BIBLIOGRAPHIC DATA SHEET

1. CONTROL NUMBER: PN-AAK-838

2. SUBJECT CLASSIFICATION (695): AF26-0000-0000

3. TITLE AND SUBTITLE (240)
Distribution and use of arable soils in the semi-arid tropics

4. PERSONAL AUTHORS (100)
Swindale, L.D.

5. CORPORATE AUTHORS (101)
Int. Crops Research Institute for the Semi-Arid Tropics

6. DOCUMENT DATE (110): 1982

7. NUMBER OF PAGES (120): 34p.

8. ARC NUMBER (170)

9. REFERENCE ORGANIZATION (130): ICRISAT

10. SUPPLEMENTARY NOTES (500)
(Reprinted from "Managing Soil Resources - Plenary Session Papers," 12th International Congress of Soil Science, New Delhi, 8-16 February, 1982.)

11. ABSTRACT (950)

Soil classification

agricultural research
rainfall

12. DESCRIPTORS (920)
Semiarid land
agricultural production
Soil Science
Soil fertility

13. PROJECT NUMBER (150)

14. CONTRACT NO.(140)
UNKNOWN

15. CONTRACT TYPE (14

16. TYPE OF DOCUMENT (160)

AID 590-7 (10-79)

J. Walker

PN-AAK-838

Reprinted from the publication 'Managing Soil Resources – Plenary Session Papers' brought out on the occasion of the 12th International Congress Of Soil Science held at New Delhi from 8-16 February, 1982.

Distribution and Use of Arable Soils in the Semi-Arid Tropics

L.D. SWINDALE*

Abstract

THE semi-arid tropical region has variable rainfall, and is subject to droughts and floods. Rainfed farming is risky, but the possibilities for large-scale irrigation are limited. Technologies that take account of the climate and soil characteristics of the region are being developed to reduce the risks and increase production in this region of 700 million people.

Very sandy soils, Psamments and Ustalfs are extensive in the semi-arid tropics, particularly in Africa. Lack of water limits their use in intensified rainfed cropping. Deep ploughing may be needed to overcome the tendency for the surface soils to harden on drying. Mineral deficiencies are common, and fairly easily corrected, but nitrogen management can be difficult, mainly because of the low buffering capacity of the soil. Extensive grazing is an alternative and interacting use for these soils.

Medium and fine-textured Alfisols are extensive in eastern Africa, India and South America. They are moderately well suited to intensified rainfed cropping. Lack of water limits yields in most years, and droughts may occur as frequently as one year in five. The soils are deficient in nutrients and have moderate to high phosphate-fixing powers. They have problems with surface sealing and are moderately erosive; suitable technologies for adequate control of erosion in cropped lands are not yet available.

Vertisols are extensive soils in the semi-arid tropics. They have good water-holding and high buffering capacities. They are difficult to work, are highly erosive and need surface drainage to prevent waterlogging in heavy rains. Suitable technologies exist to fully exploit many of these soils for intensified rainfed cropping.

Oxisols occur extensively in semi-arid regions of eastern and central Africa and Brazil. Those with high base status, the Eutrustox, have high potentials for intensified cropping. Those with low base status, the Haplustox, have more constraints, but technologies have been developed to deal with them.

Many other kinds of soils exist in the region. Even those that are not well suited to cropping generally have potentials that considerably exceed current use. The semi-arid tropical region has high solar radiation and gentle landscapes easily cleared for cropping. Food production can be increased substantially in the region through rainfed arable farming without recourse to costly irrigation schemes.

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THE region of the semi-arid tropics covers much of the African continent (Fig. 1) stretching in a broad band from west to east below the Sahara desert, and including much of eastern and south-central Africa. In Asia it includes most of India, north-eastern Burma and Thailand. Most of the northern quarter of Australia, nearly all of Mexico, and large portions of Venezuela, Guyana, Surinam, French Guiana, Brazil, Paraguay and Bolivia lie within the region. More than 700 million people are estimated to live in the semi-arid tropics with 55% of them in India.

Rainfall in the semi-arid tropics is highly variable. In low-rainfall years there may be droughts; in high-rainfall years or even for short periods in low-rainfall years there may be floods. Deficient rainfall years may be followed by similar years or by years with excess rainfall.

Sorghum, pearl millet and maize are the major rainfed cereals of the region. Rice and sugarcane are grown under irrigation and in the river deltas and wheat is grown under irrigation in the winter season mainly at higher latitudes. The major grain legumes are pigeonpea, chickpea, cowpea and mung bean. Groundnut, soybean, safflower, sesame and mustard are the main oilseed crops; cotton the main fibre crop.

Traditional agriculture in the semi-arid tropics has been evolved to reduce the risk of losses in dry years, because they can be very severe. The benefits that could accrue in good years are usually lost. Much of the effort to create new or improved technology for the region is designed to provide opportunities to invest safely in anticipation of good years.

Food production in semi-arid India is increasing, although not fast enough to improve standards of living very much. In semi-arid Africa food production is declining. (IFPRI 1977; FAO 1978; USDA 1981). The IFPRI report predicts substantial deficits in cereals in the semi-arid tropics by 1990. India may have deficits of 20 million tonnes. Per capita deficits in the African semi-arid tropics may be ten times as great as those in India. A large and urgent effort in research and development will be required to avert the human misery that such deficits foretell. The efforts will only succeed if the resources of soil and water are used wisely and well, and if the inherent variability in the climate of the semi-arid tropics is offset.

Previous efforts to increase agricultural production in the semi-arid tropics have achieved only limited success even when they have been acceptable socially, because they have not relieved climate- and soil-based constraints (Kampen and Burford 1980). Better technologies are now being developed to ameliorate the effects of drought, increase food production per unit of land, water and capital, assure stability in production and contribute directly to improving the quality of life.

Characteristics of Semi-Arid Tropical Climates

The semi-arid tropical region has high atmospheric water demand and scarce water resources. Temperatures are high, usually exceeding a mean of 18° C in all

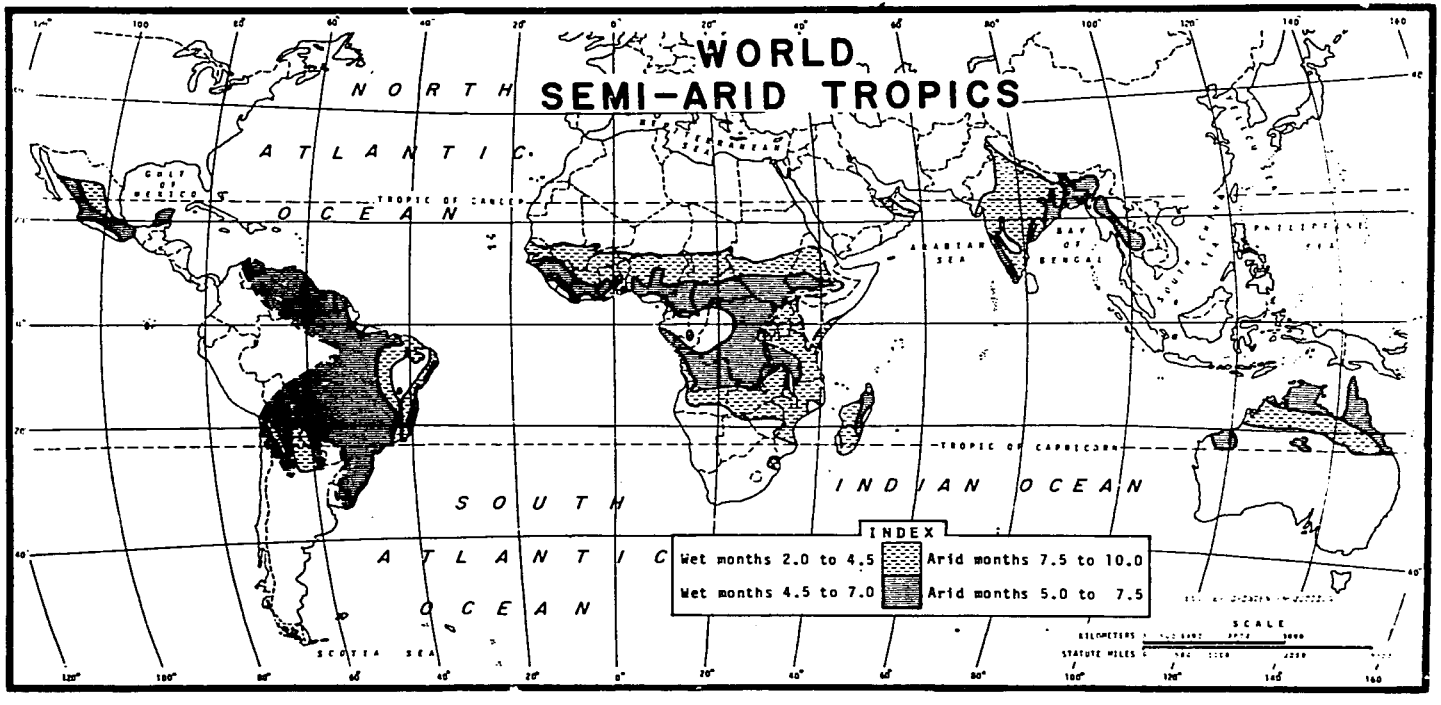

Fig. 1. The semi-arid tropics, i.e. regions with mean monthly temperatures exceeding 18°C and either 2-4½ wet months or 4½-7 wet months annually.

months of the year. Total annual rainfall varies considerably from about 400 to 1900 mm.

Rainy seasons generally are short with most of the rainfall concentrated in 2 to 5 months; from May to October in the northern hemisphere and October to April in the southern hemisphere (Table 1). According to Troll's 1965 classification, rainfall exceeds potential evapotranspiration for 2 to 4.5 months in the year in the *dry* sub-region and for 4.5 to 7 months in the *wet-dry* sub-region. The wet-dry semi-arid tropics of this classification equate approximately to the sub-humid tropics defined by other climatic classifications. Figure 1 shows the semi-arid tropics defined by using Troll's classification and a mean annual temperature of 18° C. It probably includes virtually all soils in the tropics with ustic soil moisture regimes—i.e., soils that have a dry season of 3 to 9 months—and all soils with isohyperthermic or hyperthermic soil temperatures, i.e. mean temperatures at 50 cm depth of 22° C or more, with or without a summer/winter difference of 5° C. The figure delineates the geographic mandate accepted by ICRISAT.

