Annual Report 1979/1980).

Rapid genotypic change like in the case of extra-early pigeonpeas can enhance the potential of sole-crop systems, making them more technically feasible in Alfisol regions of the SAT. But the fundamental problem in producing sole crops in Alfisols is usually that there is more than enough moisture to produce one crop harvest but not enough for two or more crops (Willey et al. 1983).

Intercropping systems can often increase cropping intensity above that of a sole-crop system. Averaged over 3 years at ICRISAT, three typical Alfisol intercropping combinations: sorghum/pigeonpea, millet/groundnut, and pigeonpea/groundnut yielded higher returns than sole-crop systems. The sorghum/pigeonpea intercrop displays the classic "temporal" complementarity between an early, fast-growing component that ensures use of early resources, and a later-maturing component that takes fuller advantage of later resources. In contrast, the millet/groundnut system is a more efficient user of light, water, and nutrients.

Experiments at ICRISAT have shown that the relative advantages of intercropping over sole cropping can be even greater under poor moisture supply regimes. However, the systems examined were "replacement" systems, where the total population of intercrops or sole crops was constant, with each intercrop component at a lower population than that of its sole crop. In such systems, the advantages of intercropping can be explained in terms of complementary resource use where each crop experiences less competition when growing in combination with the other crop than when growing alone. This reasoning does not apply to "additive" systems where additional crop components result in greater total population, so probably increasing the competition for water.

There is similar evidence that the relative advantage of intercropping increases with increase in nutrient stress, although the reported effects have been less marked than in the case of drought stress. This suggests that intercropping systems may be particularly beneficial under conditions typical of SAT Alfisols where inherent fertility is low and fertilizer application for dryland cropping is negligible or nil.

How intercropping systems benefit legumes is more difficult to document. Experiments at ICRISAT Center have shown that the nitrogen contribution from many intercropped legumes in conventional intercropping combinations is limited because legumes are only partial crops in the system; moreover, they are usually grain legumes where much of the fixed N is removed to the crop's own seeds.

Judicious manipulation of intercropping systems can also reduce the severity of such biological constraints as pests and diseases. The most common effect seems to be: one component crop in the intercropping system acting as a buffer or barrier against the spread of a pest or disease to another component crop. Some standard examples are the use of cereal intercrops to reduce insect attack on cowpeas in Africa, or the insect-borne rosette and bud necrosis diseases of groundnut in India. More complex interaction can also occur; for example, work at ICRISAT suggests that a sorghum intercrop reduces the soil-borne pigeonpea wilt disease more by active interaction than through a simple barrier effect, perhaps a root exudate. But adverse interactions are also possible. The sorghum/pigeonpea intercrop is an example (Bhatnagar and Davies 1981). In this combination, *Heliothis* pod borer is a serious insect pest of both crops. The net effect in intercropping is that pigeonpea suffers *greater* pod borer damage than when cultivated as a sole crop.

2. Nonconventional Annual Cropping Systems

Some success with minimum tillage land-use systems has been reported on Alfisols in the semi-arid tropics (Perrier 1983, McCown 1983). Such systems rely heavily on herbicide use, and on mulching from generous return to the soil of plant residues. Surface mulching reduces the risk of serious soil erosion during the early wet season, allows maintenance of higher infiltration rates, reduces surface sealing, and provides protection against temperatures injurious to emergence and crop stand. While minimum-tillage systems featuring chemical weed control are agronomically superior in the humid tropics—where an abundant water supply results in vegetative and biological activity throughout the year—their sustainability on SAT Alfisols, where rainfall is lower and less reliable, is a question that only further research can answer.

Minimum-tillage systems may also aggravate the incidence of diseases such as root rot. For instance, in castor, a common crop in the Alfisols of peninsular India, the most widely used hybrid, Gauch-1, is extremely susceptible to bacterial root wilt transported through farmyard manure (Sanghi 1983). Use of such systems may require complementary investment in crop-improvement research.

