Tillage systems and soils in the semi-arid tropics*

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ABSTRACT

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shatter, cut, invert or mix the soil and depending on the objectives, to smooth or shape the surface. This process pulverizes the large clods created during primary tillage and therefore tends to exacerbate the problem of instability of the SAT soils. In certain circumstances, tillage implements will compact the soil, particularly under the plowshare, and smear or puddle soil when the operation is performed in the plastic state. Yet many farmers in the SAT till their soils before sowing, and indeed numerous scientific reports have appeared in many journals indicating the benefits of one tillage system or the other to crop performance even if those benefits may be ephemeral. The objectives of tilling have been cited in many publications to include seed-bed preparation, weed control, improvement of soil–water relations, and reduction of mechanical impedance to root growth. The practice of incorporating crop residues has recently become a less important function of tillage because crop residues can and should be left on the surface as stubble mulch in order to protect the soil against erosion and evaporation.

This review will be concerned mainly with the major soils, tillage systems, and the effects of their interaction with soils on crop production in the SAT including the semi-arid regions of Australia and the U.S.A. (particularly Texas) where conservation tillage systems have been found to be effective in increasing crop yields as well as sustaining the fragile soils.

MAJOR SOILS OF THE SAT

Five out of the 14 soil orders (Ferralsols, Luvisols, Arenosols, Acrisols and Vertisols) occupy about 80% of the arable land area in this region (Table 1). A comprehensive description of these soil orders based on the FAO/UNESCO soil map of the world with a scale of 1 : 5 000 000 is given by Swindale (1982). We will therefore present a brief description of these five main soil orders in this review.

Ferralsols

Ferralsols (equivalent to Oxisols in the US Soil Taxonomy) are the most weathered and extensive soils of the SAT, occupying about 33.5% of the region. Ferralsols are classified as orthic (yellowish brown to reddish brown in color found mostly on basement complex), rhodic (red in color and found mostly on base-rich rocks of basement complex, on limestones and basic volcanic rocks), xanthic (have yellow to yellowish brown oxic horizons, are generally sandy and occur on acidic rocks of the basement complex), or acric (highly weathered with very low cation exchange capacities, i.e. less than 1.5 cmol kg^{-1} clay). Generally Ferralsols occur extensively on level to undulating slopes though some Orthic Ferralsols in the semi-arid tropical regions of Moz-

TABLE I

Distribution of soils on arable lands in the semi-arid tropics from the FAO/UNESCO soil map of the world[1]

Soils	Sandy (km^2)		Silty (km^2)		Clayey (km^2)		Totals (km^2)
	Flat	Rolling	Flat	Rolling	Flat	Rolling	
Fluvisols							
Calcaric	16558	–	66950	–	26729	–	110237
Eutric	37033	–	566458	11458	158474	–	773423
Thionic	1550	–	8942	–	16533	–	27025
Arenosols							
Cambic	284008	34333	4742	–	6917	–	330000
Luvic	104182	25983	7100	3333	7475	–	148073
Ferralic	1285734	169083	24166	26283	–	–	1505266
Albic	90958	23033	–	14617	–	–	128608
Andosols							
Ochric	–	–	2375	2192	2958	–	7525
Mollic	3750	–	–	–	–	–	3750
Humic	–	–	–	3950	–	–	3950
Vitric	14341	32250	2908	43108	–	–	92607
Vertisols							
Pellic	4767	–	13875	9817	295283	–	323742
Chromic	20567	–	13750	9125	788233	168942	1000617
Solonchaks							
Orthic	4500	–	9641	–	–	–	14191
Takyric	–	–	–	–	13992	–	13992
Gleyic	–	–	14316	–	15038	–	29354
Solonetz							
Orthic	11538	11642	32724	15958	32517	–	104379
Mollic	–	–	–	–	4675	–	4675
Kastanozems							
Haplic	122741	7650	1800	27367	–	–	159558
Calcic	–	–	–	46058	–	–	46058
Luvic	–	–	65399	49316	–	–	114715
Phaeozems							
Haplic	–	–	825	12559	658	5750	19792
Luvic	–	–	21991	–	102791	–	124782
Cambisols							
Eutric	20041	–	212601	6342	7458	17991	264433
Dystric	–	–	38441	–	38033	20883	97357
Humic	–	1949	–	–	–	39333	41282
Calcic	–	–	34358	29883	4808	–	69049
Chromic	8275	4150	38275	51941	483	7125	110249
Ferralic	425	550	8525	23916	4375	2175	39966
Vertic	3025	–	8050	591	3918	66767	82351

TABLE I (continued)

