Surface Crusting as a Constraint to Sustainable Management on a Tropical Alfisol: I. Soil Physical Properties

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ABSTRACT. Surface sealing and crusting on alfisols in the semi-arid tropics pose serious limitations to sustainable crop production and environmental quality. This study was conducted to assess some physical properties related to crust formation on a clayey-skeletal, mixed, isohyperthermic Udic Rhodoustalf at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India. A

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critical proportion (30 to 40%) of fine textural fractions, particularly silt, appeared to be important in structural crust formation due to aggregate breakdown, rainfall compaction, and particle rearrangement of the surface soil. Significantly higher water dispersible clay percentage (7.1%) and dispersion ratio (0.34) at 60 days after planting (DAP) indicated diminished structural stability and increased slaking tendency of surface aggregates. Infiltration rates decreased by 40 to 60% in tilled bare systems from 0 to 60 DAP. Termite activity appeared to increase cumulative infiltration and steady state infiltration rate although additional research is required to determine the precise nature of its influence on porosity and pore continuity. Soil cover and biological components may be manageable factors to improve soil structure and stability, as well as, to reduce crusting and its associated adverse effects in the semi-arid tropics.

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INTRODUCTION

Surface sealing and crusting are principal constraints to sustainable management of soil especially in the semi-arid and arid regions of the tropics (El-Swaify et al. 1985; Lal, 1990; Yule et al. 1990; Smith et al. 1992; Cogle et al. 1995). Seals form in the surface layer of poorly structured soils due to aggregate breakdown and the dispersion of fine particles upon wetting by raindrop impact or by flooding. Crusts, which form upon drying, are characterized by increased strength and density in the surface few millimeters to centimeters, with concurrently reduced porosity or pore size and infiltration capacity (SSSA, 1987). Soil seals and crusts result in adverse effects leading to increased runoff and erosion hazard, as well as, reduced infiltration, seedling emergence and crop establishment (Goyal et al., 1980; Hussain et al., 1985; Lal, 1990; Smith et al., 1992).

Sealing and crusting have major implications for sustainable agricultural production and environmental quality particularly for Alfisols in the Indian semi-arid tropics (SAT). Alfisols, the most abundant soil order in the SAT of India (more than 40% of the land area, FAO, 1974), are characterized by widespread crusting, which restricts their use and productivity (El-Swaify et al., 1985). These soils are typically shallow, with a thin, sandy surface horizon, a sub-surface argillic horizon, and, frequently, a cemented, stony layer (known as "murrum") of highly variable depth and thickness (Yule et al. 1990). Sub-surface layers often contribute to reduced profile permeability and surface crusting can cause reduced infiltration, high runoff rates and extensive erosion.

Research, during the past few decades, has focused on mechanisms of crust formation, frequently based upon examination of morphology and properties of seals and crusts (McIntyre, 1958; Onofiok and Singer, 1984; Tarchitzky et al., 1984; West et al., 1992). The precise mechanism of crust formation is not completely understood, but general conditions and factors important to its development are recognized. Soil physical properties related to structural stability and dispersibility contribute significantly to sealing and crusting susceptibility (Goldberg, 1988; Mualem et al., 1990; Bradford and Huang, 1992). Chemical constituents of soil, such as, exchangeable sodium, iron and aluminum oxides and organic carbon may have a role in imparting cohesiveness to the crust layer (Painuli and Abrol, 1986; Shainberg, 1992; Shainberg et al., 1992).

Biological factors also influence soil's susceptibility to crusting and subsequent surface characteristics. The beneficial effects of soil fauna such as earthworms and termites on increasing macroporosity and infiltration is well documented (Ehlers, 1975; Zachmann et al., 1987; Lal, 1988). Additionally, improvement of soil stability (Lal, 1990) and reduction of soil crusting (Kladivko et al., 1986; Lal, 1990) due to soil macrofaunal activity have been reported. Although, mechanisms by which soil fauna ameliorate surface sealing and crusting soils are still unclear (Cogle et al., 1995).