Of the climatic elements important for crop production—rainfall, temperature and solar radiation—rainfall is the most variable in the semi-arid tropics. The coefficient of variation for annual rainfall is 20 to 30%, for annual temperature and solar radiation of the order of 5%. Detailed studies of climate have shown that the distribution of rainfall within the year is also highly variable, and cannot be predicted with any reasonable degree of confidence. Smaller yearly or seasonal totals correlate with larger year-to-year variability.

In tropical latitudes there are large amounts of energy available for evaporation of water. Since solar radiation is the most important component affecting evaporation, and since it varies little from year to year, potential evapotranspiration is more or less constant from year to year. Small negative deviations in precipitation either from monthly or annual norms are all that are required to initiate drought. In semi-arid India moderate or worse droughts are likely to occur one year in every four (Fig. 2).

In most years the rainy season in the semi-arid tropics is long enough for annual crops to grow. Indeed there is usually excess water in the rainy season, some of which can be stored in the soil, but most of which runs off and causes soil erosion. Management of land, crops and livestock is intimately associated with the inflow and outflow of water.

Distribution of Soils on Arable Lands in the Semi-Arid Tropics

There are many kinds of soils in the semi-arid tropics. Not all of them have ustic soil moisture regimes and not all have isohyperthermic or hyperthermic soil temperatures. Many are unsuited to agriculture.

The FAO/UNESCO Soil Map of the World, published at a scale of 1:5 000 000, provides the best single reference to the soils of the entire semi-arid tropics. Table 2, showing the distribution of soils in the semi-arid tropics on arable or possibly arable land, i.e., soils on flat to rolling landscapes, has been

Table 1. Average monthly rainfall and mean monthly potential evapotranspiration for selected locations in the semi-arid tropics.

Location	Lat °	Lat ′	Long °	Long ′	Element[a]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Northern Hemisphere																		
1. Bambey	14	42	16	28W	R	0	1	0	0	3	30	125	246	187	55	2	1	651
(Senegal)					PE	136	133	164	173	165	161	138	130	135	144	130	130	1739
2. Hyderabad	17	27	78	28E	R	2	10	13	23	30	107	165	147	163	71	25	5	761
(India)					PE	110	129	181	198	220	196	140	135	119	124	104	99	1757
3. Ouagadougou	12	21	01	31W	R	0	3	8	19	84	118	193	265	153	37	2	0	882
(Upper Volta)					PE	143	152	189	195	190	151	135	113	121	149	134	133	1805
4. Bamako	12	38	08	02W	R	1	0	3	15	60	145	251	334	220	58	12	0	1099
(Mali)					PE	143	160	204	198	185	152	125	113	119	135	128	134	1796
Southern Hemisphere																		
5. Patos	07	01	37	17W	R	80	151	248	183	62	19	7	3	1	5	17	28	804
(Brazil)					PE	228	192	168	155	153	148	181	210	241	270	270	273	2489
6. Townsville	19	15	146	46E	R	332	364	275	83	34	26	22	10	10	21	55	102	1333
(Australia)					PE													
7. Formosa	15	32	47	20W	R	252	204	227	93	17	3	5	3	30	127	255	343	1559
(Brazil)					PE	143	126	136	130	125	113	122	144	148	158	125	128	1592

[a]R = Average monthly rainfall (mm); PE = Mean monthly potential evapotranspiration (mm).

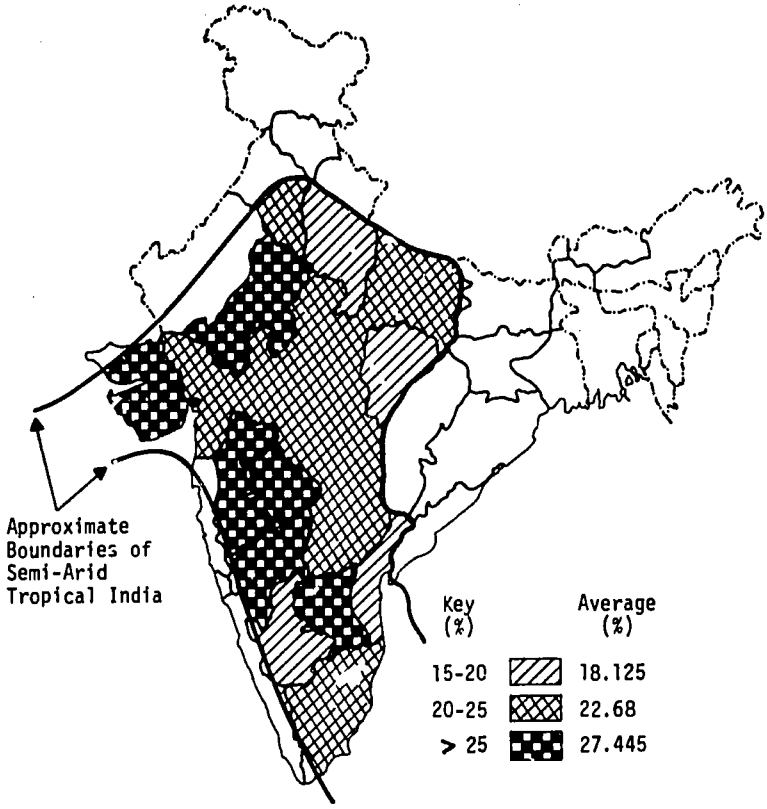

Fig. 2. Percentage occurrences of droughts of class moderate and worse in the rainy season in the Indian semi-arid tropics (Ryan 1974).

compiled from that source, with the names of the soil units taken from the legend of the Soil Map. Soils with aridic moisture regimes, the Yermosols and Xerosols, falling within the semi-arid tropics as defined above, have been excluded from the table and compilation. Figure 3 shows the distribution by continent of the major groups of the soils on arable lands in the semi-arid tropics.

The Soil Map of the World was compiled from the best data then available. Detailed soil surveys were used wherever possible, but in many areas only reconnaissance soil surveys were available, and in large areas, e.g. 55% of the African continent, estimates of the distribution of soils had to be made from general information on relief, climate, vegetation and geology with only local soils observations. Each mapping unit comprises a dominant soil, associated soils—defined as occupying at least 20% of the unit—and soil inclusions—defined as occupying less than 20% of the unit. Thus no great accuracy can be claimed for the areas of the soil units in Table 2 and Figure 3; numbers shown will be indicative only of areal extent and relative areal importance of each unit.

Table 2. Distribution of soils on arable lands in the semi-arid tropics from the FAO/UNESCO Soil Map of the World.

SOILS	SANDY Km²		SILTY Km²		CLAYEY Km²		TOTALS Km²
	Flat	Rolling	Flat	Rolling	Flat	Rolling	
FLUVISOLS							
Calcaric	16 558	—	66 950	—	26 729	—	110 237
Eutric	37 033	—	566 458	11 458	158 474	—	773 423
Thionic	1 550	—	8 942	—	16 533	—	27 025
ARENOSOLS							
Cambic	284 008	34 333	4 742	—	6 917	—	330 000
Luvic	104 182	25 983	7 100	3 333	7 475	—	148 073
Ferralic	1 285 734	169 083	24 166	26 283	—	—	1 505 266
Albic	90 958	23 033	—	14 617	—	—	128 608
ANDOSOLS							
Ochric	—	—	2 375	2 192	2 958	—	7 525
Mollic	3 750	—	—		—	—	3 750
Humic	—	—	—	3 950	—	—	3 950
Vitric	14 341	32 250	2 908	43 108	—	—	92 607
VERTISOLS							
Pellic	4 767	—	13 875	9 817	295 283	—	323 742
Chromic	20 567	—	13 750	9 125	788 233	168 942	1 000 617
SOLONCHAKS							
Orthic	4 550	—	9 641	—	—	—	14 191
Takyric	—	—	—	—	13 992	—	13 992
Gleyic	—	—	14 316	—	15 038	—	29 354
SOLONETZ							
Orthic	11 538	11 642	32 724	15 958	32 517	—	104 379
Mollic	—	—	—	—	4 675	—	4 675
KASTANOZEMS							
Haplic	122 741	7 650	1 800	27 367	—	—	159 558
Calcic	—	—	—	46 058	—	—	46 058
Luvic	—	—	55 399	49 316	—	—	114 715
PHAEOZEMS							
Haplic	—	—	825	12 559	658	5 750	19 792
Luvic	—	—	21 991	—	102 791	—	124 782
CAMBISOLS							
Eutric	20 041	—	212 601	6 342	7 458	17 991	264 433
Dystric	—	—	38 441	—	38 033	20 883	97 357
Humic	—	1 949	—	—	—	39 333	41 282
Calcic	—	—	34 358	29 883	4 808	—	69 049
Chromic	8 275	4 150	38 275	51 941	483	7 125	110 249
Ferralic	425	550	8 525	23 916	4 375	2 175	39 966
Vertic	3 025	—	8 050	591	3 918	66 767	82 351

(contd.)

Table 2. (*contd.*)

SOILS	SANDY Km²		SILTY Km²		CLAYEY Km²		TOTAL Km²
	Flat	Rolling	Flat	Rolling	Flat	Rolling	
LUVISOLS							
Orthic	15 650	12 125	96 242	43 466	983	4 725	173 191
Chromic	61 925	70 397	59 358	273 759	42 490	108 382	616 311
Calcic	10 383	23 716	14 591	27 758	—	—	76 448
Vertic	—	—	—	—	650	—	650
Ferric	766 176	49 192	424 898	129 631	75 367	207 808	1 653 072
Plinthic	76 033	—	86 007	—	2 609	—	164 649
Gleyic	79 858	—	44 291	—	15 959	408	140 516
PLANOSOLS							
Eutric	9 158	—	41 562	—	211 958	—	262 678
Mollic	1 858	—	38 058	—	9 891	—	49 807
Solodic	19 258	18 375	9 817	13 708	1 933	—	63 091
ACRISOLS							
Orthic	112 424	20 517	240 073	220 173	60 116	71 767	825 070
Ferric	242 517	28 450	194 608	96 366	—	—	561 941
Humic	—	—	3 683	467	—	950	5 100
Plinthic	11 833	—	179 208	36 916	201 725	—	429 682
Gleyic	2 991	2 083	81 058	10 142	—	29 550	125 824
NITOSOLS							
Eutric	5 733	3 458	38 217	160 608	15 791	202 291	426 098
Dystric	105 167	508	135 066	66 457	166 674	174 791	648 663
FERRALSOLS							
Orthic	39 266	37 925	592 628	459 599	622 049	1 621 761	3 373 228
Xanthic	332 558	—	548 967	8 209	203 425	2 283	1 095 442
Rhodic	2 183	15 875	39 891	40 149	276 657	148 466	523 221
Plinthic	500	—	149 150	133 200	9 999	—	292 849
Humic	—	2 916	—	1 092	129 791	14 041	147 840
Acric	—	—	462 191	—	165 408	—	627 599
TOTAL	3 929 514	596 160	4 457 776	2 109 514	3 744 823	3 016 189	18 073 976

For the purposes of this paper, associated and included soils are combined and called associated soils.