Soils	Sandy (km²)		Silty (km²)		Clayey (km²)		Totals (km²)
	Flat	Rolling	Flat	Rolling	Flat	Rolling	
Luvisols							
Orthic	15650	12125	96242	43466	983	4725	173191
Chromic	61925	70397	59358	273759	42490	108382	616311
Calcic	10383	23716	14591	27758	–	–	76448
Vertic	–	–	–	–	650	–	650
Ferric	766176	49192	424898	129631	75367	207808	1653072
Plinthic	76033	–	86007	–	2609	–	164649
Gleyic	79858	–	44291	–	15959	408	140516
Planosols							
Futric	9158	–	41562	–	211958	–	262678
Mollic	1858	–	38058	–	9891	–	49807
Solodic	19258	18375	9817	13708	1933	–	63091
Acrisols							
Orthic	112424	20517	240073	220173	60116	171767	825070
Ferric	242517	28450	194608	96366	–	–	561941
Humic	–	–	3683	467	–	950	5100
Plinthic	11833	–	179208	36916	201725	–	429682
Gleyic	2991	2083	81058	10142	–	29550	125824
Nitosols							
Eutric	5733	3458	38217	160608	15791	202291	426098
Dystric	105167	508	135066	66457	166674	174791	648663
Ferralsols							
Orthic	39266	37925	592628	459599	622049	1621761	3373228
Xanthic	332558	–	548967	8209	203425	2283	1095442
Rhodic	2183	15875	39891	40149	276657	148466	523221
Plinthic	500	–	149150	133200	9999	–	292849
Humic	–	2916	–	1092	129791	14041	147840
Acric	–	–	462191	–	165408	–	627599
Total	3929514	596160	4457776	2109514	3744823	3016189	18073976

[1]Source: Swindale (1982).

ambique east of lake Malawi, occur in highlands and mountains where the climate is humid.

Luvisols

Luvisols have a base-rich argillic B horizon and are second in areal extent, occupying about 15.6% of the SAT. They are extensive in SAT regions of Africa, South Asia and South America. In West Africa, this order is usually found in the Sudanian ecological zone. Luvisols may have textures ranging from sand to clay and usually occur on rolling land surfaces. They may be classified as ferric which are highly weathered soils, often stony or gravelly and underlain by indurated ironstones, chromic having strong brown to red argillic horizons, they are generally shallow and may be stony over calcareous parent materials, or orthic with yellow–brown horizons and associated with alluvial soils in India. Most of the Luvisols cultivated in the SAT are characterized by an unstable structure which is the result of a combination of (1) the prevailing farming practice whereby almost all crop residue is removed from the field and utilized by the farmer, and (2) the inactivity of the dominant kaolinitic clay mineral. Consequently, Luvisols in the SAT tend to exhibit structural breakdown usually from slaking, when they are rapidly wet. This action results in surface sealing, crusting and sometimes hardening of a considerable depth in the soil profile upon drying. This characteristic makes most of the Luvisols difficult to cultivate when dry. It also adversely affects seedling emergence, especially of small seeded crops like pearl millet. Furthermore, it enhances runoff and soil loss because of the reduced infiltration of water in the crusted or compacted zone.

Arenosols

Arenosols are developed in aeolian and alluvial sands overlying basement rocks or indurated iron-stone. They occur extensively on flat to undulating topography in sub-Saharan Africa, in some areas of northern Australia and in Rajasthan (India). They occupy about 11.7% of the SAT. Arenosols may be sub-divided into cambic (coarse-textured soils with some evidence of color or structural B horizon), luvic (intergrades to Luvisols and contain lenses and lamellae with more clay than the remainder of the soil), or ferralic (derived from highly weathered sands, often gravelly and shallow, with a cation exchange capacity of less than 24 cmol kg^{-1} of clay immediately below the A horizon or in some part of the cambic horizon).

Acrisols

Acrisols occupy about 10.8% of the SAT and have an argillic horizon that is poor in bases. They are usually found in SAT sub-regions which are humid or have high rainfall. They may be classified into sub-groups as orthic (which have brownish A horizons over reddish B horizons with low to moderate cation exchange capacities), ferric (mostly found in northern Nigeria, eastern Tanzania, central Burma and Thailand, occur mostly on flat to undulating landscapes, are deep and gravelly with sandy textures and have low exchange capacity and low base saturation), or plinthic (which are poorly drained either because of an indurated sub-soil or are located in depressions).

Vertisols

Vertisols occupy about 7.3% of the SAT. They are deep black soils which, by definition, contain more than 30% clay, their primary diagnostic features are swelling upon wetting and the development of deep, wide cracks upon drying. As a result of this processing profile inversion occurs over time (USDA, Soil Survey Staff, 1975). Vertisols occur on level to undulating slopes in large areas of central India, northern Australia, Ethiopia, Sudan and in scattered areas throughout eastern, central and sub-Saharan Africa particularly in Chad. Vertisols are derived either directly from base-rich rocks, alluvium or colluvium from base-rich rocks. They may be grouped as chromic (which is the most extensive group, and tends to occur on sloping lands), or as pellic (most of which occur in flat areas or depressions). Chromic Vertisols are slightly yellower, redder or browner than their pellic counterpart.