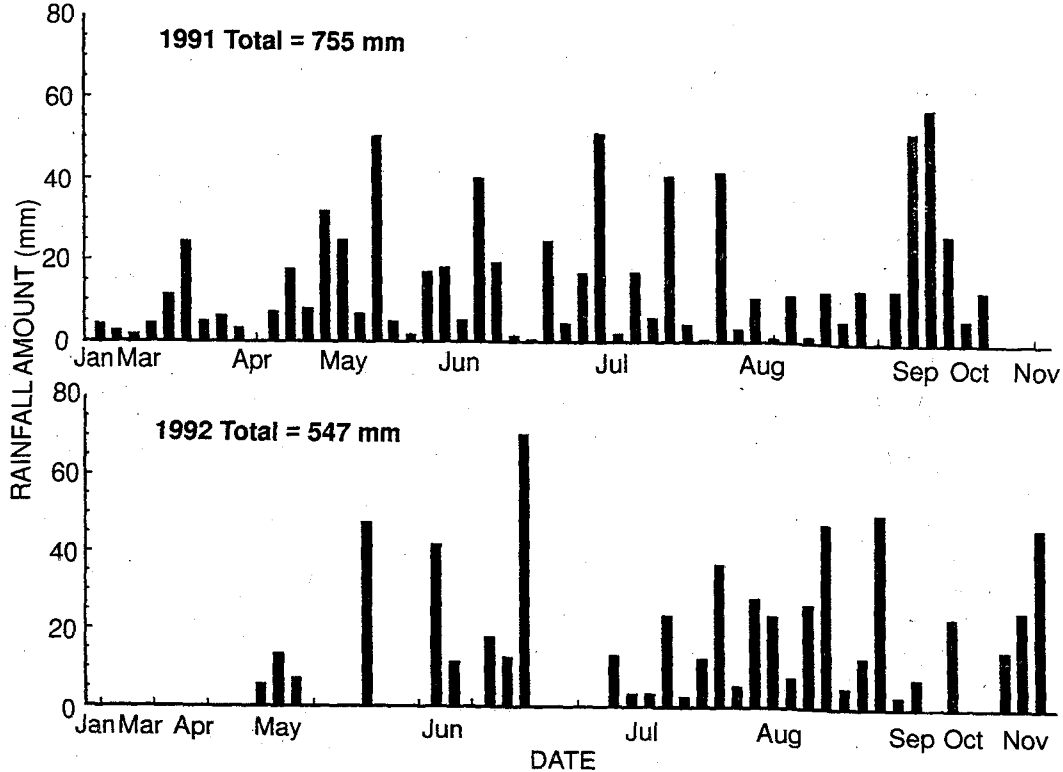
The objective of this research was to evaluate some physical properties associated with sealing and crusting of an Alfisol in south-central India in relation to water infiltration under different soil management and cropping system treatments.

METHODOLOGY

Location and Climate

The experiment site was located at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), at Patancheru in Andhra Pradesh, India (17°27′N, 78°28′E, 540 m). Mean annual precipitation of the area is approximately 750 mm, about 85% of which falls during the rainy season, between the months of June and October (Pearce and Smith, 1984). The climate of the region is semi-arid tropic, monsoonal, with a prolonged dry period of 7 to 8 months. Event-wise rainfall data for the two rainy seasons during which this study was conducted are provided in Figure 1.

FIGURE 1. Rainfall data at experimental site



Experimental Design and Data Analyses

This study, focusing on crusting and erosion, was a part of an ongoing project aimed at evaluating soil structural modification and crop performance under various soil management systems undertaken jointly by ICRISAT and QDPI,[1] Australia. For details of the project refer to Smith et al., 1992.

The sub-study included six management treatments with three replications in a completely randomized design. The treatments were: (i) Zero-till, bare (ZTB); (ii) Shallow-till, bare (STB); (iii) Shallow-till, farmyard manure (STF); (iv) Shallow-till, rice-straw; (v) Pigeonpea, *Cenchrus* and *Stylosanthes* (PCS); and (vi) *Stylosanthes hamata*. Descriptions, soil measurements and abbreviations are provided in Table 1.

The field plots were fully enclosed 5 × 28 m areas on Patancheru soil series (clayey-skeletal, mixed, isohyperthermic Udic Rhodoustalf, Murthy et al., 1982) with 2% slope. As many of the soil measurements involved repeated measures either in time or in space (depth increments), the Statistical Analysis Systems (SAS) GLM, REPEATED procedure was used to analyze the data for such parameters (Littell, 1989; SAS Institute, 1990).