Arenosols

Coarse-textured soils containing more than 65% sand and less than 18% clay comprise 11% of the arable and possibly arable soils in the semi-arid tropics. *Cambic Arenosols*, coarse-textured soils with some evidence of a colour or structural B horizon, and associated soils occupy about 330 000 km² in the region. They occur extensively, mostly on flat to undulating topography in sub-Saharan Africa, developed in aeolian and alluvial sands of Quaternary origin which overlie basement rocks or indurated iron-stone. They occur also on slightly stronger relief in Rajasthan and in scattered small areas throughout northern Australia.

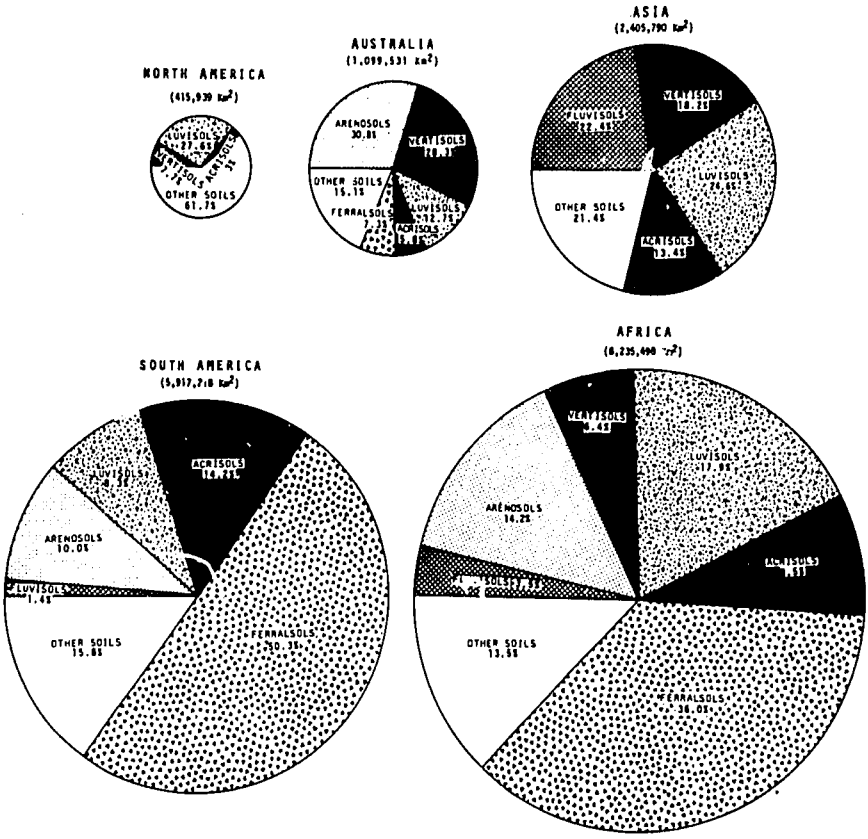

Fig. 3. Distribution by continents of the major groups of soils on arable lands in the semi-arid tropics.

Associated and included soils are other Arenosols, very shallow soils, Chromic Luvisols, hydromorphic and salt-affected soils.

Sand fractions are invariably highly quartzose with small amounts of weatherable minerals. If the soils are derived from aeolian material, fine sand tends to predominate. Kaolinite and oxides of iron and aluminium make up the clay fractions. Properties of a representative Cambic Arenosol are shown in Table 3, Profile A.

The central concept of the Cambic Arenosols in the semi-arid tropics would probably be classified as a Typic Ustipsamment in Soil Taxonomy (USDA Soil Survey Staff 1975). Soils with true cambic horizons would be Ustochrepts or Utropepts.

Ferralic Arenosols and associated soils are extensive soils, occupying over 1 500 000 km^2. They differ from Cambic Arenosols in having a CEC of less than 24 meq/100g of clay immediately below the A horizon or in some part of the cambic horizon, i.e. they contain low-activity clay of the type found in Oxisols (Table 3, Profile B). The implication is that these soils are derived from more

Table 3. Properties of selected soils of the semi-arid tropics.

Horizon	Depth cm	Moist colour	Particle Size Analysis Sand %	Silt %	Clay %	Organic C %	N %	pH H_2O	pH KC_l	CEC Meq/100 g	Base saturation (Sum) %	Ca Meq/100 g	Na Meq/100 g	$CaCO_3$	Extr. Fe. %	Volumetric water content at field capacity cc/cc	Volumetric water content at wilting point cc/cc
	Cambic Arenosol, Bambey, Senegal, "Dior" soil, Reference: Charreau, 1974 p. 155.																
	0-10	7.5 YR 6/4	95.6	0.5	3.4	2.9	0.23	5.5		2.00	47	0.45	0.10		3.8	0.12	0.03
Profile A.	10-17	7.5 YR 6/6	95.6	0.4	4.0	1.6	0.14	5.2		2.05	37	0.20	0.07		4.8		
	30-35	7.5 YR 5/4	93.8	0.9	5.4	1.3	0.13	4.5		2.40	29	0.35	0.06		8.4	0.15	0.04
	70-80	7.5 YR 5/6	96.1	0.5	3.0	1.[illegible]	0.11	5.2		2.60	37	0.30	0.06		8.0		
Profile B.	Ferralic Arenosol, Kabuyu, Zambia, Reference: Ministry of Agriculture, Zambia: Soil Map of Zambia, 1978.																
Al	0-25	7.5 YR 5/4	94.0	1.0	5.0	0.35	0.03	6.3		1.4	84	1.0					
C_1	25-61	7.5 YR 4/4	92.0	1.0	7.0	0.12	0.02	6.3		1.2	57	0.5					
C_2-C_3	61-198	7.5 YR 5/6	90.0	2.0	9.0	0.10	0.02	5.7		1.0	60	0.4					
C_4	198-335	7.5 YR 5/6	90.0	1.0	9.0	0.04	0.0[illegible]	6.2		0.8	91	0.4					
Profile C.	Luvic Arenosol, Darha, Senegal, Reference: FAO. FAO/UNESCO Soil Map of the World, Vol. VI Africa, pp. 276-7.																
A	0-25	Belge	93.0	2.6	5.7	0.20	0.02	6.9		7.4	30	1.64	0.06				
AB	45-55	Ochre-grey	89.5	4.5	7.4	0.17	0.02	5.6		4.1	46	1.28	0.06				
Bt_1	100	Ochre-rust	85.0	2.1	14.4		0.02	5.3				2.10	0.08				
Profile D.	Ferric Luvisol, Sefa Sedhiov, Senegal, Reference: FAO. FAO/UNESCO Soil Map of the World, Vol. VI Africa, pp. 262-3.																
Ap_1	0-6	5 YR 5/3	73.2	4.0	9.4	1.05	0.07	6.5	6.1	4.80	73	2.25	0.05		0.83	0.17	0.07
Ap_2	6-13	5 YR 6/2	75.0	4.1	9.4	0.68	0.05	5.6	5.8	4.05	62	1.70	0.05		0.85		
E	15-25	5 YR 6/4	61.9	4.9	21.5	0.38	0.03	5.6	5.4	4.45	63	1.70	tr		0.99		
Bt	40-60	5 YR 8/4	49.3	5.3	35.1	0.33	0.03	6.2	5.3	5.15	71	2.10	tr		1.17	0.17	0.08
Profile E.	Chromic Luvisol, ICRISAT, India, Reference: The Soils of ICRISAT, NBSS & LUP 1982.																
Ap	0-5	5 YR 4/4	79.2	6.3	14.2	0.55		6.9		4.8	74	2.6		Nil	Not determined	0.16	0.06