Cultivation practices on Vertisols are particularly affected by their stickiness, low terminal infiltration rate and impeded drainage of the soils when wet. Also its hardness when dry hampers cultivation. Therefore tillage must be timed to coincide with a specific range of soil consistency that allows easy penetration of tillage tools and production of good soil tilth.

TILLAGE SYSTEMS IN THE SAT

In the semi-arid countries of the Mediterranean and the Near East, a wooden or iron plow consisting of a stick with a hardened point is used to till the soil superficially. This plow has no inverting action and is pulled by animals. The farmer usually waits for the rains to soften the soil before he plows because of the limited draft power. Winter cereals are normally sown by broadcasting before the only tillage operation (plowing) is done. For summer cropping, the soil is plowed in the wet winter to control weeds in order to reduce water losses through transpiration. In modern agriculture in this region, e.g. in Israel, tillage is by machinery (Wolf and Luth, 1979). Research emphasis in this region is placed on the design and development of tillage equipment for dryland farming and soil management systems (e.g. scoops or small pits, tied ridges etc.) to enhance water conservation and crop establishment.

In semi-arid India, similar animal-drawn implements as used in the Near East (e.g. the non-inverting "desi" plow) are traditionally used for tillage. Other special tillage tools are the "bakhar" which is a blade harrow used for smoothing soil surface and also for weed control, and a cultivator with tubes attached for sowing. In most parts, sorghum, pearl millet and finger millet are the major cereals grown on the Luvisols; pigeonpea, cowpeas, mungbean and black gram are the major pulses while the major cash crops are castor, cotton, sunflower and groundnut. Intercropping of cereals with pulses or oilseeds is common. However, sole crops or discrete mixtures of these crops may be observed in certain areas (El-Swaify et al., 1985). In areas where water is available from dug wells or tanks, rice is grown on the poorly drained soils, while cash crops like groundnut, sugarcane and tobacco are cultivated on well-drained soils. Tillage is normally done with animal-drawn implements on flat or gently rolling land and involves mainly plowing, harrowing and intercultivation operations to remove weeds and break soil crust, especially at the early stages of plant growth in order to improve the infiltrability of the soil.

Hydrologic studies of the Indian traditional tillage system on a Luvisol conducted at ICRISAT Center (Table 2) have shown that 26 and 33% of seasonal rainfall are lost through runoff and deep percolation, respectively. Only 41% of total rainfall was used for evapotranspiration. Because Luvisols have poor water-retention characteristics, these water losses represent a serious constraint on the productivity of these soils even in short drought spells during the cropping period.

The traditional system of tillage on the Vertisols in most parts of India involves fallowing the land in the rainy season and growing a post-rainy season crop on the stored profile moisture. In this system, the land is harrowed occasionally using animal traction during the rainy season to control weeds. Krantz and Russell (1971), Kampen et al. (1974) and Binswanger et al. (1980) have stressed the undependability of rainfall and risk aversion as important reasons for rainy season fallow in the low rainfall areas of India. In the high rainfall zones (annual rainfall more than 1200 mm) rainy season fallowing is practised because cropping is risky from the standpoint of field flooding and waterlogging. Furthermore, difficulties encountered in tilling the hard clay soils prior to the commencement of rains or sticky wet soil after its onset are some of the reasons for rainy season fallow in high rainfall zones (Michaels, 1982).

Hydrologic studies of this traditional system of tillage (Table 3) indicate

TABLE 2

Water balance components and soil loss for traditional tillage system[1] on Luvisol at ICRISAT Center

Year	Rainfall (mm)	Runoff (mm)	Evapo-transpiration (mm)	Deep percolation (mm)	Soil loss ($t\ ha^{-1}$)
1978–79	1060	391	395	274	5.19
1979–80	671	113	335	223	1.83
1980–81	765	149	345	271	1.62
1981–82	1130	292	415	423	5.61
1978–82[2]	100	26	41	33	3.71[3]

[1]Traditional varieties of sorghum as sole crop and sorghum/pigeonpea as intercrop were grown, plowing and harrowing were done by animal traction. Source: Pathak et al. (1987).
[2]Percentage of rainfall.
[3]Average annual soil loss.

TABLE 3

Water balance components and soil loss for traditional rainy season fallow systems[1] on Vertisols at ICRISAT Center

Year	Rainfall (mm)	Runoff (mm)	Evaporation (fallow rainy season) (mm)	Evapotrans-spiration (mm)	Deep percolation (mm)	Soil loss ($t\ ha^{-1}$)
1976	710	238	169	272	31	9.20
1977	586	53	201	317	15	1.68
1978	1117	410	185	301	221	9.69
1979	682	202	166	272	42	9.47
1980	688	166	175	300	47	4.58
1976–80[2]	100	28.2	23.7	38.5	9.46	6.93[3]

[1]Traditional varieties of sorghum were grown as the post-rainy season crop, land was harrowed occasionally during the rainy season. Source: El-Swaify et al. (1985).
[2]Percentage of rainfall.
[3]Average annual soil loss.

that of the total rainfall received during the period under study, about 28% was lost as runoff. Evaporation losses from the bare fallow soil constituted 24% while 9% was lost through percolation. Only 39% was utilized as evapotranspiration by a post-rainy season sorghum.