Soil Measurements

The primary cropping period at the study location, which corresponds to the rainy season, is typically from mid or late June to early October. Any soil manipulation is performed after the first or second rain of the season and planting follows within a few days of tillage. In 1992, tillage was performed on June 22 and planting (maize, *Zea mays*) on June 25. Soil measurements were made on all six treatments unless otherwise specified. Soil physical properties associated with surface crust formation and water infiltration characteristics measured during the rainy seasons of 1991 and 1992 included:

1. Particle size distribution of crust, deposit and rill areas (to about 5 mm depth) was determined for plots with visible crusting, i.e., mainly bare and farmyard manure treatments. The pipet method (Gee and Bauder, 1986) was used following 5 min ultrasound dispersion, USD, with sodium hexametaphosphate, NaHMP. Rills were identified as shallow channels where concentrated overland flow of runoff occurred.

2. Soil organic carbon content, SOC, (wet combustion technique, Nelson and Sommers, 1982), and corresponding particle size analyses for

1. Queensland Department of Primary Industries.

TABLE 1. Abbreviations and description of experimental treatments and soil measurements.

Management	Description	Remarks[1]	Soil Measurements[2]
ZTB	Zero-till, bare	Narrow furrow opened for planting by hand hoe	PSD, PSF, SOC, WSA, WDC, DRI, ITA
STB	Shallow-till, bare	Tillage to 0.1m depth using tracter-drawn duckfeet tines simulating wooden animal-drawn plow, planted as with ZTB	PSD, PSF, SOC, WSA, WDC, DRI, ITA
STF	Shallow-till, farm-yard manure	Manure surface applied at 15 t ha^{-1} after 0.1m till-age, planted as with ZTB	PSF, WSA, WDC, DRI
STR	Shallow-till, rice-straw	Straw surface applied at 5 t ha^{-1} after 0.1m till-age, planted as with ZTB	PSD, SOC, WSA, WDC, DRI
PCS	Perennial pigeonpea (*Cajanus cajan*), *Chenchrus ciliaris* *Stylosanthes hamata,*	Not tilled after initial plot setup in 1988, test crop (*Zea mays*) planted in 1992 as with ZTB	PSF, WSA, WDC, DRI
SY	*Stylosanthes hamata*	Same as for PCS	PSD, SOC, WSA, WDC, DRI, ITA

1 Tillage performed on June 22nd; planting on June 25th in 1992.
2 PSD = particle size analysis for shallow depth increments; PSF = particle size analysis for surface crust, rill and deposit areas; SOC = soil organic carbon for depth increments; WSA = water stable aggregates; WDC = water dispersible clay; DRI = double ring infiltration; ITA = infiltration over termite affected and non-affected areas.

mineral fractions (Gee and Bauder, 1986) were determined for successive thin layers (0-5, 5-10, 10-20 and 20-30 mm) of surface soil. Only four treatments were used in this sub-experiment: (i) zero-till bare, ZTB; (ii) shallow-till bare, STB; (iii) shallow-till rice-straw, STR; and (iv) *Stylosanthes*, SY. The measurements were taken late in the post harvest dry period when crusts were well formed.

3. Percent water stable aggregates, WSA > 0.125 mm, and water dispersible clay, WDC, of the 0-50 mm surface layer were determined at three times during the season. A modified Yoder (1936) wet sieving technique was used for WSA analyses on initially air-dried aggregates of 5 to 10 mm diameter. This size-range of aggregates was chosen as representative of soil surface conditions after tillage and fine seed bed preparation, when the soil is most vulnerable to rain drop impact leading to crusting and erosion (Shainberg, 1992; Bradford and Huang, 1992).

Aggregates were wet-sieved for 30 min following a 30 min prewetting period in nested sieves of 5.0, 2.0, 1.0, 0.50, 0.25, and 0.125 mm openings. Prewetting was achieved by raising the water in the wet-sieve containers to the point where the water surface just touched the bottom of the 5.0 mm sieve, and the aggregates allowed to wet up under capillary action.

Soil samples (10 g) were subjected to 5 min USD, *without* NaHMP dispersing agent, to obtain WDC percentages using the pipet method as with particle size determinations described in (1) above. Total particle size analyses were also performed on duplicates of these samples for total clay determination and dispersion ratio, DR, calculations. The DR were calculated as WDC% divided by total clay%.

4. Double ring infiltrometers with 250 mm outer and 160 mm inner diameters, were used to determine infiltration capacity (Green et al., 1986). Infiltration rates, i, were calculated from cumulative infiltration, I, data and plotted against time for repeated measurements made during the season. Steady rate infiltration, i_c, was determined from fits of the data to Green-Ampt infiltration models (Jury et al., 1991) of the form:

$$i = \frac{\beta}{I} + i_c \qquad [1]$$

where β is a constant.