Table 3. *(contd.)*

Horizon	Depth cm	Moist colour	Particle Size Analysis Sand %	Silt %	Clay %	Organic C %	N %	pH H_2O	KCl	CEC Meq/100 g	Base saturation (Sum) %	Ca Meq/100 g	Na Meq/100 g	$CaCO_3$	Extr. Fe. %	Volumetric water content at field capacity cc/cc	at wilting point cc/cc
B_1	5-18	2.5 YR 3.5/6	66.4	5.3	27.5	0.52		6.9		8.2	64	3.8	—	—		0.20	0.12
B_2l_1	18-36	2.5 YR 3/6	41.4	6.6	51.4	0.63		6.4		14.8	69	5.8	—	—	—	0.22	0.14
$B_{23}t$	71-112	2.5 YR 3/6	53.9	7.1	38.3	0.10		6.5		9.8	88	5.4	0.3	—	—	0.24	0.16
Profile F.	Chromic Vertisol, Damazin, Sudan, Reference: FAO. FAO/UNESCO Soil Map of the World, Vol. VI Africa, pp. 282-3.																
Ah_2	1-18	2.5 YR 3/2	38.9	7.3	53.8	1.29	0.06	7.5		50.1	92	26.4	tr				
AC	18-60	2.5 YR 3/2	36.3	9.6	54.1	0.64	0.03	7.9		50.0	85	23.7	0.1				
CA	60-90	2.5 YR 3/2	33.1	11.2	55.7	0.48	0.02	8.6		50.4	92	26.4	0.4	0.1			
CA	90-120	2.5 YR 3/2	35.8	8.8	55.4			8.7		45.8	98	25.3	0.4	0.2			
Profile G.	Pellic Vertisol, ICRISAT, India, Reference: The Soils of ICRISAT, NBSS & LUP 1982.																
Ap	0-25	10 YR 3/1	22.0	19.1	57.4	0.96		8.1		56.5	90	39.6	1.2	1.5	Not determined	0.40	0.27
A_{11}	25-70	10 YR 3/1	18.6	17.2	64.0	0.69		8.2		60.8	97	45.7	1.1	2.0	—	0.44	0.27
A_{12}	70-143	10 YR 3/1	15.8	17.9	65.8	0.60		8.0		54.9	99	40.5	1.4	2.4	—	0.44	0.27
Profile H.	Orthic Ferralsol, Kitale, Kenya, Reference: Siderius and Muchena, 1977.																
A	0-22	5 YR 3/3	47.0	4.0	44.0	1.67	0.17	5.2	5.2	15.4	36	4.0	tr				
B_1	22-62	5 YR 4/6	39.0	8.0	53.0			5.4	5.0	11.3	30	2.4	tr				
B_2	62-141	5 YR 4/6	35.0	8.0	57.0			5.0	5.0	10.6	21	1.2	tr				
Profile I.	Rhodic Ferralsol, Jaiba, Brazil, Reference: Benchmark Soils Project 1979b.																
Ap	0-10	2.5 YR 3/4	20.5	23.1	56.4	3.10	0.35	6.1	5.5	18.9	68	10.3	0.1			0.32	0.22
A_3	10-20	2.5 YR 3/4	19.5	17.4	63.1	1.10	0.34	6.5	5.6	10.9	63	5.9	0.1				
B_{21}	20-50	10 R 3/4	16.5	25.2	58.3	0.55	0.07	6.3	5.5	9.4	56	4.5	0.1			0.28	0.20
B_{22}	50-120	10 R 3/6	19.6	28.2	52.2	0.35	0.06	6.1	5.5	7.7	61	3.5	0.1				

highly weathered sands or are themselves more weathered than the Cambic Arenosols.

The soils are co-extensive with the Cambic Arenosols in southern Africa, but occur in somewhat moister climates. They are extensive in north-central Australia, and occur in large areas in north and central Brazil.

They are often gravelly and shallow. Associated soils are sandy Ferralsols, Luvisols, Acrisols, very shallow soils, hydromorphic and salt-affected soils and—in South America—Cambisols.

The central concept of the Ferralic Arenosols would probably be classified as a Typic Ustipsamment in Soil Taxonomy, i.e. the same as the central concept of the Cambic Arenosols, or possibly as an Ustoxic Quartzipsamment if the sand is virtually all quartz. The soil in Table 3, Profile B, has a clay distribution which appears to meet the requirements for an argillic horizon, and would probably be classified as an Oxic or Psammentic Paleustalf.

Luvic Arenosols and associated soils occupy approximately 150 000 km^2 in the semi-arid tropics. These soils (Table 3, Profile C) contain lenses and lamellae with more clay than the remainder of the soil and are intergrades to Luvisols. They are particularly extensive in the Sahel—in Senegal, Mali, Upper Volta, Niger and Chad. They also occur in western Sudan and in Mozambique in moister climates than associated Cambic Arenosols. In Niger and Mali they occur in catenary associations with exposed iron-stone cuirasse or very shallow soils with iron gravels at the top of the catena, Cambic and Luvic Arenosols on the upper pediment slopes and in fossil streambeds, sandy Alfisols on the lower pediment slopes and hydromorphic soils with significant accumulations of clay in the trough.

Associated soils are Cambic Arenosols, Luvisols, Vertic Cambisols, Orthic Acrisols, shallow soils and hydromorphic soils.

The central concept of the Luvic Arenosols would probably be classified as an Alfic Ustipsamment in Soil Taxonomy. Some, including the soil in Table 3, Profile C, are probably sandy Alfisols.

Luvisols

Luvisols, soils with base-rich argillic B horizons, occupy 15% of the semi-arid tropics, occurring in moister climates than the Arenosols in what in West Africa is called the Sudanian ecological zone. The arable Luvisols may have sandy, loamy or clayey textures, and occur on level to rolling surfaces. They are extensive in semi-arid tropical Africa, South Asia and South America. The red soils of India are preponderantly Luvisols.

Ferric Luvisols and associated soils occupy more than 1 650 000 km^2 in the region. They are highly-weathered soils occurring on old stable surfaces in Africa, in Brazil, and in Bolivia east of the Andes, and to a lesser extent in south Asia. They are often stony or gravelly and underlain by indurated iron-stone. In sub-Saharan Africa and Zimbabwe they tend to be sandy and occur on flat to undulating landscapes. In East Africa and South America they have

finer textures, and can occur also on rolling topography.

Clay fractions are dominated by kaolinite and other low-activity clays. The clay in at least some part of the argillic horizon of these soils is oxidic, i.e., it has a cation exchange activity of less than 24 meq/100 g of clay (Table 3, Profile D).

Associated soils include Plinthic and Chromic Luvisols, Eutric Nitosols, Ferric Arenosols, Ferric and Orthic Acrisols, Orthic Ferralsols, very shallow soils and hydromorphic and salt-affected soils.

Ferric Luvisols have no direct correlate in Soil Taxonomy. Deep soils of the group would be mostly Oxic Paleustalfs, shallower soils would be mostly Oxic Haplustalfs.

Chromic Luvisols—soils with strong brown to red argillic horizons—and associated soils occupy about 620 000 km^2. They are very extensive in south Asia, where they are derived from rocks of the basement complex. They are extensive in southern central Africa and Brazil—where they are stony and co-extensive with Ferric Luvisols—and also occur in Australia particularly along the east coast, and in western Mexico, where they are generally shallow and stony over calcareous parent materials.

These soils are generally finer textured and have higher activity clays (Table 3, Profile E) than the Ferric Luvisols, and occur more on rolling slopes in drier regions or are derived, in Africa, from more basic parent materials.

Associated soils are Vertisols, Ferric Luvisols, very shallow soils—and severely eroded phases of the Luvisols—and hydromorphic and salt-affected soils.

Nitosols are soils very similar to Chromic Luvisols. They are always fine-textured soils on rolling slopes and occur in small areas throughout semi-arid tropical Australia, India and western Mexico. In Ethiopia and elsewhere in East Africa Eutric Nitosols occur on base-rich rocks in moister climates than Chromic Luvisols.

Chromic Luvisols in the semi-arid tropics may be Haplustalfs, Rhodustalfs or Paleustalfs in Soil Taxonomy. The Luvisol at ICRISAT (Table 3, Profile E) is a Udic Rhodustalf.

Orthic Luvisols, soils with yellow-brown argillic horizons, occur in India, associated with alluvial soils in the Indo-Gangetic plain and in coastal Tamil Nadu. They also occur in Mexico usually as shallow soils on rolling to hilly landscapes. *Plinthic Luvisols*, although less extensive than other sub-groups, are the important soils on the Mossi Plateau of Upper Volta, one of the most densely populated areas of West Africa.

Vertisols

Vertisols occupy 7% of the arable soils in the SAT region. They generally occur on level to undulating slopes. They occupy a large area of central India and of northern Australia where they are contiguous with extensive Vertisols in sub-tropical areas. They also occupy large areas in Ethiopia and the Sudan,

and occur scattered throughout sub-Saharan Africa, particularly in Chad, in Tanzania south of Lake Victoria and elsewhere in East and Central Africa along some of the major rivers. Smaller areas of Vertisols occur in Mexico and central America and in Venezuela. Vertisols are derived from base-rich rocks or colluvium or alluvium derived from these.

Chromic Vertisols are the most extensive group. They tend to occur on more sloping land in better drained conditions and are slightly yellower, browner or redder (Table 3, Profile F) than the Pellic Vertisols (Table 3, Profile G) with which they are usually contiguous. Extensive areas of Chromic Vertisols occur in arid areas outside the semi-arid tropics, particularly in the Sudan.

Associated soils are Vertic, Cambic and Calcic Cambisols, Cambic and Ferric Luvisols, Cambic Arenosols—around Lake Chad only—and, very frequently, hydromorphic and salt-affected soils. Vertisols are often calcareous, contain gypsum or have more than 15% exchangeable sodium in the subsoil.

Chromic Vertisols in the semi-arid tropics are Chromusterts in Soil Taxonomy. Pellic Vertisols are Pellusterts.

Ferralsols

Ferralsols are soils with oxic horizons as defined in Soil Taxonomy. They are the most weathered and extensive soils of the semi-arid tropics, occupying 33% of the region. They generally occur in the wet-dry (sub-humid) sub-region or on very old surfaces. They are most extensive on level to undulating slopes, but occur also on rolling land.

Orthic Ferralsols and associated soils are the most extensive, occupying nearly 3 370 000 km^2. They are yellowish brown to reddish brown in colour and occur mostly on rocks of the basement complex throughout Africa and South America. They occur in Kenya, Uganda and eastern Tanzania, in Mozambique, Malawi and Zambia, in Angola and southeastern Zaire and in Venezuela and Brazil. They are clayey in texture, with varying amounts of sand, but little silt (Table 3, Profile H). They occur on level to rolling slopes.

Many Orthic Ferralsols in the semi-arid tropics, e.g. in Mozambique east of Lake Malawi, occur in highlands and mountainous regions in humid climates. They are not truly soils of the semi-arid tropics, but it has not been possible with the evidence available to separate them accurately from the semi-arid soils.

Associated soils in Africa are other Ferralsols, Nitosols, Ferric and Plinthic Acrisols, Chromic and Pellic Vertisols, very shallow soils and hydromorphic soils. In South America the associated soils are Ferric Arenosols, Ferric Luvisols, Orthic Acrisols, Nitosols and very shallow soils.

Orthic Ferralsols in the semi-arid tropics, i.e. with ustic moisture regimes, equate to the Ustox of Soil Taxonomy. They may be either Haplustox, Eutrustox or Sombriustox. The soil profile in Table 4, Profile H, would

probably be classified as a Typic Haplustox.