Tillage in semi-arid Australia is discussed in a comprehensive review by Sims (1977). Here all agricultural operations are performed by tractors and mechanized equipment. Seedbed preparation for cereals is done in late autumn using moldboard or disk plows and tine implements. Tillage research in this region concentrates largely on minimum tillage and weed control systems for the fallow period (Grierson, 1979).

A common tillage practice in the semi-arid regions of North America is to use tined implements or disk plows to bury crop residues, control weeds and to prepare seedbed for the subsequent crop. In some cases the soil may be plowed and subjected to more than five tillage operations to control weeds during a fallow year. In other cases special equipment has been developed for a stubble mulching system in which crop residues are continuously left on the soil surface. The sweep plow and rod weeder are often used together with the conventional tined implements in this system. In this region considerable attention is given to "conservation farming".

The tillage system in eastern and southern Africa is difficult to describe. While agriculture in the Republic of South Africa is highly mechanized, tillage in some of the states in southern Africa depends on either manual power or animal traction (Gibbon, 1975). Research on tillage systems by the Ministry of Agriculture in cooperation with the U.K. Overseas Development Agency in Botswana have concluded that a polydisc or one-way disc harrow produced a good seedbed that allowed a consistent depth of sowing to be

:hieved with mechanical planters. The moldboard plow was not recom-ıended for primary tillage when using a tractor. On the other hand single ırrow moldboard plows were recommended because of their low capital cost. weep implements were ineffective in cultivating plots with tall weeds and rop residues because they resulted in implement blockages (Willcocks, 1980).

The sandy soils that are dominant in the Sahelian ecological zone of West ıfrica are used traditionally to produce pearl millet, and to a lesser extent orghum, both intercropped with cowpeas. Groundnut and bambara ground-ıut are also grown as cash crops on small fields (El-Swaify et al., 1985). In his ecological zone resource-poor farmers tranditionally use the hoe (locally alled "daba") for superficial seedbed preparation (Rawitz et al., 1981). The oil is scraped together into mounds of varying shapes and dimensions, rang-ng in height from 30 to more than 50 cm. Sowing is done at various locations on or between the mounds. Whenever animal drawn implements are used in :his zone, ridges replace the mounds. Except on poor sandy soils, a crop cul-ture on flat land is not common although it is seen around villages near house-holds where intensive cropping using household refuse and litter to improve the fertility level may be practised.

Conventional tillage systems

In view of the characteristics of the five dominant soil orders in the SAT, soil tillage usually has a distinct but short-term effect of the physical condition of the soil. In semi-arid agriculture with low mechanization levels, two types of tillage may be distinguished: (1) the main tillage operation possibly involving plowing, chiselling using animal traction, or deep hoeing (manual labor) which is done before sowing; and (2) the superficial tillage operations carried out either at the beginning of the growing season (seed-bed preparation) or during the crop season as a weed control operation.

Conventional tillage, whether done by hand hoeing or plowing with draft animals or tractor is a high energy demanding cultural operation. In most of the SAT, it is a bottle-neck to the areal expansion of cultivated land by farmers either because of labor shortage in the case of hand hoeing or inadequate financial resources in the case of draft animal and tractor plowing. Also by removal of vegetation from the soil during the initial land clearing operation, conventional tillage exposes the soil to the rains of the SAT, resulting in most cases in high runoff and erosion. However, if done properly and at the appropriate time, tillage operations serve the purpose for which they are intended. For example intensive primary tillage has been found to be generally necessary to create a favorable root proliferation zone (Fig. 1) and to increase rainwater infiltration in Luvisols. In a normal rainfall year (about 800 mm), Klaij (1983) reported that "split strip plowing" increased the pearl millet yield from 1500 to 1840 kg ha^{-1} (s.e.= ± 79) (in this system a ridger is used

Fig. 1. Roots of sorghum plants grown on a Luvisol under three tillage systems (left to right: deep tillage, moldboard plowing and traditional plowing) sampled 75 days after emergence. ICRISAT Center, 1986