5. A second set of infiltration measurements were conducted using a CSIRO (Australia) Disc Permeameter (Perroux and White, 1988) during the post harvest, late crust stage, dry period (air-dry surface soil, 1-2% soil moisture content). This was a separate one-time sub-experiment, using a factorial design, to examine the effects of termite activity on infiltration

characteristics. Three widely differing treatments, namely, ZTB, STB and SY were chosen for disc permeameter measurements. Infiltration measurements were made on areas with high termite activity, T, typically within row areas, directly above corn stubble or dried *Stylosanthes* plants and, termite non-affected, NT, areas, between rows or on bare patches. An area was prepared for infiltration by clipping any stubble or vegetation down to the surface (2-3 mm) and creating a level, circular bed of fine sand (3 mm height) upon which the permeameter rested. Two soil-water potentials, 10 and 30 mm, were used to assess the dominant pore size through which infiltration occurred.

Steady state infiltration rate, i_c, was calculated as the slope of the long-time (ranging from 0.25 to about 1 h depending on treatment) plot of I versus time, t, i.e., the last 8-10 points on the plot (CSIRO, 1988). Sorptivity, S, was calculated from early-time data of I vs. $t^{1/2}$, namely, the slope of the best-fit line through the first 8-10 points (Equation 3).

From the Philip infiltration equation (Williams and Bonnell, 1988), we get:

$$I = St^{1/2} + At \quad [2]$$

For short infiltration times (during the early stages) the system behaves as if it were one-dimensional and transmissivity, $A<<1$, then:

$$I = Q/a_d = St^{1/2} \quad [3]$$

Where, Q = volume of water infiltrated and, $a_d = \pi r^2$ = area of disc permeameter.

Characteristic mean pore size, m, was calculated using the relationship shown in Equation 4 as described by White and Sully (1987).

$$m = \Gamma/(\rho g \lambda_c) = 7.4/\lambda_c \quad [3]$$

Where, λ_c is macroscopic capillary length, Γ is the air/water surface tension, ρ is water density, and g is the acceleration due to gravity. The value of $\Gamma/\rho g$ was taken approximately as 7.4 (CSIRO, 1988).

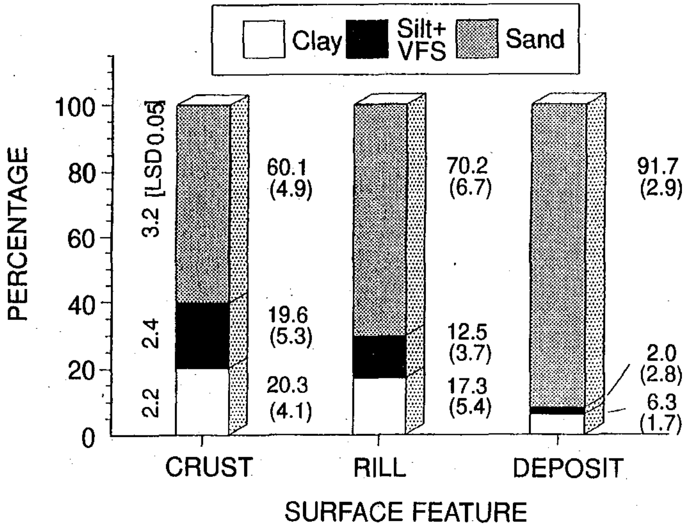
The WSA, WDC and double ring infiltration determinations were conducted three times (repeated measurements in time) between June and October, 1992: at early; middle; and late season. The SOC content and particle size distribution by depth increments were treated as repeated measures in space (Littell, 1989). These measurements were chosen to detect changes in surface conditions which reflected crust development.

RESULTS AND DISCUSSION

Particle Size Analyses

Particle size distributions of surface crusts, rill areas and deposits, had contrasting proportions of textural fractions, attributable to different processes in effect (Figure 2). Crusted areas had high amounts of clay and silt (about 40% on average), suggesting the importance of fine particles in close packing from compaction and consolidation of surface soil. The role of raindrop impact in causing physical compaction of surface soil particles is well documented (Morin et al., 1981; Tarchitzky et al., 1984; Moss, 1991a; b). In contrast, depositional areas were predominantly sand (about 90%) with little or no silt-sized particles, indicating selective removal of this size-fraction by surface runoff and possibly downward movement into the crust zone. Rills, however, had textural composition similar to the original, uncrusted soil, i.e., about 73% sand, 18% clay and 9% silt (Murthy et al., 1982). Analysis of variance revealed significant differences

FIGURE 2. Means comparison for soil surface features



in clay, silt (+very fine sand, VFS) and sand contents among surface features but not among management treatments. Comparison of means for surface feature using Fisher's $LSD_{0.05}$ (Figure 2) indicated significant differences in each size-fraction.