Rhodic Ferralsols are red. With associated soils they occupy 520 000 km², mostly on base-rich rocks of the basement complex, on limestones and basic volcanic rocks. They are clayey in texture (Table 3, Profile I) and, as a group, are the Ferralsols of highest agricultural productivity and potential. Because of their high value they are often intensively farmed even on strongly rolling to hilly slopes.

They occur in Kenya, Uganda, northeastern Tanzania, in Mozambique along the shores of Lake Malawi, in Angola and in large areas in Zambia, south-eastern Zaire and Zimbabwe. They occur also in northern Sri Lanka, on the York Peninsula in Australia, in Latin America, and on the volcanic islands and atolls of the Pacific Ocean.

Associated soils are mostly Orthic and Xanthic Ferralsols, Arenosols, Ferric and Plinthic Luvisols; Pellic Vertisols and some hydromorphic soils.

Rhodic Ferralsols are mostly classified as Eutrustox and Haplustox in Soil Taxonomy. The soil profile in Table 4, Profile I, is classified as a Tropeptic Eutrustox.

Xanthic Ferralsols have yellow to yellowish brown oxic horizons. With associated soils they occupy 1 000 000 km² in the semi-arid tropics, mostly in Australia on the York Peninsula, in northeastern Brazil and in Angola. These soils are generally sandy in texture. They occur on acidic rocks of the basement complex, usually in the wettest parts of the semi-arid tropics and in the lower, less well-drained portions of the landscape. *Plinthic Ferralsols* usually occur on the lowest, imperfectly or poorly drained land.

Associated soils are Plinthic, Orthic and Rhodic Ferralsols, Ferric Arenosols, Orthic Luvisols, and hydromorphic soils. The Xanthic Ferralsols would mostly be classified as Haplustox in Soil Taxonomy.

Acric Ferralsols are very highly weathered soils that occur on the central plateau of Brazil. They have extremely low cation exchange capacities (less than 1.5 meq/100 g clay) in the oxic horizon, which usually carries a positive charge. Base saturation is also low. These soils cover more than 600 000 km²; they are often deep, on level to undulating slopes and are comparatively well watered. They are largely unpopulated, but are now coming into agricultural use through the introduction of technologies developed over the last two decades (Lobato and Goedert 1977).

Acric Ferralsols in the semi-arid tropics would be lassified as Acrustox in Soil Taxonomy.

Acrisols

Acrisols, soils with base-poor argillic horizons, are mainly soils of humid regions. They occupy 10% of the semi-arid tropics in the wet-dry (sub-humid) sub-region where seasonal rainfall is high, or in humid areas occurring within the semi-arid region. These soils are often associated with Ferralsols, occurring on steeper slopes or younger erosional surfaces. Population

Table 4. Local name, classification, location and soil profile reference of four benchmark soils of the semi-arid tropics.

Local Name	Classification		Location	Soil
	Soil family in Soil Taxonomy	Soil unit in FAO/ UNESCO Soil Map of the World		
	Sandy Soils of the Sahel			
Dior Soil	Typic Ustipsamment, siliceous, hyperthermic	Cambic Arenosol	Bambey Research Station Senegal	Table 3, Profile A
	Alfisols (Luvisols) of Peninsuar India			
Patancheru series	Udic Rhodustalf, clayey-skeletal, mixed, isohyperthermic	Chromic Luvisol	ICRISAT Center, Patancheru, AP, India	Table 3, Profile E
	Vertisols of the Deccan, India			
Kasareddipalli series	Typic Pellustert, fine montmorillonitic, isohyperthermic	Pellic Vertisol	ICRISAT Center, Patancheru, AP, India	Table 3, Profile G
	Oxisols (Ferralsols) of Brazil & Hawaii			
Jaiba	Tropeptic Eutrustox, clayey, kaolinitic, isohyperthermic	Rhodic Ferralsol	EPAMIG Experimental Farm, Jaiba, M.G. Brazil	Table 3, Profile I
Wahiawa series			Wahiawa, Oahu, Hawaii, USA	

densities are low, and the soils are generally better suited to tree crops or pastures than to annual crops.

Orthic Acrisols and associated soils occupy more than 820 000 km^2. They generally have brownish A horizons over reddish B horizons with low to moderate cation exchange capacities. They occur on late Tertiary or younger erosional surfaces derived from acid rocks. They are extensive in South America, in Bolivia east of the Andes, on the central uplands of Brazil and in Venezuela north of the Orinoco River. They occur in Africa in the Ivory Coast, Ghana and Nigeria, and in southwestern Tanzania, in Mexico, in northeastern

Thailand and in small scattered areas in the rest of the semi-arid tropics.

Associated soils are Orthic Ferralsols, Ferric and Plinthic Acrisols, Ferric Arenosols and some Cambisols, usually on even younger erosional surfaces.

Orthic Acrisols in the semi-arid tropics would mainly be classified as Haplustults, Rhodustults, or Paleustults in Soil Taxonomy. It is possible that some of these soils in higher rainfall areas would be classified as Udults.

Ferric Acrisols, Paleustults or Haplustults, and associated soils occupy 560 000 km^2 mostly in northern Nigeria, eastern Tanzania, central Burma and Thailand. The soils occur mostly on flat to undulating landscapes, are well watered, deep and gravelly with sandy textures. Exchange capacities and base saturations are low, but like the Acric Ferralsols of Brazil, the Ferric Acrisols seem to be worth more research attention. These soils in north-eastern Thailand have been exploited widely and profitably in recent years for the production of cassava for animal feed.

Plinthic Acrisols are soils with poor or imperfect drainage either because they are low-lying or because they have indurated subsoils. They occupy 420 000 km^2 under forest or savanna, particularly in South America and mostly in recent sediments overlying crystalline rocks.

Other Soils

Many other kinds of soils occur in the vast area of the semi-arid tropics. Most important are the *Fluvisols* (Fluvents) that occupy 900 000 km^2 in the floodplains of rivers. Associated with these are *Cambisols* (Inceptisols), often vertic, on more stable terraces. The soils are usually silty to clayey in texture, occur on level to undulating terrain and are intensively used for irrigated agriculture.

Kastanozems, or Ustolls, occur in Mexico, Bolivia and Paraguay around the fringes of arid zones. The soils are often shallow and stony on rolling to steep slopes and are generally unsuited to arable farming. Where they are suited, they are used for the production of cereals and vegetables. They are relatively high in natural fertility, have good structure and respond well to irrigation.

Salt-affected soils, Solonchaks, Solonetz and related hydromorphic soils occur widely throughout the region, particularly under rainfalls greater than 800 mm. They usually occur as associated soils or inclusions in areas of more extensive soils. They occur in large areas in depressions and swampy areas throughout the region. Where the salt content is low, they are much used for the production of rice.

Use and Management in Arable Farming

It is not possible to describe in a review paper the use and management of all the kinds of soils in the semi-arid tropics. To generalise at the level of the units of the legend to the Soil Map of the World would introduce many inaccurate and unsubstantiable statements. I have chosen instead to focus on

four extensive and different groups of soils, somewhat representative of the dominant arable soils, viz. Arenosols, Luvisols, Vertisols and Ferralsols, in the semi-arid regions of Africa, Asia and America. The four groups are the sandy soils of the Sahel, the Luvisols (Alfisols) of peninsular India, the Vertisols of the Deccan, India, and the Ferralsols (Oxisols) of Brazil and Hawaii.

To illustrate potential yields and measures to increase yields in rainfed farming, I have focused more narrowly on one benchmark soil classified at the family level in Soil Taxonomy in each of the four groups. The soil family provides the link between soil classification and soil use. The family groups 'the soils within a subgroup having similar physical and chemical properties that affect their responses to management and manipulation for use. The responses of comparable phases of all soils in a family are nearly enough the same to meet most of our needs for practical interpretation of such responses.' (USDA Soil Survey Staff 1975, p. 80).

The four soil families, their classifications in the legend of the FAO/UNESCO Soil Map of the World, local names, and locations are given in Table 4. The four soil groups and their benchmark soil representatives illustrate the problems of and possibilities for rainfed farming in the semi-arid tropics.

Although irrigation could help significantly, the potential for large-scale irrigation in the region is quite limited. (OECD 1976; Ministry of Agriculture and Irrigation, New Delhi, 1976; Sanchez and Cochrane 1980) most of the arable land will continue to be cropped in rainfed conditions.

The Sandy Soils of the Sahel

Sandy Alfisols, Ustipsamments, and related hydromorphic soils also containing much sand are the dominant soils in the Sahelian ecological zone of the semi-arid tropics. They occur in the driest parts of the region on level to gently rolling topography. Natural vegetation is dry savanna, population is sparse and subsistence agriculture is the rule, except in the immediate vicinity of cities and towns.

Towards the arid zone boundary, the soils are used for extensive grazing by transhumant livestock. Even in the more settled areas, animal grazing is important in the total farming system.

These soils are used in traditional agriculture to produce staple cereals of pearl millet and, to a lesser extent, sorghum intercropped with cowpeas. Cash crops such as groundnut, bambara nut and sorrel are grown on small fields as sole crops. Cassava is also grown where it can be protected from livestock and given some supplementary water soon after planting.

Fertilisers and improved seeds are seldom used, but animal manure and household refuse are used on the fields nearest the homes. Bush fallowing and burning return some fertility to other soil. Cropping intensities seldom exceed 75% (0.75 crops per year per field) except for the land closest to the homes.

Land far from the village may be cropped only one year in four. The use of animal traction is not common and soils are seldom ploughed. All agricultural operations are done manually and are very time-consuming. Crop yields are low—the average for most crops is 600 to 700 kg/ha or less—and declining (Swindale *et al.* 1981). There is serious concern in the region about increasing food deficits (IFPRI 1977; USDA 1981).

Potential Yields. It is difficult to find satisfactory data to show the true potential of these soils. Although much work, ably summarised by Ahn (1970, 1977), Charreau (1974, 1977) and Jones and Wild (1975), has been done in the savanna region of West Africa, the reports often leave important factors—particularly soil water—unspecified, the identification of the soils at experimental sites is rarely given or the duration of the experiments appears to be insufficient to provide response probabilities over time. Not the least of the problem appears to be an underlying belief among some researchers that these soils should not be used in continuous agriculture. To quote one reference, 'the question whether continuous cropping will be possible under all conditions without the use of "resting" crops or bush fallows cannot yet be answered'. (Jones and Wild 1975, p. 216).