to split the old bed followed twice by tillage in which the bed is rebuilt using plows set successively more widely apart. The mean bulk density of the upper soil layer in this tillage system was reduced from 1.44 to 1.11 Mg m^{-3}. Clear benefits from deep tillage (25 cm deep) have also been recorded from a tillage experiment conducted at ICRISAT Center where in addition to high crop yields, deep tillage was effective in reducing runoff and soil loss (Table 4). Deep tillage is strongly recommended by Charreau (1974) for the Cambic Arenosols and the Luvisols of the Sahelian region. It helps to overcome the low porosity and hardening of the soil after rains and permits root proliferation and exploitation of soil water and nutrients at deep horizons of the soil profile, thereby producing higher yields. Charreau (1978) suggests that the benefits of deep tillage are gained only with soils with a poor structure having a sandy texture and less than 20% activity clays. Thus, meaningful and consistent results are obtained with deep tillage only if proper characterization of the soil is first undertaken. Long-term effects of subsoiling Luvisols have been studied at ICRISAT where normal tillage was compared with normal tillage with subsoiling every year, and normal tillage with subsoiling every third year. Subsoiling increased the sorghum grain yield from 3.09 t ha^{-1} for normal tillage alone to 3.97 t ha^{-1} for the mean of normal tillage with subsoiling either every year or every third year (s.e. ± 0.33), and total dry matter from 6.16 to 7.78 t ha^{-1} (s.e. ± 0.68) ICRISAT (1987). Subsoiling also resulted in better root proliferation, especially at greater depths (Table 5). Steady state infiltration rates at 2.5 h after the commencement of infiltration were 0.3 ± 0.0 cm h^{-1} for the conventionally tilled soil and 1.4 ± 0.55 cm h^{-1} for the subsoiled treatments. The accumulated amounts of water infiltrated at this time were 4.1 ± 0.97 cm for the normal tillage and 8.6 ± 2.37 cm for the subsoiled treatments (ICRISAT, 1985).

In contrast to primary tillage, secondary tillage (cultivation practice exe-

TABLE 4

Effect of different tillage treatments on sorghum grain yield, runoff and soil loss, Luvisol, ICRISAT Center, 1983–87[1]

Treatment	Sorghum grain yield[2] (t ha^{-1})	Runoff[3] (mm)	Soil loss[3] (t ha^{-1})
10 cm deep traditional plowing	2.52	128	1.66
15 cm noninverting primary tillage	2.83	102	1.62
15 cm deep moldboard plowing	2.76	106	1.70
25 cm deep moldboard plowing	3.22	85	1.41
s.e.	±0.07	±4.9	±0.279

[1]Source: ICRISAT (1988).
[2]Average values of four years (1983, 1984, 1986 and 1987).
[3]Average values of 1986 and 1987.

TABLE 5

Effect of subsoiling on root density (cm cc^{-1}) 89 days after emergence of maize ('Deccan Hybrid 103') on a Luvisol, ICRISAT Center, rainy season 1984[1]

Soil depth (cm)	Root density (cm cc^{-1})		
	Subsoiling	Normal tillage	s.e.
0–10	0.55	0.42	±0.072
10–20	0.29	0.21	±0.022
20–30	0.20	0.09	±0.034
30–40	0.15	0.10	±0.028
40–50	0.12	0.06	±0.016
50–60	0.14	0.05	±0.039

[1]Source: ICRISAT (1985).

TABLE 6

Effect of interrow cultivation (shallow tillage) in addition to normal tillage on runoff, soil loss and grain yield from a Luvisol, ICRISAT Center, 1981–83[1]

Year	Rainfall (mm)	Tillage treatment	Runoff (mm)	Soil loss (t ha^{-1})	Grain yield (kg ha^{-1})			Sole pearl millet
					Sole sorghum	Intercrop		
						Sorghum	Pigeonpea	
1981	1092	Normal[2]	246	5.0	2350			
		Additional[3]	223	4.9	2360			
		s.e.	±10.6	±0.34	±50			
1982	780	Normal	159	3.1		2260	925	
		Additional	120	2.6		2620	920	
		s.e.	±8.0	±0.33		±25	±41	
1983	990	Normal	231	4.2				2620
		Additional	196	4.0				2970
		s.e.	±12.3	±0.24				±32

[1]Source: ICRISAT (1985).
[2]Two interrow cultivations.
[3]Two additional shallow interrow cultivations.

cuted after seeding a crop) may be repeated several times usually up to the time crop canopy prohibits further entry into the field. Shallow cultivations (interrow cultivation), used as a secondary tillage practice control weeds, enable incorporation of fertilizer, break surface crust and may create a "dust mulch" to reduce soil evaporation. In years when early rains are poor, additional shallow tillage can be effective in reducing seasonal runoff and increasing yield (Table 6).

On Luvisols off-season tillage serves several useful purposes and should be done whenever feasible. At ICRISAT Center in India off-season tillage has been found to be helpful in increasing the rain water infiltration and in decreasing weed problems. In most years, off-season tillage alone can increase crop yields by 7–9% over the control. Also it significantly reduced the early season runoff and soil loss. Furthermore off-season tillage has been found to minimize the evaporation of stored water by a "mulching" effect and thus allowing the acceleration of planting operations and extension of the growing season (Pathak et al., 1987).