Particle size distribution in *shallow depth increments* of the surface 30 mm of soil for four treatments showed no significant differences between management (Table 2). Also, no significant *depthwise* trends were observed for clay and sand contents. Silt (+VFS) content, however, exhibited significant differences ($P < 0.05$) with depth despite non-significant treatment differences (Table 3). Silt contents in the crusted, top 0 to 5 mm layer were significantly higher than in lower layers, particularly for STB, STR and ZTB in which extensive crusting was observed, and least in the minimally crusted SY treatment. Such a trend of silt content in crust layers of a sandy arid-zone soil in India were also observed by Dhir et al. (1974). Small amounts of silt and VFS likely fill pores and associate with aggregates and larger primary particles to form a dense packing arrangement which effectively reduces porosity and pore size in the surface soil layer. Dense packing of particles and pore-blockage by fine particles (<125 μm) have also been reported by other researchers (Le Bissonnais et al., 1989; Loch, 1989; Moss, 1991b; Bresson and Cadot, 1992).

The SOC content in the crust and immediately underlying layers did not exhibit notable trends with depth in the top 30 mm soil layer, although

TABLE 2. Management effects on particle size distribution and soil organic carbon (SOC) in the top 0 to 30 mm soil layer.

Management[1]	Sand (%)	Silt (%)	Clay (%)	SOC (%)
ZTB	71[a]	6	23	0.47[a]
STB	76[b]	5	19	0.44[a]
STR	72[a]	7	21	0.60[ab]
SY	76[b]	5	19	0.73[b]
Signif.[2]	*	NS	NS	**
LSD[3]	4	–	–	0.20

[1] ZTB = zero-till, bare; STB = shallow-till, bare; STR = shallow-till, rice-straw; and SY = *Stylosanthes hamata*.
[2] * and ** indicate 0.05 and 0.01 levels of significance; and NS = non-significant.
[3] Fisher's least significant difference at $\alpha = 0.05$. Means with same letters are not significantly different.

TABLE 3. Depth effects on particle size distribution in the top 0 to 30 mm soil layer.

Depth (mm)	Sand (%)	Silt (%)	Clay (%)
0-5	74	7^a	19
5-10	75	5^b	20
10-20	73	6^{ab}	21
20-30	74	5^b	21
Signif.[1]	NS	*	NS
LSD[2]	–	2	–

[1] * indicates significance at P = 0.05; NS = non-significant.
[2] Fisher's least significant difference at $\alpha = 0.05$. Means with same letters are not significantly different.

significant differences (P < 0.01) were seen between management treatments (Table 2). A lack of depth effects of SOC content was probably due to: (a) soil homogenization in the case of tilled plots; and, (b) the overall very low amounts (0.41 to 0.79%) found in the soil studied.

Aggregate Stability and Clay Dispersion

Analysis of % WSA > 0.125 mm, WDC, and DR data using the SAS/GLM repeated measures procedure (SAS Institute, 1990) resulted in non-significant differences between management treatments for all three measurement times (0, 60 and 120 DAP). Differences between measurement times, within management treatments, were however, highly significant (Table 4) indicating distinct temporal changes in soil structural stability.

Low stability of initially wet aggregates (characteristic of 0 and 60 DAP, rainy conditions), resulting in rapid breakdown have been noted by researchers (Shainberg et al., 1992; Le Bissonnais et al., 1989). By the end of the season, with well developed surface crusts, aggregate stability increased and clay dispersion decreased, due probably to drying and soil consolidation over time (Nearing et al., 1988). This was supported by high surface soil strength observed during the late season (Bajracharya et al., 1996).

Percent WSA was negatively correlated with WDC and DR (Table 5) reflecting reduced aggregate stability with increased clay dispersion. Significant differences in DR observed between management (data not tabulated) suggested that DR may be more sensitive to small changes in soil

TABLE 4. Temporal changes in percent water stable aggregates (WSA), water dispersible clay (WDC), and dispersion ratio (DR) at 0, 60, 120 days after planting (DAP).