Deep and intensive tillage is the exact opposite of minimum tillage. But the systems are similar in one respect: neither is now in use on Alfisols in the SAT. Benefits conferred by intensive tillage have been documented on many Alfisols (El-Swaify et al. in press). Deep tillage decreases bulk density, increases porosity, enhances root development, and results in more yields. Even limited tillage enables crops to escape the detrimental effects of dry spells early in the rainy season. Although deep and intensive tillage may be technically superior to conventional or minimum tillage, its adoption depends on tractor density in Alfisol regions. Presently, tractor: land ratios are low in the SAT of India and Africa.

3. Perennial Sole Cropping

Sole-cropped perennials are not widely grown on Alfisols and our knowledge (data base) on their technical feasibility is meager. I n some regions, such as the Alfisol areas of Karnataka in

SAT India, sole-cropping of certain tree species such as casuarina *(Casuarina equisetifolia)* and eucalyptus appears to be on the increase (Patil 1983). While the technical feasibility of such cash crop based systems depends on the selection of species appropriate for the given location, they have the potential to be technically attractive, particularly on marginal Alfisols. Because of the current developmental focus on small farmers and food crops, cropping systems for cash crops have probably not received the research attention they deserve. Certain species, particularly eucalyptus, have also been the subject of controversy as regards their ecological and socioeconomic impact.

4. Agroforestry Systems

Many of the technical implications of intercropping annual species on Alfisols can be extended to agroforestry land-use systems (Willey et al. 1983). In principle, these can supply large amounts of crop material which can be used for improving the soils' nutritional and physical properties. The concept of temporal complementarity implies that if the growing period can be extended still further, with deep-rooting trees able to tap more moisture, overall productivity can be further increased. Combination of different crop canopies may also aid more efficient use of sunlight.

Where an additional tree species capable of using deeper profile water not accessible to conventional crops is planted, there is no doubt a greater total demand for water, but this does not necessarily lead to a commensurate increase in water stress. To some extent the same reasoning can be applied to the exploration of deeper nutrients by tree species. This is the basis for the now rapidly vanishing practice of bush fallowing. Indeed, when some of the tree material is returned to the soil, either as mulch or green manure, a beneficial recycling of some nutrients for shallow-rooting crops can result. But agroforestry systems of greater productivity can lead to removal of larger amounts of nutrients. In such cases, use of more fertilizer to maintain high productivity is inevitable. Agroforestry systems can also exacerbate production instability in the cereal component. In low-rainfall years, if agroforestry systems are additive ones with greater total plant populations, competition for water is likely to be increased.

As regards contributed nitrogen, legume-based agroforestry systems may have much to offer since they enable return of much larger amounts of material to the soil than annual-cropping systems. Intervening rows of trees can also enhance the barrier against the spread of a pest or disease to a component cereal.

While agroforestry systems might lead to adverse pest and disease incidence, and with higher populations environmental stresses could intensify, these systems nevertheless promise greater overall stability. It is not difficult to imagine, for example, a situation where the conventional crop components might fail because of drought and the tree species would still produce something. Equally important is the increased overall level of biological activity in the soil—a factor which should favor the much needed long-term structural buildup in Alfisols (El-Swaify et al. in press). When properly designed, the tree species can help protect the system against erosion by wind and water (El-Swaify et al. in press).

Other agroforestry cropping systems such as agro-silvi-horticulture are receiving increasing research attention in India's SAT (Patil 1983). While such systems have technical potential, it should be pointed out that incorporating fruit and vegetable species increases the need for efficient plant protection. Addition of different types of vegetation into an improved or even a new complex land-use system usually means greater location specificity. This recommendation has limited applicability since the suggested components are radically different from the farmers' current practices.

In summary, agroforestry systems have many positive features, but the size, quality, and timing of the benefits that result from them are uncertain as they depend heavily on the selection, design, and management of such systems. Woody perennials may face more problems in the SAT than in the humid tropics.

5. Grass and Legume Ley Farming

Land-use systems designed to increase the production of livestock products and improve physical and nutritional properties of the soil have received considerable attention in India and in Africa's Savanna zone, where the emphasis is on increasing the soil's organic contents, and on improving its structure and infiltration through use of animal manure, green manures, and grass leys. Research has shown that substantial benefits result from these practices, but these gains are not long lasting and stop on resumption of normal cultivation. The practice most effective in improving water stable aggregation after cultivation is grass fallowing; but this exacerbates the already low supply of available N in the cropping phase (McCown 1983). However, supply of P, often less adequate than that of N in Africa's Savanna zone, shows modest improvement when grass vegetation is burned prior to cropping.