Conservation tillage systems

The tillage of semi-arid soils is critically dependent upon available draft power and soil moisture. Timeliness of tillage operations is important, as the rainfall is erratic and the limited water-holding capacity of some of the soils may make them either too wet or too dry to cultivate. "Conservation tillage" techniques that lower energy inputs and prevent the structural breakdown of soil aggregates have been used particularly in the U.S.A., Australia and in experimental station trials of developing countries of the SAT. Conservation tillage as defined by the Conservation Tillage Information Center (CTIC) and cited by Mannering et al. (1987) is "any tillage or cultivation system that maintains at least 30% of the soil surface covered by residue after planting to reduce soil erosion by water; or where soil erosion by wind is the primary concern, maintains at least 450 kg ha^{-1} of flattened small grain residue equivalent on the surface during critical erosion periods." Conservation tillage may be (1) a no-till or slot planting in which the soil is left undisturbed prior to planting, which is usually done in a narrow seedbed approximately 2–8 cm wide, and in which weed control is achieved primarily with herbicides; (2) ridge-till (including no-till on ridges) where the soil is essentially left undisturbed prior to planting but about one-third of the soil surface is tilled at planting with sweeps or row cleaners; planting is done on ridges of about 10–15 cm (above the middle of rows) while weed control is done using herbicides and cultivation to reform ridges; (3) strip-till where about one-third of the soil surface is tilled at planting and the remainder of the soil left undisturbed; rototiller, in-row chisel, row cleaners etc. may be used to till the rows and weed control is done using a combination of herbicides and cultivation; (4) mulch-till in which the total soil surface is tilled with tools such as chisels, field cultivators, disks, sweeps or blades prior to planting, weed control is done with both herbicides and cultivation; and (5) reduced-till which covers other tillage and cultivation systems not covered above but meets the 30% residue requirement.

In conservation tillage it is still necessary to follow the accepted and recognized cultural practices of fertilization, pest control, variety selection and correct planting time. It has been found to reduce production costs, greatly reduce energy needs, ensure better soil water retention, reduce runoff, water and wind erosion, ensure little or no damage from machinery and save labor (Young, 1982).

The success of mechanized conservation tillage depends largely on herbicides (which may be expensive and hazardous to the resource-poor farmers of the SAT), crop residues being left on the soil surface to protect it against the impact of torrential rains, and no-till planting equipment to allow precision sowing through trash. Unfortunately, most of the farmers in the SAT use crop residues to feed their animals and to construct fences and buildings. In most parts of semi-arid India, animals are allowed to roam freely on the field after crops have been harvested. Consequently, most of the residue left over is consumed by these animals.

Notwithstanding, a comparison between different tillage practices (Table 7) on a Vertisol at ICRISAT Center showed runoff to be highest from zero-tilled plots and it was higher from soil tilled to a normal depth (15 cm) than from deep-tilled (30 cm) soil (Tables 7 and 8). Phosphogypsum treatment gave the least runoff, less than 20% of that from the zero-tilled treatment. The treatments ranked differently for soil loss. Normal tillage (15 cm depth) caused the greatest soil loss while phosphogypsum treatment caused the least, with losses being similar in the other three treatments in Table 7. On flat land, the highest yield of maize–chickpea relay cropping on the Vertisol in the two seasons was obtained from the 30 cm deep primary tillage treatment while zero-tilled plots gave the lowest yield. On broadbed and furrow (BBF) configuration, incorporation of 5 t ha^{-1} crop residue with deep primary tillage (30 cm) gave on average the highest yield of maize and chickpea. There were no significant differences between the other treatments for both maize and chickpea.

On a Luvisol at the ICRISAT Center however, Yule et al. (1990) compar-

TABLE 7

Effect of different tillage practices and amendments on runoff and soil loss from maize plots, Vertisol, ICRISAT Center, rainy season 1984[1]

Treatment	17 July Rainfall 39 mm		1 August Rainfall 91 mm	
	Runoff (mm)	Soil loss (kg ha^{-1})	Runoff (mm)	Soil loss (kg ha^{-1})
Zero tillage	6.8	60	14.8	103
15 cm deep tillage (normal tillage)	4.4	110	12.9	205
30 cm deep tillage	2.1	65	7.5	93
30 cm deep tillage + phosphogypsum	1.3	25	1.8	35
Crop residue + 30 cm deep tillage	2.0	70	7.4	98
s.e.	±0.20	±5.9	±0.53	±4.9

[1]Source: ICRISAT (1986).

Effect of different tillage practices and amendments on grain yields (kg ha^{-1}) of maize and chickpea, Vertisol, ICRISAT Center, 1983/84 and 1984/85[1]

Treatment	Yield (kg ha^{-1})			
	1983/84		1984/85	
	Maize RS[2]	Chickpea PRS[2]	Maize RS	Chickpea PRS
Flat configuration				
Zero tillage (including chemical weed control)	3500	330	2320	340
15 cm deep primary tillage (normal tillage)	4030	990	2970	970
30 cm deep primary tillage	4390	1160	3140	1060
BBF configuration				
15 cm deep primary tillage (normal tillage)	4380	1150	3320	1090
15 cm deep primary tillage, cross plowing and reformation of beds every year	4290	1160	3110	1030
30 cm deep primary tillage	4240	1050	3300	1170
30 cm deep primary tillage (without blade hoeing before sowing second crop)	4210	830	3280	1060
30 cm deep primary tillage + application of phosphogypsum at 10 t ha^{-1}	4710	1280	3270	1060
Crop residue[3] incorporation at 5 t ha^{-1} with 30 cm deep primary tillage	5010	1240	3240	1250
s.e.	± 133	± 49	± 105	± 56