Blondel (1971) records yields of about 2000 kg/ha of pearl millet on the Dior soil, a siliceous, hyperthermic Typic Ustipsamment at the Bambey Research Station, Senegal. (Table 3, Profile A, and Table 4). Nicou (1977) records 2000 kg/ha of groundnuts on the same soil. Singh (private communication) records 1600 kg/ha of pearl millet on a similar soil at Maradi, Niger.

These very sandy soils in climates with only 3½ wet months (cf. Table 1, No. 1) are close to the bottom of any scale or index of soil suitability for rainfed cropping. The suitability would increase with increasing clay content in the soil.

Figures on profitability under intensive agriculture are not available. Charreau (1974) has given figures to show that semi-intensive agriculture, with basal dressings of rock phosphate and moderate dressings of N and K fertilisers plus deep tillage, did not give better economic returns than traditional agriculture.

Increasing Yields. Low fertility, lack of water and poor physical conditions are constraints to crop production on the sandy soils of the Sahel. The soils are generally low in organic matter, N and P (Jones and Wild 1975; Ahn 1977). Potassium, sulphur and zinc deficiencies show up quickly if the soils are put to intensive use.

Blondel (1971) and IRAT/Senegal (1972) recommended 50 to 60 kg N/ha for pearl millet on the Dior soil with a comparatively high N efficiency index of about 20 kg grain/kg N. Nitrogen management can be difficult because the soil has low buffering capacity. It can be acidified easily by ammonium sulphate and urea. The problems have been well summarised by Charreau (1974). Losses of N due to volatilisation may occur if the fertiliser is not

properly covered, and leaching losses occur in wetter years or under irrigation.

Phosphate deficiencies can be fairly easily corrected. Rock phosphate, which is widely available throughout the region, is used to improve the general phosphate level in the soil. Its usefulness can be upgraded by fine grinding. Phosphatic fertilisers are used for annual dressings. The soil has low phosphate-fixing capacity.

The Dior soil has an erratic annual rainfall of 651 mm, an atmospheric water demand of 1739 mm (Table 1) and less than 100 mm/m of plant-available soil moisture. Lack of water is clearly the greatest constraint to intensified cropping.

Although the soil is often several metres deep, and most of the water throughout the profile is potentially available to plants, pearl millet, the main cereal crop, does not appear to exploit water much below 1 m (Dancette 1971).

The water constraint can be overcome to some extent by harvesting the water over a large area by low density extensive cropping, or perhaps over a large depth by using deep-rooted plants. Stroosnidjer (1977), working with fertilised native grasses in Mali, has suggested that nutrients, not water, are the limiting constraints in these sandy soils. There is obviously need for more thorough investigation of this crucial point.

Variation in texture down the profile, e.g. in Ustipsamments derived from alluvial sands or in soils with clay lenses or lamellae in the profile, will improve the water-holding capacity of the soil. Ustalfs will also have higher water-holding capacity at depth. Charreau and Nicou (1971) recorded 210 mm available water in the rooting zone of pearl millet in a sandy Paleustalf also at the Bambey Station.

The Dior soil has poor structural stability at the surface. When dry it is susceptible to wind erosion. It is not particularly susceptible to erosion by water, but total porosity is around 40% (Charreau 1974) and the infiltration rate decreases sharply and runoff increases with saturation. Rainfall intensities can also be very high for brief periods. Incorporation of crop residues would be a beneficial practice. Tied ridges can be used to increase the contact time of the rain at the soil surface.

A major physical problem is the tendency for the surface horizon to harden when the soil dries out at the end of the rainy season. When the problem is severe, the soil can become so hard that oxen cannot pull a plough through it. The problem increases exponentially with increasing clay content and increasing bulk density to a limit of about 18% clay if the clay contains 2:1 minerals (Nicou and Charreau 1980). A related problem is the impedance to shoot and root growth. Charreau and Nicou (1971) reported that sorghum yields decreased linearly by 450 to 600 kg/ha for every 4% decrease in porosity.

Deep ploughing is strongly recommended by Charreau (1974). It helps overcome the low porosity and the hardening of the soil after rains and allows

improved root proliferation, exploitation of soil water at greater depth and higher yields. Charreau (1977) suggests that the benefits of deep tillage are gained only with soils with weak structure containing much fine sand and low-activity clays. Thus, meaningful and consistent results are obtained only if proper characterisation of the soil is undertaken first.

The Alfisols (Luvisols) of Peninsular India

Haplustalfs and Rhodustalfs (Chromic Luvisols) are the predominant red soils of semi-arid tropical India. They occur mostly in the south in the states of Andhra Pradesh, Karnataka and Tamil Nadu on gneisses and indurated and metamorphosed rocks of Precambrian age, mostly on undulating to rolling topography. The rainfall on these soils varies from about 600 mm to the upper limit of the semi-arid tropics. Natural vegetation is mostly destroyed, but probably was tall grass savanna and deciduous forest. Population density is high but not as high as on the Indo-Gangetic Plain in northern India or along the coasts.

Mixed arable farming is the rule with some crops produced almost entirely for home consumption and others for the market. Animal production for meat and milk utilises virtually all the rural land not used for crops. The land is both over-populated and over-grazed.

In rainfed agriculture, sorghum, pearl millet and finger millet are the major cereals; pigeonpea, mung bean and urd bean the major pulses; castor and, to a lesser extent, cotton, the major cash crops. Intercropping with as many as four or five crops together, usually combining at least one cereal and one pulse, is very common. Almost all the arable land is cropped each year during the rainy season (Jodha 1980). Where irrigation is available, mostly from dug wells or tanks, paddy is grown on imperfectly to poorly drained soils and cash crops such as groundnut or tobacco on the better drained soils. Sole cropping then largely replaces intercropping. Cropping intensities rise to 120% but seldom higher.

Fertilisers, agricultural chemicals and improved seeds are used only where the land is irrigated. Land preparation, even in the drylands, is carried out with steel-tipped implements drawn by bullocks. Seeding and weeding are done partly by bullock-drawn implements and partly by manual labour. Yields are low in traditional agriculture, approximately 400 to 600 kg/ha—about the same as in the sandy soils of the Sahel.

Potential Yields. The All India Coordinated Research Project on Dryland Agriculture (AICRPDA) has obtained data that reveal the potential yields at several locations in southern India on Ustalfs (Randhawa and Venkateswarlu 1980). At Hyderabad, at two separate sites on similar soils (Udic Rhodustalfs), AICRPDA and ICRISAT have obtained average yields over several years of about 3500 kg/ha of hybrid sorghum (CHS-6) (Randhawa and Venkateswarlu 1980; ICRISAT 1980). AICRPDA on the same soil averaged 1500 kg/ha of improved (Aruna) castor. At Bangalore on an Oxic

Haplustalf, AICRPDA obtained 2700 kg/ha of finger millet averaged over a 4-year period.

Profitability is increased several-fold by the use of improved practices. At ICRISAT in five field-scale experiments over a 4-year period (1976-1979) using several crops, average gross returns rose from Rs.1403/ha under simulated traditional practices to Rs.3823 using improved seed, fertiliser and management. Average gross profits rose from Rs.424/ha to Rs.2625 (Table 5). The average gross profit when irrigation was included was Rs.2281/ha.

Increasing Yields. Nitrogen and phosphorus are the major nutrient deficiencies in the Patancheruvu soil, a clayey-skeletal, mixed, isohyperthermic, Udic Rhodustalf (Table 3, Profile E, and Table 4) at ICRISAT Center. The deficiencies are easily corrected using chemical fertilisers with or without additions of farmyard manure (ICRISAT 1976). Applications of 40 to 60 kg N/ha and 5 to 10 kg P/ha are recommended for improved cultivars of sorghum or pearl millet. Local cultivars also respond to fertiliser applications, but fertiliser alone produces a profit increase of only 60% over the control (Table 5, treatment 3), and will not be economical in all years. The real benefit comes when fertilisation is combined with improved management, meaning accurate and timely seed and fertiliser placement and good weed control or improved varieties or, preferably, both.

The soil at ICRISAT is underlain by strongly weathered parent rock (*murram*) at variable depth. The infiltration rate and available water of the soil are equally variable. When the *murram* layer is below 1.5 m, there are 110 mm of available water in the first metre of depth; most of this (69 mm) is held in the upper 60 cm (ICRISAT 1978).

Table 5. Average gross returns to improved technology, inputs and gross profits (Rs/ha) on the Patancheruvu soil (Udic Rhodustalf) at ICRISAT, 1976-1979.

Treatment No.	Description of treatment				Average		
	Seed	Fertiliser	Management	Irrigation	Gross returns (Rs/ha)	Inputs (Rs/ha)	Gross profit (Rs/ha)
1.	Local	Local	Local	No	1403	979	424
2.	Local	Local	Improved	No	1919	968	951
3.	Local	Improved	Local	No	1872	1176	696
4.	Local	Improved	Improved	No	2853	1149	1704
5.	Local	Improved	Improved	Yes	2977	1371	1606
6.	Improved	Local	Local	No	1887	1024	863
7.	Improved	Local	Improved	No	2277	1011	1266
8.	Improved	Improved	Local	No	2295	1206	1089
9.	Improved	Improved	Improved	No	3823	1198	2625
10.	Improved	Improved	Improved	Yes	3676	1395	2281

Mean annual rainfall on the Patancheruvu soil is 893 mm, the atmospheric water demand is 1757 mm. Seventy-five percent of the annual rainfall occurs in the 4-month rainy season. About 50% of the seasonally available water is lost through evaporation and drainage. Root extraction experiments, even with vigorously growing crops, show that most of the water used by the plant comes from the upper 60 cm of the soil. There is, therefore, considerable scope for increasing the soil water harvest for greater crop yields and resistance to short periods of drought within the rainy season.

The soil has poor structural stability at the surface and when cropped, it is quite susceptible to erosion by water. Mulches can be recommended, but are not really practicable because at present almost all crop residues are used for animal feed. The soil also has problems with surface crusting which reduces infiltration, affects seedling emergence and reduces plant stands. Bullock power is sufficient to break the crust, but the crust reforms after rain. No satisfactory technology exists so far for dealing permanently with this problem.