As earlier emphasized, both N and P deficiencies should be overcome if crop yields on SAT Alfisois are to improve. Even if legumes succeed in providing the N without the ash from burned fallow vegetation, farmers will still have to buy P. Contribution of N by the legume is dependent not only on P supply but also on the ability of the subsequent nitrophilous crop to respond to biological N.

In the SAT of northern Australia, a legume/ley no-till system using phosphate fertilizer gave encouraging results over the last 5 years (McCown 1983). This system has the following features: (1) cultivation of self-regenerating legume/ley pastures, lasting 1-3 years, in rotation with maize or sorghum; (2) cattle grazing on native grass pastures during the wet season, and on leguminous crop pastures and crop residues in the dry season; (3) crops planted directly on pasture, which is chemically killed at or shortly before planting; and (4) allowing a pasture legume sward that volunteers from hard seed to form an intercrop in the main crop.

The fourth system rates high on technical feasibility and has given some impressive results. After 1 year, the legume provided 40 to 60 kg N/ha equivalent. Maize yields were 20% higher with no-tillage/mulch than with conventional tillage. Soil temperature gets reduced by 3 to 4℃. Large legume intercrop yields can b e obtained with little loss in cereal yield at high N rates. Cattle that graze on natural grass pasture in the wet season and on crop residues in the dry season after the maize harvest, gain weight during the dry season. The system holds promise for regions in Africa's SAT where livestock is a major component of traditional farming systems and fallowing is common.

While many of the "newer" alternative land-use systems score on several important technical grounds, they often rate much lower in terms of the economic and social criteria that govern adoption. This is because these land-use systems represent significant changes from the farmers' present practices. In India's SAT, crop residues are highly valued; man : land ratios are high; and farmers are more concerned about present consequences than future outcomes. Therefore the technical benefits from innovative systems on Alfisois must be clearly demonstrated and backed by solid experimental findings. They should also be convincingly significant if farmers are to accept them.

Research Needs

Technical Elements

We will here outline some general and some location-specific research needs that were assigned high priority at the workshop. But before we describe them, it is necessary to reiterate that Alfisols and related soils are poor in physical and chemical resources. Therefore the likelihood of developing improved farming systems that can "unlock" their underutilized or unexploited resources is less than, for instance, on Vertisols in higher and dependable-rainfall regions where fallowing in the rainy season is common. This should be kept in mind while exploring management options for crop-production systems for resource-poor farmers. Poverty of natural and human resources implies that a strong bias towards capital-intensive production strategies is unwarranted. At the same time, because of the diversity of socioeconomic and institutional conditions prevailing in SAT Alfisol regions of India and Africa, improved production systems should be given full opportunity to demonstrate their benefits quantitatively; in other words, such improved systems should not be screened too rigorously at too early a stage. These two implications are not contradictory but rather interact to form a desirable and healthy tension. Lastly, scarcity of resources also implies that both general and location-specific research objectives should be tackled in a sequential fashion, focusing on identifying and measuring the contribution of each improved or new component in the system. Measuring interactions among subsystems is necessary but not sufficient to advance our knowledge on Alfisol management in the SAT. While component research is not enough in itself, it is essential for arriving at an understanding of general principles, and for indicating how location-specific land-use systems can be tailored to suit contrasting Alfisol regions.

Resource Inventory and Agroclimatic Characteristics

Soil aspects. The extreme diversity among Alfisols and the ill-defined distinctions between them and many associated soils are symbolized by the need to include the phrase "related soils" in the title of this workshop. The issue is further clouded by the numerous systems used for classifying them in various regions. Detailed and accurate characterization and inventory, using standardized techniques, are therefore necessary: 1) to place the soils in an orderly systematic classification; 2) to achieve full understanding of existing and proposed management alternatives and an objective projection of their range of applicability; 3) to develop coordinated plans for needed network studies; and 4) to select pertinent representative (benchmark) locations for these studies. In India, the broad distribution of Alfisols and related soils is now available in a soil map of scale 1 -6.3 million. Presently, maps with a scale of 1 -1.0 million are being prepared. Retrieval of data on these soils in Africa and other regions in the SAT is not easy. In some instances, considerable data may be already in existence from various sources, such as the French Archives, Office de la Recherche Scientifique et Technique d'Outre-Mer (ORSTOM), and Institut de Recherches Agronomiques Tropicales et des Cultures Vivrieres (IRAT). A collaborative effort among the concerned institutions will be required to bring about a common basis for comparison among locations where different schemes of classification are in use.

