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Soil management options for Alfisols in the semi-arid tropics: annual and perennial crop production

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Abstract

A field experiment was conducted in the semi arid tropics to study the effects of soil structural modification on cropping systems. The aim was to improve crop production and land resource protection using innovative soil management practices. Tillage, mulch and perennial/annual rotational based systems were compared for 5 years in an Alfisol at ICRISAT in India. Crop yield parameters, including grain and biomass yield, leaf area index, crop cover, and plant height were measured. Results indicate significant benefits to annual crop yield (maize, sorghum) from improved water supply due to mulching with farmyard manure or and rice straw, and due to rotation with prior-perennial crops. Grain yields were 16 to 59% higher in mulched treatments compared to unmulched treatments, with similar increases for fodder yields. Annual crop yields after 4 years of perennials were 14 to 81% higher than unmulched treatments, except for low fertility maize grown after buffel grass. The interaction with chemical fertility was less clear than for water supply. The results have implications for soil management throughout the semi-arid tropics. © 1997 Elsevier Science B.V.

Keywords: Soil management; Semi-arid tropics; Crop production; Water availability

1. Introduction

Management options to slow land degradation and ameliorate degraded soils are urgently needed for the semiarid tropics (SAT) (Lal, 1989). Viable options must include

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profitability gains since, regardless of the environmental benefit of soil management, clear financial benefits to farmers are necessary before new practices are widely accepted. The identification of alternative practices requires field studies of crop responses to provide appropriate information.

Approximately one third of the soils in the SAT are Alfisols (Kampen and Burford, 1980). These soils have low productivity, particularly under rainfed situations, but are critical for food production for large numbers of the world population. Mullins et al. (1990) note that the crusting and hardsetting characteristics found in some Alfisols are also evident in other soil types in tropical and Mediterranean regions. Major constraints of Alfisols include low water holding capacity, poor nutrition, low cation exchange capacity, low organic matter content particularly in cultivated soils, and poor soil physical characteristics. Examples of the latter are such as a tendency to surface seal, crust and hardset on drying and low soil strength under saturated soil conditions leading to slumping, increased bulk density and loss of surface roughness (El-Swaify et al., 1985). Hence, agricultural practices which cause further losses in soil fertility, such as tillage, make a difficult soil even harder to manage profitably.

A range of potential management systems exist for Alfisols of the SAT (El-Swaify et al., 1985; Venkateswarlu, 1987). These options generally relate to soil management between bunds (interbund management) and can be categorised as tillage and biologically based systems.

The advantages of tillage options may include increased crop establishment and yields, weed control, improved infiltration and reduced runoff (Laryea et al., 1991; Gupta and Moncreif, 1994), but the longevity of these effects may be short (Vittal et al., 1983). The principles behind tillage are to increase soil porosity, to destroy surface crusts, and to manipulate surface roughness to improve water intake (Hoogmoed, 1995). However, continuous tillage accelerates organic matter loss resulting in the decline of soil chemical, physical and biological fertility and subsequent land degradation (Lal, 1989). Tillage depths vary, depending on the purpose and availability of implements, and range from shallow non inverting tillage to deep profile modification.

Biologically-based options include mulch-based and pasture-based systems (Rao et al., 1992). Mulches are used to protect the soil surface from raindrop impact and subsequent crust formation and to reduce the rate of organic matter decline. In addition to these mulching benefits, a pasture phase creates root channels and increases organic matter throughout the profile. A legume pasture may contribute soil nitrogen. Both mulch-based and pasture-based systems have been reported to change the soil biota (Cogle et al., 1995b). Pasture/crop rotations, such as the tropical ley system (McCown et al., 1985), are one example of biologically-based systems. Dalal et al. (1991), Jones et al. (1991) and Cogle et al. (1991, 1995a) have discussed the advantages and disadvantages of pasture/crop rotations in tropical and subtropical environments.

The purpose of this study is to assess tillage and biological options for managing Alfisols in a semi-arid tropical area. Smith et al. (1992) reported an experiment, which commenced in 1988, and studied tillage and biologically options for managing Alfisols. Their paper covered the establishment phase of the study project and discussed all biophysical aspects. Few benefits to crop yield were found after 1 year in 1988, but it was suggested that benefits would slowly develop overtime. In the study, perennials were removed after 4 years and these treatments cropped to annual cereals to assess the benefits of the perennial phase. Our paper interprets agronomic data for the study between 1989 and 1993 for annual crops, and evaluates whether, and why, crop yield benefitted from alternative management practices.