Land management research has failed so far to find satisfactory methods of land preparation suited to Indian conditions to prevent runoff and erosion from this soil when the soil is not covered. Contour bunds reduce runoff and erosion from watersheds as a whole but not from the area between the bunds. Contour bunds also lead to waterlogging of the soil immediately above the bund. Narrow ridges break down easily in heavy rains. Broad ridges and furrows, much investigated by ICRISAT (Kampen and Krantz 1977), although providing advantages in improved seed and fertiliser placement, weed control and supplementary irrigation, lead to increased runoff and erosion. Where the runoff water is collected in small reservoirs, it can be re-used on the fields for life-saving irrigation, but the soil loss is severe and damaging.

Because the water-holding capacity of this soil is too low to allow post-rainy season cropping, efforts are being made to extend the cropping season through the use of intercropping or relay planting or by shortening the cereal growing season by transplanting seedlings. Some promising cropping systems have been identified (Table 6). Combinations involving castor gave maximum net returns. For food crops the extended cropping systems gave higher net returns than sole crop.

The Vertisols of the Deccan, India

The Vertisols and associated soils (Black Cotton soils) of the Deccan are the major resources for dryland agriculture in India. They extend over a vast area of the northern peninsula, from Gwalior in the north to Raichur in the south, extending through six states.

The soils are developed *in situ* from the Deccan trap rocks (mostly augite basalts) and other base-rich rocks and from colluvium and alluvium derived from these. Most of the soils lie between 300 and 900 m above sea level on flat

Table 6. Extended cropping on Alfisols, 1978-79.

Cropping system	Yield (kg/ha)		Total gross value (Rs/ha)	Net returns (Rs/ha)
	Crop 1	Crop 2		
Pearl millet + Horse gram (sequential)	1940	616	2168	1079
Mung bean + Castor (relay)	634	885	2772	1514
Sole Castor	1462	—	2485	1630
Sorghum + sorghum (ratoon crop)	2516	505	2417	1322
Sorghum/pigeonpea (intercrop)	2169	417	2694	1584
Pearl millet/groundnut + safflower intercrop	849	208	2347	1119
Sole millet	1940	—		753
Sole sorghum	2506	—		1118

Source: ICRISAT 1979, 1980.

Value for 100 kg pearl millet Rs. 80; mung bean Rs. 200; sorghum Rs. 80; pigeonpea Rs. 230; groundnut Rs. 150; safflower Rs. 175; horse gram Rs. 100 and castor Rs. 170. Costs of seeds, fertilisers, operations, insecticides and initial land preparation are deducted for the estimation of net returns.

to undulating surfaces. Natural vegetation is dry, deciduous forest, but most of the soils are now under cultivation. Rural population densities on these soils are about the same as on the Alfisols to the south.

Sorghum, maize and pearl millet are the main cereal crops under dryland farming; pigeonpea, mung and chickpea are the main pulses; safflower the main oilseed; cotton the main industrial crop. Soybean production is increasing on the wetter soils. Sugarcane, paddy, wheat and cotton are grown under irrigation. Intercropping is common in rainfed agriculture (Jodha 1980). Although many crops are grown together, the major combinations are sorghum and pigeonpea, cotton and pigeonpea and cotton, sorghum and pigeonpea. The mixtures usually combine crops with different maturity lengths, drought-sensitive with drought-resistant crops, cereals with legumes and cash crops with food crops.

Much of the land is fallowed in the rainy season, either because the rainfall is erratic or so high that it causes problems in land management. Milk production from extensively grazed sheep and goats is important on these soils.

Fertilisers and agricultural chemicals are used almost entirely on irrigated crops. The use of fertilised hybrids of sorghum and cotton is slowly spreading in dryland agriculture.

Land preparation using bullock-drawn implements is usually limited to loosening of the surface soil in February or March or before the soils dry out too much. The use of a blade harrow to break up the soil and remove weeds just before planting is common. Yields are low, about 800 kg/ha for

unirrigated sorghum.

Potential Yields. The potential of these soils significantly exceeds current average yields. Sorghum yields of 4600 kg/ha and maize yields of 3100 kg/ha have been obtained in intercrops with pigeonpea over 3 years without irrigation on a Typic Pellustert at ICRISAT. Higher yields, often exceeding 5500 kg/ha of sorghum, are obtained with sole crops. AICRPDA has averaged 4300 kg/ha of maize as a sole crop for 5 years at Indore on a Typic Chromustert (Randhawa and Venkateswarlu 1980).

Realisation of part or all of the potential greatly increases profitability. Five field-scale experiments over 4 years (1976-1979) at ICRISAT, using several crops, gave gross returns of Rs.1716/ha under simulated traditional practices and Rs.4802 using fertilisers, improved seeds and improved management. Average gross profits rose from Rs.486/ha to Rs.3245 (Table.7). The use of supplementary water increased profits to Rs.3812.

Because the soils have excellent water-holding capacities, improved cultivars plus fertiliser gave significant increases in gross returns and profits (see Table 7, treatment 8), but the additional use of improved soil and water management was needed to obtain maximum returns. The increases in gross returns and profits are even greater when compared with the traditional cultivation of a post-rainy season crop only.

Increasing Yields. At ICRISAT Center on Kasareddipalli soil, a fine, montmorillonitic, isohyperthermic Typic Pellustert (Table 3, Profile G, and Table 4), crops respond to the application of N, P and zinc. Profitable responses by improved cultivars were obtained with 80 kg N and 5 kg P/ha. Maize proved more responsive than either sorghum or pearl millet.

Table 7. Average gross returns to improved technology, inputs and gross profits (Rs/ha) on the Kasareddipalli soil (Typic Pellustert) at ICRISAT, 1976-1979.

Treatment No.	Description of treatment				Average		
	Seed	Fertiliser	Management	Irrigation	Gross returns (Rs/ha)	Cost of inputs (Rs/ha)	Gross profit (Rs/ha)
1.	Local	Local	Local	No	1716	1230	486
2.	Local	Local	Improved	No	2147	1116	1031
3.	Local	Improved	Local	No	2385	1576	809
4.	Local	Improved	Improved	No	3003	1491	1512
5.	Local	Improved	Improved	Yes	3374	1745	1629
6.	Improved	Local	Local	No	2610	1273	1337
7.	Improved	Local	Improved	No	3069	1225	1844
8.	Improved	Improved	Local	No	3891	1672	2219
9.	Improved	Improved	Improved	No	4802	1557	3245
10.	Improved	Improved	Improved	Yes	5623	1811	3812

The soil has high available water-holding capacity. Rainfall and atmospheric water demand are the same as for the Patancheruvu soil, but crops are less prone to drought than crops grown on sandy soils or on most Alfisols. There is 165 mm of water available to crops in the first metre of the fully charged soil and over 300 mm of available water in the soil depth of 1.8 m. Virtually all of this water is available to plants but lack of full root penetration below 40 cm depth reduces the usage by about 30% (ICRISAT 1978, Fig. 74). For example, in 1978, a wetter-than-average year, a deep-rooting pigeonpea crop used 327 mm of water from 4 September until harvest on 21 December; 146 mm from rainfall during the period and 181 mm from soil moisture. At harvest time available soil water in the top 50 cm was essentially depeted, the available water from 50 cm to 1 metre was about 75% depleted and the available water in the final 81 cm was half depleted by the crop. Root densities below 1 m were low (ICRISAT 1980. p. 179). The hydraulic conductivity is low—of the order of 1 mm/day at 100 millibars soil moisture tension—and vigorous root growth is necessary to exploit the soil water at depth.

The infiltration rate of the dry soil is very high (70 mm/hour) because of the many cracks. The permeability drops to very low values (0.2 mm/hour) once the soil is saturated. Under a transpiring crop the surface cracks open after a few days without rain. For this reason runoff from cropped Vertisols is usually less than runoff from cropped Alfisols.

The soil is very susceptible to erosion. Land treatment, particularly the use of ridges or broadbeds or bunds can reduce soil loss by 50% or more, but crop cover even without land treatment greatly reduces soil erosion. (Binswanger *et al.* 1980). The use of ridges, broadbeds or graded bunds also helps in improving surface drainage, which is often a problem during the rainy season.

The common traditional practice of fallowing the land during the rainy season leads to severe runoff and loss of soil. In a wet year as much as 10 tonnes of soil may be lost from fallowed land. Furthermore, cropping in the post-rainy season only, almost entirely on soil-stored moisture, puts the plants under moisture stress even on these soils and yields are significantly less than in the rainy season (Sivakumar *et al.* 1979).

The cropping and profitability of many Vertisols can be increased by improved intercropping or sequential cropping. At ICRISAT maize/pigeonpea or sorghum/pigeonpea have proved to be useful combinations of crops. The cropping season is extended by more than 2 months and the combination gives 60 to 70% advantage over sole cropping in terms of land productivity. Examples of sequential cropping combinations for the same soil are maize/chickpea or maize/safflower. (Natarajan and Willey 1980).

In dry years crops come under drought stress. In wet years, waterlogging is a problem. A solution to both can be found by making use of the natural

topography and drainage patterns. The small watershed is a natural framework for resource development aimed simultaneously at stabilising and increasing crop production through more effective use of available water and at resource conservation through *in situ* conservation measures.

At ICRISAT over the last 8 years a technology for land and water management on Vertisols using graded broadbeds and furrows within small watershed units has proved successful in achieving both the above objectives (Kampen 1980). The experiments have experienced 2 years of drought (1973-1979) and 2 years of excessive rainfall (1975 and 1978).

The 150-cm-wide beds are graded across the contour to a 0.6% slope and are separated by furrows that drain into grassed waterways. The broadbeds are not likely to be breached in heavy rainfall, and allow a flexible planting pattern in rows spaced at 30 cm, 45 cm, 75 cm or 150 cm. They reduce runoff under both fallow and cropped conditions and greatly reduce soil erosion in comparison with ungraded fallow soils (Binswanger *et al.* 1980). The use of graded broadbeds and furrows gives gross returns and profits five to six times greater than traditional systems (Ryan and Sarin 1981). They can be established successfully within existing field boundaries at some loss in profits.

Dry seeding of the crop about 2 weeks before the onset of the rains is possible on these soils if the early rainfall is fairly reliable (Virmani 1980) and in most years enables intercropping of short-season and long-season crops, or the taking of a post-rainy season crop, thereby increasing greatly the gross returns, profits and the rainfall use efficiency.