When comparable locations have been identified, colloborative research on production systems, including viable options for transfer of technology, may be contemplated. The criteria for determining regional similarities in crop production potential and for selection of benchmark sites are summarized below.

1. Regional base.
   a. Soil profile depth and textural differentiation.
   b. Capacity for available water storage.
   c. Thermal regimes.
   d. Land topography and soil position in the toposequence.
   e. Soil acidity.
   f. Structural characteristics of the soil.

2. Benchmark site: in addition to the above data, the following information is needed.
   a. Soil erodibility and runoff generation potential, and flooding hazard.
   b. Infiltration rates and other water- transmission characteristics.
   c. Ion-retention properties, including cation- exchange capacity.
   d. Level of organic matter, essential nutrients, and nutrient availability.
   e. Trafficability and workability.
   f. Susceptibility of the soil to sealing and crusting.

Agroclimatic aspects. Quantitative data on the amount of rainfall and its distribution provide important guidelines regarding potential cropping. These data and those on potential evapotranspiration provide the building blocks for estimating the length of the growing season at a given location.

Simple models for estimating plant-available water, using soil and climatic data, would be useful for planning crop production. Data on time and intensity of water sufficiency or stress would be useful in planning critical operations such as selecting adaptable genotypes, sowing, tillage, or the timing of supplemental irrigation where needed. Air and water temperature are not only important in controlling dynamic changes in soil-water status but also in influencing temperatures in the seed zone during crop establishment. It is essential to evaluate these thermal characteristics in Alfisols where temperature may affect seedling emergence directly or indirectly by increasing crust formations.

Evaluating rainfall characteristics is critical not only for crop-related management but also for planning soil and water conservation. Storm totals, peak intensities for different durations, and probability distribution (return periods and frequency) are the primary determinants of runoff, floods, and soil erosion by water. They also bear heavily on seal and crust formations, fertilizer leaching, pollen wash, and grain-mold incidence. Extensive data on the above factors are available in India with the Indian Meteorological Department but are apparently lacking in other SAT regions, particularly in western Africa. Hence, as with soils, a data-gathering effort may be necessary.

The climatic data requirements for regional and benchmark sites are as follows.

1. Regional.
   a. Rainfall quantity, distribution, and probabilities.
   b. Storm characteristics including intensity and return periods.

c. Air and soil temperatures at various depths.
d. Potential evaporation.
e. Wind patterns and velocity characteristics.
f. Solar radiation.

2. Experimental site.
   In addition to the above requirements the following information will also be needed.
   a. Thermal regimes in the seed zone.
   b Timing and intensity of likely water stress.

Soil and Water Conservation and Management

The high runoff-generation potential and erodibility, susceptibility to seal and crust formation, poor water storage, profile-hardening tendency, and structural instability have been identified as the primary physical constraints to productivity in SAT Alfisols (see Physical Constraints). Several gaps in knowledge were identified at the workshop as priority areas for research, in an effort at a more systematic understanding of these constraints to productivity in SAT Alfisols (see Physical Elements).

Predicting runoff and soil loss. Both runoff and soil loss depend on rainfall characteristics, the soil's structural and hydrologic properties, overall catchment characteristics (particularly area and topography), land-management treatments, and crop cover and residue management. All of these are often site-specific properties for which a general research approach may be formulated for collection of baseline data and analysis (rainfall, soil, and topography) and systematic gathering of management data (land and crop management). Since profile water-storage in Alfisols is quite limited, making them drought-prone, a strategy for harnessing runoff or groundwater for supplemental irrigation is essential. We list below specific topics for research.

a. Rainstorm erosivity and soil erodibility characteristics.
b. Topographic effects on runoff and soil loss.
c. Mechanisms for seal/crust formations and their interrelationships with infiltration-runoff balance.
d. Ideal land-surface configurations for enhancing crop establishment, maximizing infiltration and control of runoff and erosion. Emphasis here should be on "flat" or mildly graded terraces with interterrace management that may involve ridging, tied-ridging or other configurations as appropriate for the soil's infiltration rate and rainfall patterns. In some countries (e.g., India) certain land-management treatments have already been imposed in many areas. It would be prudent to take these into account while searching for more effective alternatives.