2. Materials and methods

2.1. Experimental site

The project was established in July 1988 at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru (18°N, 78°E), 26 km northwest of Hyderabad, Andhra Pradesh, India. Details of the experimental site and the 1988 crop season were given by Smith et al. (1992).

The soil is a Udic Rhodustalf (I have not checked the books on this but I think the s is applied in the plural sense when talking about the family of soils), locally regarded as a crusting, profile hardening soil. The surface texture is a sandy loam merging to a sandy clay loam or light clay at 10–15 cm and then to gravelly sandy loam overlying murrum (a layer of decomposing parent material); the depth of the murrum varies between 30 to 100 cm. ICRISAT has an average rainfall of 784 mm, with over 80% falling between the months of June and October. Rainfall at the experimental site was measured with a tipping bucket pluviometer. Average monthly air temperature in the rainy season ranges from 25 to 29°C.

2.2. Experimental design

The experimental design was an incomplete randomised block with an embedded factorial for the tillage by mulch comparisons. Each plot was 28 m long (down slope) and 5-m wide with a land slope between 1.5–2.0%. There were three replications. Fifteen treatments were imposed in the experiment. These were made up of: (a) a tillage by mulch factorial for annual crops, comprised nine treatments, and compared three different tillage depths at (0 cm (T_0), 10 cm (T_{10}) and 20 cm (T_{20})) and three mulches (no mulch (N_m), 15 t ha^{-1} farmyard-manure (F_m), and 5 t ha^{-1} rice straw (R_m)); (b) perennial crops, which were rotated to annual crops after 4 years comprised six treatments: sole perennial pigeonpea (Pp) (*Cajanus cajan* L.), sole buffel grass (C) (*Cenchrus ciliaris* L.), sole Verano (St) (*Stylosanthes hamata* L.) and mixtures of these species viz. PpSt, PpCSt and CSt.

Between 1988 and 1991, the tillage and mulch treatments were cropped annually to cereal crops. In 1992, perennial crops were removed and in 1992 and 1993 all treatments, including those previously under perennial crops, were planted to a cereal crop to compare the cumulative effects of different soil management histories. For discussion of the 1992 and 1993, results the perennial treatments are referred to as 'prior-perennial' treatments when compared with the treatments that been cropped to annual crops before 1992.

Data were analysed using GENSTAT (GENSTAT 5 Committee, 1993) with data adjusted to take account of the incomplete block design, prior to analysis. Adjusted means are presented.

2.3. Annual crops: (tillage by mulch) factorial

The crop sequence was millet (*Pennisetum glaucum* L.) (1988), sorghum (*Sorghum bicolor* L.) (CSH9) (1989, 1990), maize (*Zea mays* L.) (Proagro 3448) (1991, 1992) and sorghum (CSH9), (1993). In this paper, we consider the sorghum and maize crops, as Smith et al. (1992) discussed the millet crop.

Tillage for T_{10} and T_{20} treatments occurred after the first major rain in June and was performed with a tractor-mounted toolbar using chisel tines. The initial tillage operation was 10 cm in both treatments, while a second tillage 10 cm and 20 cm was performed for T_{10} and T_{20} treatments respectively. There were a total of two passes in tilled plots. In each year, planting (Table 1) was performed as soon as possible after tillage, but in 1989 and 1990 a delay of several weeks occurred because of unfavorable weather conditions. Seeds were sown by hand in a furrow at double the desired plant population and furrows were firmed to promote soil–seed contact. Approximately 20 days after planting, seedlings were thinned to give the desired population (Table 1).

Fertiliser was placed in the seed furrow and mixed with soil prior to planting. Nitrogen (N) applications were made 2–3 times during the crop season. Fertiliser (diammonium phosphate and urea) at a rate of(100 kg N ha^{-1} and 46 kg P ha^{-1}) was applied over most of the plot and has been designated as the normal fertiliser level (NF). In addition, a high fertiliser (HF) subplot (2 × 2 m) (186 kg N ha^{-1}, 62 kg P ha^{-1}, 27 kg K ha^{-1}) was placed at the base of the plot. In 1990, an extra 60 kg N ha^{-1} and 140 kg N ha^{-1} were applied to the normal and high fertility plots respectively. Zinc was soil applied as 40 kg ha^{-1} $ZnSO_4$ 1990 and as a 2 kg ha^{-1} foliar spray in 1991, 1992 and 1993. In 1992 and 1993, a low fertility (LF) subplot (0 kg N ha^{-1}, 46 kg P ha^{-1}) (10 rows by 3 m) was placed at the top of each plot to compare the N input from the prior crop.