Time after planting	WSA (%)	WDC (%)	DR
0 DAP	30.0^{ab}	5.8^{a}	0.28^{a}
60 DAP	28.5^{a}	7.1^{b}	0.34^{b}
120 DAP	32.7^{b}	4.0^{c}	0.23^{c}
Significance[1]	**	***	***
LSD[2]	4.0	1.0	0.05

[1] ** and *** indicates significance at 0.01 and 0.001 levels of probability, respectively.
[2] Fisher's least significant difference at $\alpha = 0.05$. Means with the same letters are not significantly different.

TABLE 5. Correlation matrix of relevant soil parameters[1] and corresponding levels of significance.

	WDC	Clay	DR	i_c
WSA	−0.226	0.045	−0.257	−0.100
	0.10	NS	0.10	NS
WDC		0.445	0.761	−0.136
		0.01	0.01	NS
Clay			−0.225	−0.122
			0.10	NS
DR				−0.064
				NS

[1] WSA = percent water stable aggregates; WDC = percent water dispersible clay; Clay = total clay percent; DR = dispersion ratio (WDC/Clay); i_c = steady state infiltration rate.

stability than WSA and WDC. Thus, DR, which can be easily determined, may be a useful single index for quick assessment of relative structural stability of soils. Poor correlation of i_c with data of WSA, WDC and DR, however, indicated that infiltration response of structurally weak soils prone to crusting is not always consistent with indices of aggregate stability.

Infiltration

Infiltration rates, i, were considerably higher at the time of planting compared to mid season (60 DAP) when visible crusting had occurred and surface structure had deteriorated (Figure 3). A comparison of treatment means using Fisher's LSD at $\alpha = 0.05$ (indicated by bars) revealed significant differences between management at each measurement time. The between management differences at 0 and 120 DAP were larger than at 60 DAP, which also had the lowest overall i values. In tilled treatments, i showed about 40 to 60% reduction by mid season, while those for non-tilled and straw-applied treatments had substantially less reduction. The tilled treatments had initially high surface roughness enabling greater surface storage of water and rapid infiltration. The benefits of tillage, however, rapidly diminished (by 60 DAP), due to aggregate disintegration and crusting, except in the straw-applied STR treatment.

Cumulative infiltration, I, and steady state infiltration rates, i_c, differed significantly between management treatments ($P < 0.05$), as well as, between measurement times within management ($P < 0.001$) (Tables 6 and 7). Tilled and amended treatments (STB, STF and STR) had the highest overall I and i_c despite a 40 to 68% decline by 60 and 120 DAP, respectively. Perennially cropped and no-till management systems offered lower (by 15 to 60%) values of infiltration parameters from the outset, but less marked changes compared to tilled plots. Straw-application retarded the decline in I and i_c from 0 to 60 DAP by 20 to 30% compared to STB and STF.

Reduction in I and i_c by 60 DAP and correspondingly lower aggregate stability reflected surface crusted conditions. Crust formation likely resulted from breakdown of surface aggregates leading to pore size reduction from rain drop compaction of surface soil and pore clogging due to particle migration and rearrangement. Such mechanisms have also been proposed by Morin et al. (1981), le Bissonnais et al. (1989), Bresson and Cadot (1992) and West et al. (1992) in the formation of structural crusts.

Effects of Termite Activity on Infiltration

Infiltration into soil on termite affected and non-affected areas during the post harvest, dry season showed significant differences in infiltration characteristics between areas with and without termite activity (Table 8). On average, termite affected areas had 48 to 280% higher i_c and 0 to 100% higher S than areas without termite activity. Mean pore size, however, was not significantly different between areas with and without termite activity