Optimized primary and secondary tillage. Selection and timing of tillage operations, when necessary, must be based on a systematic understanding of the crop's requirements (rooting habits, water, air, and thermal properties), soil characteristics (strength, bulk density, compactability, particle-size distribution, and textural differentiation within profile, water retention, crusting tendency, and thermal conductivity) and other relevant factors (weed control, available and potential specialized implements, and draft sources). Of particular importance are the intensity (depth and horizontal spacing), type (with or without soil inversion), and frequency of tillage operations.

Minimum or no tillage may be appropriate in certain instances where little is to be gained from improved matching of soil characteristics with crop requirements; this would appear to be the case in the highly sandy Psammentic Alfisols.

Improved soil structure. The short-lived effects of tillage and the extreme instability of those land-surface configurations installed to control runoff and soil loss can be overcome by a systematic investigation into the methods for improving the structural and aggregation properties of Alfisols. Short-term methods include the application of crop residues (surface mulching or incorporation) or other beneficial organic and inorganic byproducts. Long-term measures are based on altering the cropping systems to include a component of permanent vegetation (see Research Needs). Clearly, there are nutritional implications to both short-term and long-term strategies which need to be investigated.

Water supply for supplemental irrigation. Watershed- or catchment-based strategies for assessing and recapturing runoff and seepage waters in Alfisols are important priorities for research. Many gaps in knowledge remain in the areas listed below.

a. Optimized strategies for runoff harvesting, storage, and use in different climatic and soil zones. High seepage rates in Alfisols are a critical limitation to surface storage structures.
b. Reliability of groundwater detection and tapping methods.
c. Interrelationships between surface-water storage and groundwater recharge: how important and predictable is the role of the percolation tank?
d. Optimum strategy for irrigation to ensure maximum water use efficiency.
e. Catchment-based optimum combinations of surface and underground water resource developments.

Fertility

While the importance of fertilizer use in Alfisols even under rainfed conditions has been clearly established, considerable gaps in knowledge still exist in the following areas.

Methods of enhancing and maintaining organic matter levels. Short- and long-term strategies for sustained productivity on these soils should consider ways of sustaining adequate organic-matter levels. Specifically, there is need for systematic research on the following aspects.
a. Residue management.
b. Farmyard manure and green manure utilization.
c. Methods of efficient application of organic fertilizers.
d. Effects of organic matter on the soil's physical properties (see Soil and Water Conservation and Management).

Soil-water-fertility interactions under different agroclimatic conditions. Uncertainties in rainfall, its frequency and quantity affect not only water storage but also nutrient status and availability. Clear gaps exist in the following areas.
a. Water-fertility interaction.
b. Release, movement, and leaching of nutrients.
c. Fertilizer-use efficiency.
d. Fertility requirements in view of variable rainfall and soil-water status.

Fertilizer requirements and management of cropping systems. Since intercropping and other alternative land uses represent an important risk-reducing strategy in Alfisols, the following systems require systematic investigation.

a. Legume/nonlegume sequential cropping.
b. Legume/nonlegume intercropping.
c. Rotation of ley crop with cultivated crop.
d. Sole cropping.

In all cases, studies must emphasize the quantity, timing, and methods of fertilizer application.

Alternative Land-use Systems

Work on crop rotations designed to maintain soil fertility ranked high on the workshop's general research agenda for conventional annual-cropping systems. The workshop felt such research should concentrate on the frequency and duration of legumes in cereal rotations rather than on specific crops. The technical performance of deep intensive tillage as opposed to minimum tillage in diverse Alfisol regions of the SAT was also considered a high research priority. Identification of the boundary conditions where one system is technically superior to the other was also emphasized.