[1]Source: ICRISAT (1986).
[2]RS is rainy season; PRS is post-rainy season.
[3]Chopped dry rice straw incorporated in 1983/84, chopped dry maize stalks incorporated in 1984/85.

ing the effects of tillage (i.e. no-till, 10 cm deep, 20 cm deep till), amendments (i.e. bare soil, rice straw mulch applied at 5 t ha^{-1}, farmyard manure applied at 15 t ha^{-1}), and perennial species, (e.g. perennial pigeonpea, *Cenchrus ciliaris* and *Stylosanthes hamata* alone or in combination) on runoff and infiltration found that straw mulch consistently reduced runoff compared with bare plots. Tillage produced variable responses in their study. Runoff was reduced for about 20 days after tillage but the tilled plots had more runoff than no-tilled treatments during the remainder of the cropping season, suggesting some structural breakdown of the soil aggregates in the tilled plots. On average, straw mulch and tillage increased annual infiltration by 127 and 26 mm, respectively. No-till mulched plots had 101 mm more water infiltrated during the year than 20 cm deep-tilled bare plots, while annual infiltration in *Stylosanthes* plots was only 13 mm more than no-till with straw mulch plots. These results of Yule et al. (1990) indicate that mulching or keeping the soil covered (as in the case of *Stylosanthes*) should be an important component in the cropping systems of the SAT.

Other studies conducted in semi-arid regions in Africa also indicate that some of the conservation tillage systems, particularly no-till techniques give lower yield than conventional tillage methods. For example, Huxley's (1979) no-till experiments at Morogoro in Tanzania showed that no-tilled maize yielded two-thirds to three-quarters the amount of that in cultivated soil. In Huxley's studies, tillage increased the yield of Ilonga composite from 1.08 to 1.60 t ha^{-1} (47%) in the first year (1975) and for maize cultivar 'Mas' increased the yield from 2.14 to 2.71 t ha^{-1} (27%) in the second year and with hybrid 512, tillage increased the grain yield from 1.15 to 1.36 t ha^{-1} (19%). Furthermore, Nicou and Chopart (1979) conclude in their studies in Senegal, West Africa "that in order to be effective, straw mulch in conservation tillage systems needs to be applied in sufficient quantity to cover the surface of the soil completely so that it can fully protect the soil against evaporation and runoff. Straw tends to be used for animal feed in most parts of the SAT, particularly in India, Senegal and Mali. Therefore while mulches appear to be useful theoretically, from a practical point of view it is difficult to see how they can be used in the present conditions of SAT agriculture." It is even debatable if production of more biomass through breeding will induce farmers in the region to apply residue to their soils or induce them to sell their extra residues in view of the attractive prices offered for fodder during the dry season. Nicou and Chopart (1979) further indicate that their comparison of mulching with plowing clearly showed the advantages of plowing in Senegal. Measurement of rooting, while not spectacular also confirmed the advantages of cultivation on the semi-arid regions of West Africa. Finally their studies showed that it is essential not to neglect the effects of plowing on the nitrogen fixation of groundnut and the mineralization of nitrogen in the soil.

CONCLUSION

In this review we have briefly presented a description of the major soils of the SAT and their soil properties that are affected by tillage systems. We have also outlined the various tillage systems found in the SAT including the more prosperous regions of the SAT, such as the U.S.A. and Australia. We conclude that even though some of the research findings from semi-arid Africa indicate little or no beneficial response to no-till or reduced-tillage systems, the concepts of conservation tillage are good and they should be reappraised in the semi-arid regions of Africa and Asia. Soil properties and processes should be considered in the re-examination of conservation tillage systems in this region in order to evolve a tillage system that ensures sustainable agriculture.