FIGURE 3. Soil infiltration rates over time

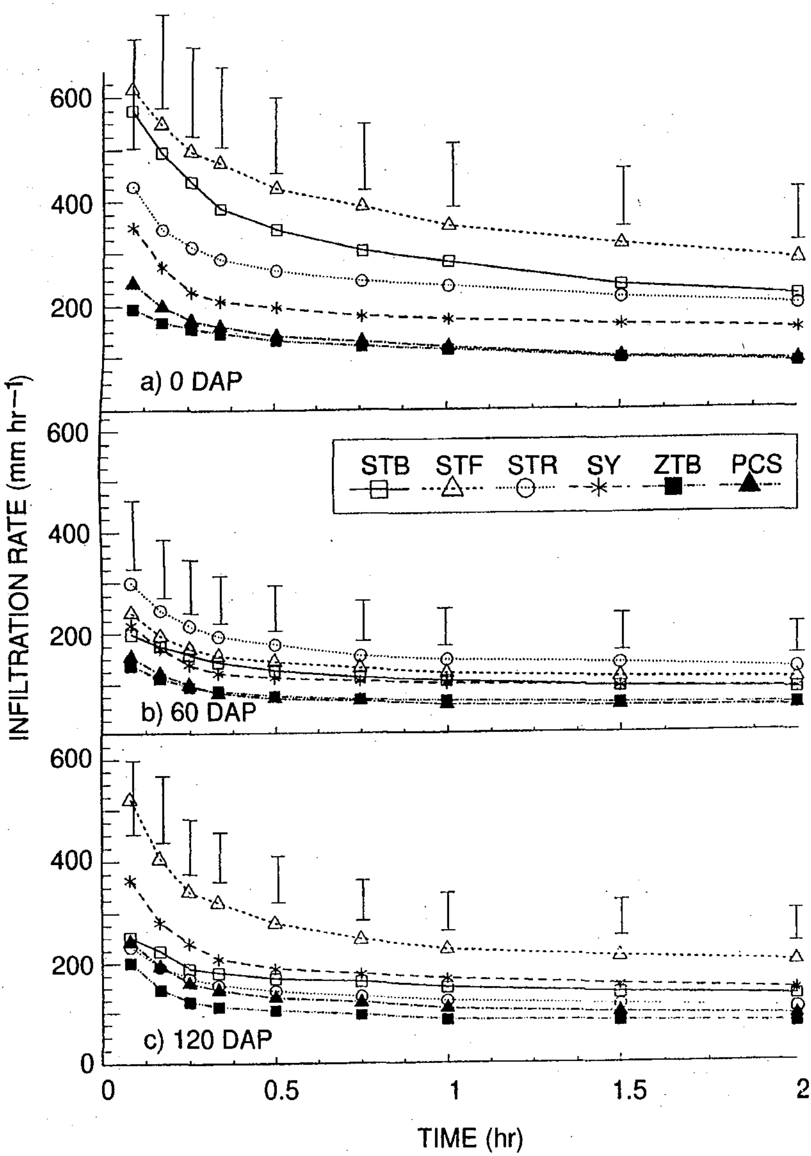


TABLE 6. Management effects on cumulative infiltration (I) and steady state infiltration rate (i_c).

Management[1]	I (mm)	i_c (mm h^{-1})
ZTB	198[a]	72[a]
STB	401[ab]	155[ab]
STF	495[b]	195[b]
STR	378[ab]	139[ab]
PCS	215[a]	69[a]
SY	331[ab]	113[ab]
Significance[2]	*	*
LSD[3]	223	91

[1] ZTB = Zero-till, bare; STB = Shallow-till, bare; STF = Shallow-till, FYM; STR = Shallow-till, rice-straw; PCS = Pigeonpea + *Cenchrus* + *Stylosanthes*; SY = *Stylosanthes hamata*.
[2] * indicates significance at the 0.05 level of probability.
[3] Fisher's least significant difference at $\alpha = 0.05$. Means with the same letters are not significantly different.

TABLE 7. Temporal changes in cumulative infiltration (I) and steady state infiltration rate[1] (i_c).

Time after planting	I (mm)	i_c (mm h^{-1})
0 DAP[2]	454[a]	180[a]
60 DAP	233[b]	80[b]
120 DAP	323[ab]	112[ab]
Significance[3]	***	***
LSD[4]	217	86

[1] Determined using Green-Ampt's model: $i = \beta I^{-1} + i_c$; β = constant.
[2] Days after planting.
[3] *** indicates significance at the 0.001 level of probability.
[4] Fisher's least significant difference at $\alpha = 0.05$. Means with the same letters are not significantly different.

TABLE 8. Termite effects on steady infiltration rate (i_c), sorptivity (S) and mean pore size (MPS) for three management systems.

Management[1]	Termite			No-termite		
	i_c ($mm\ h^{-1}$)	S ($h^{-1/2}$)	MPS (mm)	i_c ($mm\ h^{-1}$)	S ($h^{-1/2}$)	MPS (mm)
ZTB	76^{aA}	27^{aA}	0.17^{a}	20^{aA}	13^{aB}	0.20^{ab}
STB	72^{aA}	24^{aA}	0.20^{a}	49^{aA}	25^{bA}	0.10^{b}
SY	352^{bA}	51^{bA}	0.26^{a}	191^{bB}	39^{cB}	0.25^{a}
Signif.[2]	***	**	*	***	***	*
LSD[3]$_{(Mgmt.)}$	110	12	0.14	110	12	0.14
Signif.[2]	**	**	NS	**	**	NS
LSD[3]$_{(Termite)}$	135	15	–	135	15	–