After planting, farmyard-manure (15 t ha^{-1}) was applied to F_m plots and rice straw (5 t ha^{-1}) was applied to R_m plots. Both mulches were applied to the surface and not incorporated. In 1992 and 1993, rice straw was applied to all prior-perennial plots, except PpCSt. The rationale was to prevent the development of a surface seal/crust and therefore allow a comparison of the effect of sub-surface structural changes. The PpCSt treatment did not receive straw so as to be able to measure the effect of a pasture/crop

Table 1
Crop data for the period between 1989 and 1993

Year	Crop	Planting date	Harvest date	Plant population plants ha^{-1}
1989	Sorghum (CSH9)	19-7-89	3-11-89	180,000
1990	Sorghum (CSH9)	12-7-90	6-11-90	180,000
1991	Maize (proagro 3448)	22-6-91	18-9-91	50,000
1992	Maize (proagro 3448)	25-6-92	28-9-92	50,000
1993	Sorghum (CSH9)	30-6-93	18-10-93	180,000

rotation in a non-mulched situation. The farmyard-manure used contained 157 kg N ha^{-1}, 81 kg P ha^{-1} and 127 kg K ha^{-1}, and the rice straw contained 35 kg N ha^{-1}, 7 kg P ha^{-1} and 86 kg K ha^{-1}.

During the cropping period, weeds were removed by hand or by application of the herbicide, (Paraqat (24% Emulsifiable Concentrate (EC)). In 1991, 1992 and 1993, Atrazine (50% EC) was applied as a residual herbicide at planting. To control shootfly (*Atherigonia soccata* (Randani)) in 1989, 40 kg ha^{-1} Carbofuran (3% EC) was mixed with soil in the rows before sowing and was also dribbled in the whorls on August 25. In 1990, Fenvalerate (20% EC) was sprayed on July 20 and Carbofuran was dribbled in the whorls on August 25 for shootfly. Endosulphan (35% EC) was sprayed on September 3 and Rogor (30% EC) on October 17 for stemborer (*Chico partellus* (Swinhoe)) and mirid (*Calocoris angustatus*) attack on sorghum heads. In later years, chemical insect control was not required.

Agronomic data collected included total leaf number to the last fully expanded leaf, (three plants from two adjacent centre rows at the top, middle and bottom of each plot), plant population (total counts per replicate plot), projected cover using a camera set at 4.2 m above the canopy and analysis of slide photos by projection onto a 10 × 10 cm grid (three sites per replicate plot), and leaf area index with a LICOR LI2000 in 1991 and 1992.

Crops were harvested at physiological maturity (Table 1) except in 1991. In 1991, the crop was harvested 10–15 days before physiological maturity because a termite attack appeared to potentially affect the F_m treatment and hence affect treatment comparisons. To ensure a uniform comparison, all treatments were harvested at the same time. The harvest sample unit was 22 m of the central 6 rows of each plot for NF. The HF and LF treatments were sampled entirely. Plants were cut at ground level and separated into grain and fodder (remaining plant material). Grain and fodder yields, grain and fodder nutrients (1991, 1992 and 1993) and 100 seed weights (1991, 1992 and 1993) were determined.

2.4. Perennial crop treatments

The perennial species were perennial Pp (*C. cajan*), a deep rooting shrubby legume; C (*C. ciliaris*), a clumping vigorous tropical grass; and St (*S. hamata*), a tropical pasture legume. The perennial species were sown alone or in mixtures (Pp, PpSt, PpCSt, C, CSt, St).

Pp, variety ICPL88040, was sown at 1 m row spacing in July, 1988. Due to high plant mortality (Reddy et al., 1992), variety ICPL9174 was sown in August 1990 and gap filling with ICP11298 occurred in July 1991. As individual plants died in the 1991/1992 period, no gap filling was done as Pp was to be removed prior to the 1992 kharif or wet season. Fertiliser was applied annually at the rate of 7 kg Zn ha^{-1} (as $ZnSO_4$), 36 kg S ha^{-1} and 46 kg Ca ha^{-1} (as gypsum), 18 kg N ha^{-1} (as diammonium phosphate). In 1989, an extra 32 kg N ha^{-1} (as urea) was applied. Grain and fodder sampling were done between December and April of each year by cutting at 75 cm height; grain was threshed from fodder. Pruning to 75 cm was done during the kharif to check excessive vegetative growth.