Research into the use of perennial vegetation, particularly agroforestry systems, has been strongly recommended. With agroforestry systems, one can extend and build on the principles and concepts generated from annual intercropping systems. Alley cropping a cereal with a leguminous or nonleguminous tree species appears initially to be a promising alternative land-use system for Alfisol regions in the SAT. Research should specifically focus on the following.

1. The potential of temporal complementarity to better exploit productive resources.
2. The scope for increasing nutrient, water, and light-use efficiency.
3. The impact of woody perennials on pest and disease incidence, stand establishment, runoff and erosion, and yield stability during years of adverse rainfall.
4. The changes in relative productivity advantages, since agroclimatic and edaphic resources differ, particularly in relation to areas with shallow soils where "forestry" has ecological advantages; and deep-soil regions where a perennial crop may be able to use soil resources not exploited by annual crops.
5. The contribution of nitrogen and carbon from leguminous tree species under alternative management practices.

Knowledge is lacking on optimal design and on how to use harvested runoff water on the perennial in the system, using either a "key line" or a storage system.

General research priorities for legume/ley systems and the more complex legume-ley/no-till production strategies embrace a number of concerns within the subsystems: legume/ley crop rotation, no tillage/mulch, crop/live mulch, and cattle/crop subsystems. Specific impacts that should be quantified are the effects of a legume/ley-crop rotation on crop production; of minimum tillage on crop production; of competition between the crop and forage legume intercrop on crop, legume forage, and legume seed production; and of cattle-ley pasture interactions on animal and crop production.

Implementation

Because of the extreme diversity of Alfisols and their agroenvironments, a network approach is highly recommended for investigating key baseline data and management alternatives for planning to enhance productivity of these soils. Selection of locations for the network should be based on representative soils, climates, and land-use patterns. The selection requirements should be satisfied by several of the existing experiment stations, such as the one operated by AICRPDA and similar stations overseas.

The formation of a committee from among the workshop participants for designating benchmark locations, (see Resource Inventory and Agroclimatic Characteristics) has been recommended. In India, where increasing emphasis is being placed on watershed-based agricultural development, serious consideration should be given to inclusion in the network pertinent "model" watersheds for strategic field-scale investigations.

The priority of research needs (see Research Needs) will differ by location. A standard set of procedures is, however, recommended for formulating state-of-the-art plans for needed studies. A farming systems research team should be charged with interdisciplinary coordination to assess the full impact of a given management input. It is possible to assemble such a team from among workshop participants or other nominees of cooperating institutions. Research on components as well as watershed-based integrated systems should be given equal emphasis.

The focus should be on the research team, with contact personnel positioned at each selected site to ensure coordination and regular consultations on cooperative research at the various locations. Regular meetings involving these individuals and needed resource personnel or consultants should be held at appropriate intervals to review progress and formulate plans for future investigations. For the benefit of all concerned, these meetings should rotate among cooperating institutions.

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Appendix A

Morphology of the Patancheru Soil Series[1]

General Description

The Patancheru series is a member of the clayey-skeletal, mixed, isohyperthermic family of Udic Rhodustalfs. The A horizons of Patancheru soils are yellowish red to reddish brown, and slightly acid loamy sand to sandy loam. The horizons are reddish brown to dark-reddish brown, neutral to mildly alkaline, sandy clay loam to sandy clay, over weathered granite-gneiss. Such soils occur on level to gently sloping pediments at an elevation of 540 to 575 m above MSL. Mean annual air temperature is 25.8°C, and m ean annual rainfall about 760 mm. The principal associated soil—called Lingampalli series—is a Lithic Rhodustalf.

Typifying pedon. Patancheru sandy loam—cultivated.

Ap 0-10 cm—Yellowish red (5YR 5/6, D and M), sandy loam; weak, fine-to-medium granular structure; loose, very friable and slightly sticky; many fine-to-very-fine roots inside peds; common very-fine-to-fine tubular imped pores; pH 6.5; gradual, smooth boundary.