[1] ZTB = zero-till, bare; STB = shallow-till, bare; and SY = *Stylosanthes hamata.*
[2] *, ** and *** indicate significance at 0.05, 0.01 and 0.001 levels of probability, respectively; NS = non-significant.
[3] Fisher's least significant difference at $\alpha = 0.05$ management and termite effect comparisons. Means with the same letters are not significantly different. Lower case letters for between management and upper case letters for between termite, within management mean comparisons.

at the water potentials (−10 and −30 mm) used. The increase in i_c in termite affected areas may then be due to a greater proportion of continuous and conductive pores (Cogle et al., 1995; Ehlers, 1975; Zachmann et al., 1987) rather than increased pore size or total porosity. Additional work is, however, needed to verify this conclusion.

The water supply potential had a significant effect on i_c, S and mean pore size, which were all higher at −10 mm than at −30 mm potential, although mean differences were significant primarily for SY using Fisher's LSD at $\alpha = 0.05$ (Table 9). *Stylosanthes* treatments, typically had the least visible crusting and extensive termite, as well as earthworm, activity resulting in higher mean pore size (and probably pore continuity) in the surface soil and to substantial depths, allowing rapid water flow (Ehlers, 1975; Zachmann ét al., 1987). The ZTB and STB treatments, which were planted to maize, had termite activity restricted primarily to the stalk stubble resulting in one or two large channel-pores leading down from the surface, but less continuous subsurface porosity.

TABLE 9. Effects of water potential on steady state infiltration rate (i_c) sorptivity (S), and mean pore size (MPS) for three management systems.

Management[1]	10 mm Water potential			30 mm Water potential		
	i_c (mm h^{-1})	S ($h^{-1/2}$)	MPS (mm)	i_c (mm h^{-1})	S ($h^{-1/2}$)	MPS (mm)
ZTB	69^{aA}	22^{aA}	0.22^{abA}	27^{aA}	17^{aA}	0.15^{aA}
STB	88^{aA}	30^{aA}	0.15^{aA}	32^{abA}	18^{aA}	0.16^{bA}
SY	435^{bA}	55^{bA}	0.35^{bA}	108^{bB}	34^{bB}	0.17^{cB}
Signif.[2]	***	***	*	***	***	*
$LSD^3_{(Mgmt.)}$	110	12	0.14	110	12	0.14
Signif.[2]	***	***	**	***	***	**
$LSD^3_{(W.Pot.)}$	135	15	0.18	96	15	0.18

[1] ZTB = zero-till, bare; STB = shallow-till, bare; and SY = *Stylosanthes hamata.*
[2] *, ** and *** indicate significance at 0.05, 0.01 and 0.001 levels of probability, respectively.
[3] Fisher's least significant difference at α = 0.05 for management and termite effect comparisons. Means with the same letters are not significantly different. Lower case letters for between management and upper case letters for within management mean comparisons.

CONCLUSIONS

A concentration of fine particles in the crust layer suggested that a critical proportion of fine and coarse material is required for surface crust formation on the sandy, Patancheru soil series. Reduced water stable aggregates and increased clay dispersibility at 60 DAP, indicated reduced stability and increased slaking tendency of surface soil. Structural crusts, a few millimeters in thickness, formed were likely due to breakdown of surface soil aggregates and packing of particles by rearrangement and rainfall compaction with subsequent consolidation upon drying.

Infiltration rates decreased rapidly from 0 to 60 DAP due presumably to crust development, suggesting rapidly diminished benefits of tillage. Management treatments using farmyard manure and straw application had significantly higher infiltration, while those with perennial crops had less dramatic changes in I and i_c. Termite activity appeared to increase I and i_c, although the precise mechanism and effect on porosity was unclear. Further work is needed to establish the type and extent of macroporosity created by the soil fauna.

Clearly, management systems which maintain adequate soil cover, vegetative or residue, and encourage high soil faunal activity are least subject to crusting and its adverse impacts. Cropping systems that incorporate pasture legumes and grasses, such as *Stylosanthes* and *Chenchrus*, as initial cover crops or post-harvest dry season crops may circumvent soil crusting. Alternatively, management involving substantial soil disturbance and exposure to rain drops greatly reduces soil faunal activity and infiltration capacity due to surface crust formation. This study has highlighted the importance of considering surface condition and soil biological components in soil management for long-term productivity and sustainability.

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