C and St were sown in July and August 1988 in rows at 38 cm spacing. In the mixtures, the species were sown in alternate rows. A similar fertiliser regime as for P was applied. Dry matter harvests were conducted each year (C: 6 July 1989, 16–22 September 1989, 21 February 1990, 26–31 July 1990, 15 September 1990, 10–16 October 1990, 2–5 July 1991, 3–5 September 1991, 7–10 April 1992; and St: 16–22 September 1989, 26–31 July 1990, 10–16 October 1990, 3–5 September 1991, 7–10 April 1992). Total plot dry matter was sampled by removing plant material to ground level; air drying and weighing.

In the dry season of 1992 (January–May), perennials (Pp, C, St, PpSt, PpCSt and CSt) were removed for sampling and regrowth was controlled by herbicide applications. An outline of the annual crop management for 1992 and 1993 has been given above.

2.5. Interaction of soil management, water relations, nutrition and yield

An assessment of the effect of increased infiltration on crop growth due to soil management was made by plotting total biomass yield vs. infiltration. Infiltration, calculated as rainfall minus run-off is used as a simple measure of available soil moisture, but takes no account of drainage and soil evaporation. Run-off was measured with tipping buckets at the base of each plot (Smith et al., 1992). In any growing season, there were up to 15 run-off events. The cumulative runoff total was used in calculations for this paper. Total grain and fodder weights were summed to give total biomass. Plots were of treatment averages (each of three replicates). Two relationships were considered: (a) total dry matter for normal fertility vs. infiltration; and (b) total dry matter for low, normal and high fertility vs. infiltration. The latter shows the effect of differing additions of fertiliser, and compares yields from the LF and HF subplots with the larger NF plot. An arbitrary line, which encloses almost all the highest yielding crops at different levels of water use, and thereby defines a linear relation between potential yield and water use, was drawn for each figure, using the technique of French and Schultz (1984). A figure of 110 mm was used as the x intercept as suggested by these authors for growing seasons receiving more than 150 mm. The slope of the arbitrary line is the water use efficiency (Perry, 1987), or in this case, the potential water-use efficiency.

3. Results

3.1. Rainfall

Rainfall distribution varied between cropping seasons (Fig. 1) and there was a substantial difference (236 mm) between the wettest (1989) and driest (1991) cropping season rainfall. In July 1989, exceptionally large rainfalls occurred early in the season over short time periods (e.g., 162 mm over 4 days and 221 mm over 3 days). In 1990, the lack of good planting rains limited establishment and early growth, even though rain was evenly distributed later in the season. The lowest seasonal rainfall was in 1991 and the post anthesis period was particularly dry. The wetter year in 1992 provides a useful