A2 10-20 cm—Reddish brown (5YR 4/4, D and M), sandy loam; weak, medium, subangular blocky structure breaking to fine granular; slightly hard, friable, slightly sticky, and slightly plastic; few fine roots between peds; few fine tubular imped pores; pH 6.5; clear, smooth boundary.

B1 20-30 cm—Reddish brown (2.5YR 4/4, M), sandy clay loam; moderate, medium subanglar blocky structure; firm, slightly sticky, and slightly plastic; few fine roots inside peds; 2 to 5 mm size angular quartz fragments 8 to 10% by volume; few fine-to-medium tubular and fine irregular imped pores; pH 6.7; gradual, smooth boundary.

B211 30-49 cm—Dark-reddish brown (2.5 YR 3/4, M), sandy clay loam; strong, medium-to-coarse subangular blocky structure; firm, sticky, and plastic; few fine roots inside peds; 2 to 5 mm size angular quartz fragments 10 to 15% by volume; few 2 to 5 mm size dark-red-to-black rounded iron concretions; patchy, thick, clay cutans on ped faces; medium, irregular, and few medium tubular imped pores; pH 6.7; gradual, smooth boundary.

B22t 49-102 cm—Dark reddish brown (2.5 YR 3/4, M), gravelly sandy clay; strong, medium-to-coarse angular, blocky structure; firm, sticky, and plastic; very few very fine roots inside peds; 2 to 10 mm size angular quartz fragments 30 to 50% by volume; 2 to 5 mm size rounded iron concretions 3 to 5% by volume; patchy thick clay cutans on ped faces; medium irregular pores; few medium round krotovinas; pH 7.8; gradual, smooth boundary.

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1. Adopted from Pedon description by the core group, N.K. Barde, K.V. Seshagiri Rao, K.R. Venugopal and others; 5 August 1980. Source: Murthy, R.S., Hirekerur, L.R., Deshpande. S.B., and Venkata Rao, B.V., eds. 1982. Benchmark soils of India: morphology, characteristics and classification for resource management. Nagpur, Maharashtra, India: National Bureau of Soil Survey and Land Use Planning (ICAR). pp 312-315.

BC 102-145 cm—Reddish brown (2.5 YR 5/4, M), brown (7.5 YR 5/4, M) and light yellowish brown (10 YR 6/5 M) gravelly sandy clay loam; moderate medium subangular blocky structure breaking to fine subangular blocky structure; friable, slightly sticky and slightly plastic; 2 to 5 mm size angular quartz fragments about 15% by volume; few 2 to 5 mm size rounded iron concretions; pH 7.0; gradual, wavy boundary.

C 145-160 cm—Weathered, soft, brownish yellow (10 YR 6/6), light yellowish brown (10 YR 6/4), reddish yellow (7.5 YR 6/6), and light brown (7.5 YR 6/4) granite-gneiss.

Range of characteristics. The depth of solum ranges from 125 to 150 cm. The estimated MAST is 26.8℃. The difference between MSST and MWST is 4.3℃. The moisture regime is ustic.

The A horizon is about 15 to 25 cm thick. Its color is in hue 5 YR, value 4 to 5, and chroma 4 to 6. Its texture is loamy sand to sandy loam. The Bt horizon is 65 to 80 cm thick. Its color is in hue 2.5 YR, value 3 or less, and chroma 4. Its texture is sandy clay loam to sandy clay. Angular quartz fragments and iron concretions are present in varying proportions in the B horizons.

Drainage and permeability. Well-drained with moderate permeability.

Use and vegetation. Cultivated to rainfed sorghum, maize, and pulses; natural vegetation: neem, *Pongamia* spp, and grasses.

Distribution and extent. Extensive in Medak district, Andhra Pradesh, India.

Type location. Village Patancheru; distict and state: Medak, Andhra Padesh; plot no. RA 32, ICRISAT Farm; 17° 35'N, 78° 17'E.

Interpretation. The soils have good air-water relationship. Their available water-holding capacity is medium. The soils are drought prone. Adapted crops, such as sorghum and pulses, are raised as dryland crops.

Interpretative grouping.

i) Land capability subclass-IIIs.
ii) Irrigability subclass-3s.
iii) Productivity potential-Medium.