The Oxisols of Brazil and Hawaii

The red and reddish-brown soils of semi-arid Brazil and Hawaii are Haplustox and Eutrustox; Orthic and Rhodic Ferralsols in the Soil Map of the World. Camargo and Falesi (1975) call the Brazilian soils Dark Red and Dusky Red Latosols.

Haplustox occur on a wide range of rocks on level to rolling slopes. Eutrustox, much less prevalent than Haplustox, occur mainly on base-rich sedimentary volcanic rocks. Natural vegetation is savanna or dry deciduous forest. Population density in the rural areas is low.

In traditional agriculture in Brazil the soils are used in shifting cultivation for the production of cotton, castor, maize and beans. Many of the soils lie virtually unused, particularly those with low pH values and high exchangeable aluminium.

Potential Yields. The potential of these soils is high. It has been realised in Hawaii under irrigation and is now being realised in Brazil under rainfed conditions. Sanchez and Cochrane (1980) estimate that about 5 million ha of extensive pastureland in Central Brazil have been converted into intensive cropland in the last 10 years. Upland rice, soybeans, coffee and irrigated wheat in the winter season are the main crops.

In Hawaii, Tropeptic Eutrustox and Haplustox are used in the production

of pineapple and irrigated sugarcane. Pineapple yields of 90 to 110 tonnes/ha are obtained for the 20- to 25-month plant crop and 40 to 90 tonnes/ha for the ratoon crop of a similar duration. The crop is largely rainfed. Sugarcane yields under irrigation may exceed 250 tonnes cane/ha for a 20- to 25-month crop; sugar yields are 30 to 40 tonnes/ha.

Experiments with irrigated maize on these soils in Hawaii and Brazil by the Benchmark Soils Projects of the Universities of Hawaii and Puerto Rico have given yields of 8000 to 11 000 kg/ha. With adequate irrigation and fertiliser applications, Tropeptic Eutrustox constitute some of the most productive soils in the tropics (Benchmark Soils Project 1979a).

Increasing Yields. Sanchez and Cochrane (1980, Table 6) indicate that general nutrient deficiencies, high P fixation, aluminium toxicity, low water-holding capacity and soil water stress for more than 3 months are the major constraints to increasing yields on the Oxisols of semi-arid tropical America. The chemical deficiencies and toxicities can be corrected but the cost is high. Farmers prefer to develop the more fertile soils, presumably the Eutrustox, if the climate is not too dry.

Nitrogen is fairly high in Eutrustox under natural vegetation, but is quickly depleted in cropping and becomes a constraint to continuous production. Because the buffering capacity of these soils is fairly low, care is needed in N management to prevent acidification. Under irrigation, responses by improved cultivars of maize have been obtained up to N levels of 120 kg/ha or more on a Jaiba soil, a clayey, kaolinitic, isohyperthermic Tropeptic Eutrustox (Table 3, Profile I and Table 4). Phosphorus is low in this soil, which has a moderate ability to fix P in forms unavailable to plants; this fixed P is released slowly to later crops. Thus the response to P depends on the previous cropping history: where P has not previously been applied, responses by improving cultivars of irrigated maize have been obtained up to 25 kg P/ha (Benchmark Soils Project 1979a). Potassium is not limiting on this soil, but small maintenance dressings are needed in highly intensive agriculture.

The water available to plants between 0.3 and 15-bar soil moisture tension in this soil is about 110 mm/m. However, 100 millibars is probably a better approximation to field capacity in these soils (Wolf 1975; El Swaify 1980, p. 314). Judging from Hawaiian soils in the same family (cf. Sharma and Uehara 1968; Tsuji *et al.* 1975; El Swaify 1980) the total available water-holding capacity of the soil is probably closer to 150 mm/m. The Jaiba soil has a mean annual rainfall of 895 mm and an atmospheric water demand of 1648 mm.

Because the hydraulic conductivity is fairly low—of the order of 1 mm/day at 100 millibars soil moisture tension—the available water even in deep soils of the family can only be exploited by vigorous root growth. Except for xerophytic plants like pineapple, crops can be grown on these soils only during the rainy season in rainfed agriculture and even then some supplemental irrigation will be needed for maximum production.

Infiltration rates are high on these soils and structural stability is excellent. Erosion susceptibility is low and trafficability high. The soils display mechanical behaviour which does not reflect their true particle size distribution (El Swaify 1980). Because of the high aggregate stability and inactive clays, there is little swelling of clay with change in base status. Low-quality irrigation waters can be used safely on these soils. (El Swaify *et al.* 1977).

Conclusion

Soil qualities, traditional yields and potentials for use under high management in rainfed farming of the four soil families are summarised in Table 8. The potential yield shown is an estimate based on experimental data of the average yield obtainable over time in rainfed agriculture. The differences in potential are due in part to the inherent properties of the soils themselves and their environment, in part to genetic limitations in the best adapted cereal and in part to the state of technology relevant to each. Even the best can be improved.

The difference in potential between the Typic Ustipsamment, Udic Rhodustalf and Typic Pellustert is adequately indicated by the combination of rainfall and available soil water. Solar radiation is needed to explain the greater potential of the Tropeptic Eutrustox. Stochastic water balance calculations incorporate these three characteristics and help quantify the risks in rainfed arable farming (Virmani *et al.* 1980; Franquin 1980). For example, Virmani *et al.* (1980) have shown that the growing season at ICRISAT is 4 to 6 weeks longer on the Vertisol than on the Alfisol under various rainfall probabilities (Table 9).

The potential of the Typic Pellustert is somewhat under-estimated in Table 8, because neither sorghum nor maize fully exploit the water-supplying capacity of this soil. Intercropping the cereal with a long-season crop like pigeonpea utilises soil water more efficiently and increases the potential by 60 to 70% (Natarajan and Willey 1980). Were the potential to be expressed in profit terms, the difference between the Typic Pellustert and Tropeptic Eutrustox would be lessened because of the higher fertiliser requirements of the latter.

Other soils in the region—Haplustox, Acrustox, and the more weathered sub-groups of Ustults—particularly in the wet-dry semi-arid tropics, have high to very high nutrient requirements that limit productivity. The problems can be corrected technically if not always economically. Very low cation exchange capacities occur in Acrustox and Ustipsamments and some Haplustox, Ustults and Ustalfs, and, like physical limitations, are difficult to correct. Sanchez and Buol (1975) have proposed that efforts be concentrated on the better soils in each sub-region. It may at least be wise to proceed gradually, one step in technology at a time, after first ascertaining which steps to take first, as has been done at ICRISAT and illustrated in Tables 5 and 7.

Table 8. Management characteristics and unirrigated yields for four soil families in the semi-arid tropics (SAT).

Soil family	Solar radiation (PE)	Annual rainfall (mm)	Available soil water (mm) in first metre	Nutrient requirements (kg/ha)	Soil toxicities	Workability	Erosivity	Main cereal	Drought susceptibility with main cereal	Yields—unirrigated	
										Traditional (kg/ha)	Estimated potential (kg/ha)
Typic Ustipsamment, siliceous, hyperthermic	High	Low	Low	Moderate	Low	Fair	Low	Pearl millet	High	400	2500
Udic Rhodustalf, clayey-skeletal, mixed, isohyperthermic	High	Moderate	Low	Moderate	Low	Good	Moderate	Sorghum	Moderate	600	3500
Typic Pellustert, fine, montmorillonitic, isohyperthermic	High	Moderate	High	Moderate	Low	Poor	High	Sorghum Maize	Low Moderate	700 ?	5500 4500
Tropeptic Eutrustox, clayey, kaolinitic, isohyperthermic	Very high	Moderate	Moderate	Moderate to high	Low	Excellent	Low	Maize	Moderate	?	8000

Table 9. Length of the growing season (in weeks)[a] on the Alfisol and Vertisol at ICRISAT under three rainfall probabilities.

Rainfall probability	Alfisol	Vertisol
Mean	21	26
75%	19	23
25%	24	30

Source: Virmani *et al.* (1979).

a. From seed-germinating rains—25 June—to end of season—time when soil moisture stress reduces to 0.5 the ratio of actual evapotranspiration to potential evapotranspiration.

Table 10. Annual compound growth rates of five crops in the less-developed countries of the semi-arid tropics, 1964-1974.

Crop	Area (%)	Yield (%)	Production (%)
Sorghum	0.71	2.08	2.81
Millets[a]	0.04	1.20	1.24
Chickpea	−1.29	1.46	0.15
Pigeonpea	−0.08	0.83	0.75
Groundnut	−0.40	0.02	−0.38

Source: Ryan and Binswanger (1980).

a. Includes pearl millet (*Pennisetum americanum*), as well as the minor millets such as *Setarias*, *Panicums*, and *Eleusines*.

The semi-arid tropical region receives ample solar radiation. It is a region of gentle landscapes easily cleared for cropping. Its proven ability to sustain high population densities is an indication of its agricultural value. Food production can be increased in the region without recourse to major irrigation schemes.

For the semi-arid tropics as a whole, yields and production of sorghum, pearl millet and the two major grain legumes are increasing slowly (Table 10). Only for sorghum does the increase in production exceed the average annual increase in population for the region—approximately 2.5%. This paper has tried to illustrate that much more can be accomplished. The long-term prospects for food production seem reasonably good from a technological viewpoint. If buffer stocks are accumulated for distribution in the driest years, the major risk in rainfed farming of the semi-arid tropics will be reduced and the farmers will be able to invest more of their time and resources for the good years. The benefits will be substantial and will pervade a huge and disadvantaged portion of the world's population.

Acknowledgments

Sardar Singh helped obtain the soil physical data in this paper. S.J. Reddy and M.N.S. Bose compiled Figures 1 and 3 and the data for Table 2. J.G. Ryan and R. Sarin provided the data on economic returns. F.H. Beinroth, J.R. Burford, C. Charreau, M. Drosdoff, R. Dudal, S.M. Miranda, R.S. Murthy, K.L. Sahrawat, P.A. Sanchez, J.A. Silva, G. Uehara and A. van Wambeke read the manuscript and contributed comments, advice and data. The help of all these good friends is gratefully acknowledged.

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