REFERENCES

Binswanger, H.P., Virmani, S.M. and Kampen, J., 1980. Farming Systems components for selected areas in India: Evidence from ICRISAT. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, A.P. 502 324, India, Research Bulletin, no. 2, 40 pp.
Charreau, C., 1974. Soils of tropical dry and dry–wet climatic areas of West Africa and their use and management. Cornell University, Ithaca, NY, Ag. Mimeo, 74-76, 434 pp
Charreau, C., 1978. Some controversial technical aspects of farming systems in semi-arid West Africa. In: G.H. Cannell (Editor), Proc. International Symposium on Rainfed Agriculture in Semi-Arid Regions. University of California, Riverside, CA, pp. 313–360.
El-Swaify, S.A., Pathak, P., Rego, T.J. and Singh, S., 1985. Soil management for optimized productivity under rainfed conditions in the semi-arid tropics. Adv. Soil Sci., 1: 1–63.
Gibbon, D., 1975. Dryland crop production systems in semi-arid Botswana: their limitations and potential for improvement. In: Proceedings of an International Workshop on Farming Systems, November, 1974, ICRISAT Center, Patancheru, India, pp. 351–372.
Grierson, I.T., 1979. Effects of varying tillage procedures on crop growth factors in Southern Australia. Proceedings of ISTRO Conference, Stuttgart, 1: 17–20.
Huxley, P.A., 1979. Zero-tillage at Morogoro, Tanzania. In: R. Lal (Editor), Soil Tillage and Crop Production, International Institute of Tropical Agriculture, Ibadan, Nigeria, Proceedings, no. 2, pp. 259–265.
ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), 1985. Annual Report 1984. ICRISAT, Patancheru, A.P. 502 324, India, 376 pp.
ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), 1986. Annual Report 1985. ICRISAT, Patancheru, A.P. 502 324, India, 379 pp.
ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), 1987. Annual Report 1986. ICRISAT, Patancheru, A.P. 502 324, India, 367 pp.
ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), 1988. Annual Report 1987. ICRISAT, Patancheru, A.P. 502 324, India, 390 pp.
Kampen, J., Hari Krishna, J., Sachan, R.C. and Sharma, P.N., 1974. Soil and water conservation and management in farming systems research for the semi-arid tropics. In: Proceedings of the International Workshop on Farming Systems, ICRISAT, Patancheru, A.P. 502 324, India, pp. 3–43.
Klaij, M.C., 1983. Analysis and evaluation of tillage on Alfisol in a semi-arid tropical region of India. Ph.D. thesis, University of Wageningen, Netherlands, 147 pp.
Krantz, B.A. and Russell, M.B., 1971. Avenues for increased wheat production under Barani condition. Presented at Wheat Symposium, U.P. Agricultural University, Pantnagar, Uttar Pradesh, India.
Mannering, J.V., Schertz, D.L. and Julian, B.A., 1987. Overview of conservation tillage. In: R.J. Logan, J.M. Davidson, J.L. Baker and M.R. Overcash (Editors), Effects of Conservation Tillage on Groundwater Quality – Nitrates and Pesticides. Lewis Publishers, Chelsea, MI, pp. 3–17.
Michaels, G.H., 1982. The determinants of Kharif fallowing on the Vertisols in semi-arid tropical India. Ph.D. Thesis, University of Minnesota, MN, 191 pp.
Nicou, R. and Chopart, J.L., 1979. Water management methods in sandy soils of Senegal. In: R. Lal (Editor), Soil Tillage and Crop Production. International Institute of Tropical Agriculture, Ibadan, Nigeria, Proceedings, no. 2, pp. 248–257.

Pathak, P., Singh, S. and Sudi, R., 1987. Soil and water management alternatives for increased productivity on SAT Alfisols. In: Soil Conversion and Productivity; Proceedings of the IV. International Conference on Soil Conservation, 3–9 November 1985, Maracay, Venezuela. Soil Conservation Society of Venezuela, pp. 533–550.
Rawitz, E., Hoogmoed, W.B. and Morin, Y., 1981. Development of criteria and methods for improving the efficiency of soil management and tillage operations, with special reference to arid and semiarid regions. Final Report on research activities in Israel, Mali and Holland on the effects of primary tillage, crust control and modification on crop response, soil infiltrability and water conservation measure effectiveness. The Hebrew University of Jerusalem, Israel, 260 pp.
Sims, H.J., 1977. Cultivation and fallowing practices. In: J.S. Russell and E.L. Greacen (Editors), Soil Factors in Crop Production in a Semi-Arid Environment. University of Queensland Press, St. Lucia, pp. 243–261.
Swindale, L.D., 1982. Distribution and use of arable soils in the semi-arid tropics: In: Managing Soil Resources. Plenary session papers. Transactions of the 12th International Congress of Soil Science, 8–16 February 1982 New Delhi, India; Indian Agricultural Research Institute, pp. 67–100.
USDA (United States Department of Agriculture) Soil Survey Staff, 1975. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. Soil Conservation Service, USDA Handbook, 436, Washington, DC, 754 pp.
Willcocks, T.J., 1980. Dryland Farming Research Scheme (DLFRS) Botswana. Final scientific report of phase II, Vol. 1. "Scheme summary and semi-arid tillage studies." Overseas Development Administration, UK, Research project R3045. Ministry of Agriculture, ARS Sebele, P/Bag 0033, Gaborone, Botswana. 206 pp.
Wolf, D. and Luth, H.J., 1979. Tillage equipment for clod-forming soils. Trans. ASAE, 22: 1029–1032.
Young, H.M., 1982. No Tillage Farming. No-till Farmer Inc., Brook-field, WI, 202 pp.
Yule, D.F., Smith, G.D. and George, P.J., 1990. Soil management options to increase infiltration in Alfisols. In: Proceedings of the International Symposium on Water Erosion, Sedimentation and Resource Conservation, 9–13 October, 1990. Central Soil and Water Conservation Research and Training Institute, Dehradun 248195, Uttar Pradesh, India, pp. 180–187.