Appendix B

Morphology of the Soil in Map Unit 3 at ICRISAT Sahelian Center, Niamey, Niger.[1]

General description

This level, gently undulating soil is classified as a sandy, siliceous, hyperthermic Psammentic Paleustalf. It occurs primarily west of the Sahelian Center, and generally rims the plateau-like surface found there. Ironstone gravels are found at depths of 1 to 2 m belowthe soil surface. Slopes are plane to convex and range from 1 to 3%. Many areas are gently undulating, with relief between the 'highs' and the 'lows' less than 0.5 m.

The A horizon of this soil is yellowish red, fine sand typically 32 cm thick. The upper 92 cm of the Bt is red, loamy, fine sand with little structural development. The lower Bt which extends to more than 2 m is red, very gravelly, loamy fine sand consisting of approximately 50% ironstone gravels and cobbles that may be up to 25 cm in diameter.

Location. ICRISAT Sahelian Center, approximately 40 km south of Niamey, Niger. This site is on the west side of the Center, approximately 600 m south of the north fence and 450 m east of the west fence.

Vegetation. Annual grasses and forbs. The Sahelian Center is located in an old field now fallow.

Parent material. Eolian sands over lateritic gravels.

Physiography and slope. Gently undulating; 1.5% slopes.

Pedon description.

A1 0 to 17 cm; yellowish red (5 YR 5/6, m,5 YR 6/6, d) fine sand; massive-to-very-weak, medium, subangular, blocky structure; very friable, soft; common very fine roots; few very fine pores; sand grains mostly uncoated; common pedotubules; moderately acid; abrupt, smooth boundary.

A2 17 to 32 cm; yellowish-red (5 YR 5/6, m), red (2.5 YR 4/6, d), loamy, fine sand; few fine dark-red (2.5 YR 3/6, m) mottles; massive-to-very-weak, medium, subangular, blocky structure; very friable, soft; common very fine roots; few fine pores; 50% of sand grains are coated; common pedotubules with uncoated sand grains; moderately acid; clear, smooth boundary.

3t1 32 to 59 cm; red (2.5 YR 4/6, m, 2.5 YR 5/8, d), loamy, fine sand; very weak, coarse, subangular blocky structure; friable, slightly hard; few very fine roots; few fine pores; sand grains mostly coated; thin, patchy clay bridges between sand grains; common 2-5 mm pedotubules filled with uncoated sand; moderately acid; gradual, smooth boundary.

1. Adopted from the description by the Soil Characterization Laboratory, Soil and Crop Sciences Department, Texas Agricultural Experiment Station, Texas A&M University, College Station, Texas 77843, USA.

Bt2 59 to 85 cm; red (2.5 YR 4/8, m, 2.5 YR 5/8, d), loamy, fine sand; weak, very coarse, subangular blocky structure; friable, slightly hard; few fine and very fine roots; common fine pores; sand grains mostly coated; thin, patchy clay bridges between sand grains; less than 1% ironstone gravels; few coarse (5 cm) termite cavities; common pedotubules; few decayed root shells with sand in filling; moderately acid; gradual, smooth boundary.

Bt3 85 to 126 cm; red (2.5 YR 4/8, m, 2.5 YR 5/8, d), loamy, fine sand; massive-to-weak, coarse-to-very-coarse, subangular, blocky structure; friable, hard, and slightly brittle; few very fine roots; common fine pores; sand grains mostly coated; thin, very patchy clay bridges between sand grains; few coarse termite cavities; common pedotubules; slightly acid; abrupt wavy boundary.

2Bt 126 to 225 cm; red (2.5 YR 4/6, m, 2.5 YR 5/6, d) very gravelly, loamy sand; massive-to-weak, coarse-to-very-coarse, subangular, blocky structure; friable, hard, and slightly brittle; few fine roots; 50% 2 to 25 mm ironstone gravels; gravels increase in size with depth and some have a pisolitic structure; gravels are weakly cemented in some areas in pedon; 5% large (30 cm) blocks of indurated laterite; slightly acid.

Remarks: Colors are for moist soil unless otherwise stated. The gravels could not be augered deeper than 225 cm, but this did not seem to be because of indurated laterite. Approximately 10% of the gravels were ferriginous sandstone.

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