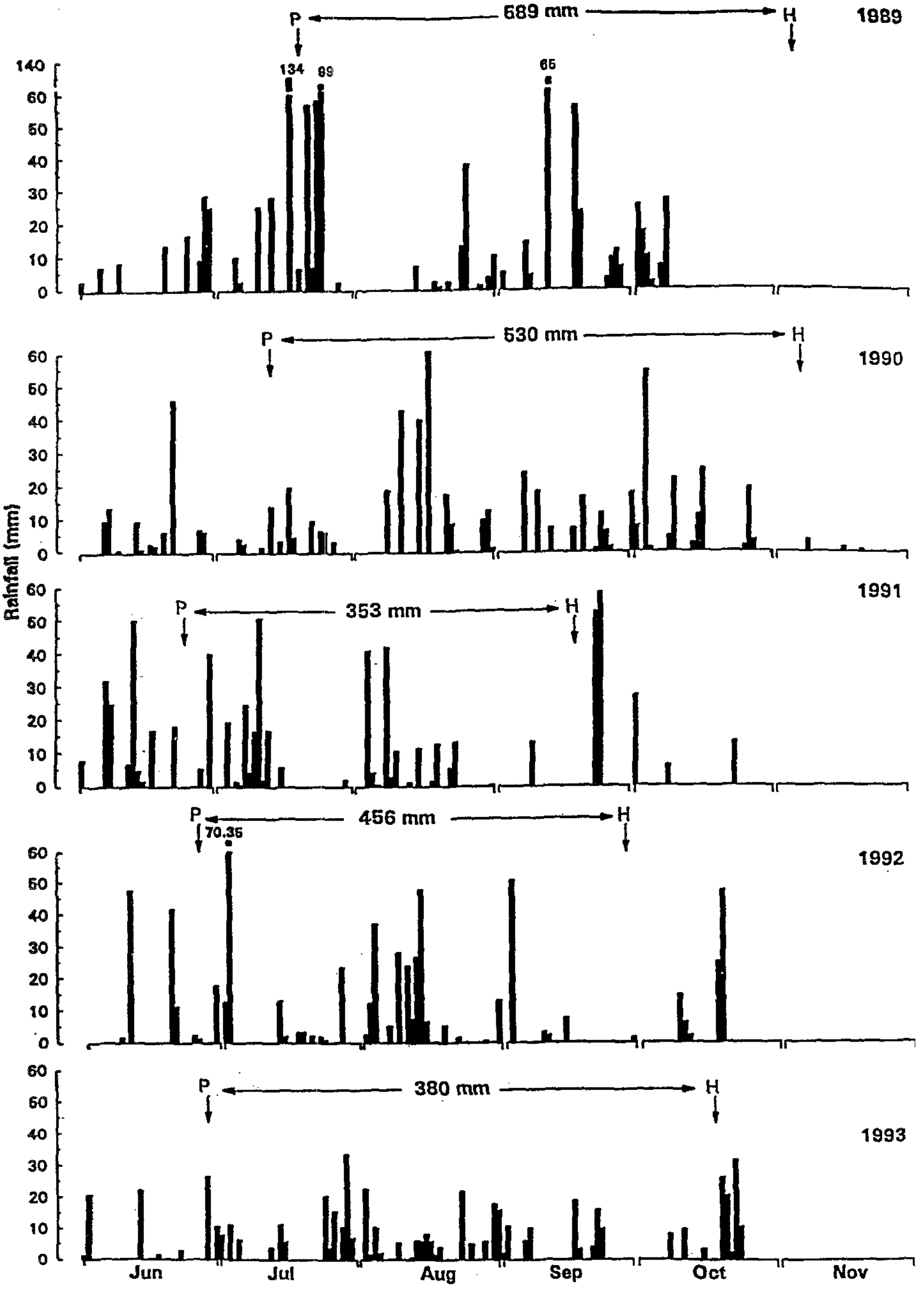

Fig. 1. Daily rainfall distribution (mm) for 5 years at the experimental site. Rainfall presented on the figure between planting (P) and harvest (H) are crop season totals. Annual rainfalls were 1021, 804, 755, 664 and 632 for 1989–1993 inclusive.

comparison to 1991, although there was also a dry finish. The notable aspect of 1993 was a low but relatively evenly distributed rainfall.

3.2. Annual crops (tillage by mulch factorial) 1989–1993

Mulching (F_m and R_m) produced significant ($P < 0.05$) increases in grain yield in all years; there were no significant responses to tillage (data not shown); and the tillage-by-mulch interaction was only significant in 1993 (Table 2). Among mulch treatments, F_m yielded significantly higher than N_m in all years and higher than R_m in 1989, 1990 and 1993. R_m outyielded N_m significantly in all years except 1989 when R_m produced the lowest yield. There were no significant effects of tillage and mulch treatments on grain yield from high fertility subplots, except in 1992 when mulching (F_m, 4716 kg ha^{-1} and R_m, 4675 kg ha^{-1})) significantly increased yields ($P < 0.05$, 484 kg ha^{-1}) over N_m (3448 kg ha^{-1}).

In 1991, maize 100 seed weights were lower ($P < 0.05$) for N_m (14.9 g) compared with F_m (16.6 g) and R_m (17.0 g) treatments (data not shown). There was no difference in high fertility maize 100 seed weights (15.8 g). In 1992, maize 100 seed weights for F_m and R_m were significantly higher than N_m ($P < 0.05$) for both fertility levels. The values for normal fertility were 14.9 g (N_m), 18.6 g (F_m), 18.9 g (R_m) and for high fertility 15.7 g (N_m), 19.9 g (F_m), 20.9 g (R_m). Sorghum 100 seed weights ranged between 2.2 and 2.6 g in 1993, with no significant differences.

Table 2
Sorghum and maize grain yields (kg ha^{-1}) between 1989 and 1993, under normal fertility, for the tillage by mulch factorial (adjusted means)

Treatment	Sorghum (kg ha^{-1})		Maize (kg ha^{-1})		Sorghum (kg ha^{-1})
	1989	1990	1991	1992	1993
Individual effects					
T_0N_m	3819	1358	2224	2313	2785
T_0F_m	3459	2013	3624	4407	5517
T_0R_m	1902	1355	3293	4306	4542
$T_{10}N_m$	2233	1100	2502	3242	3282
$T_{10}F_m$	3453	1768	2947	4264	5046
$T_{10}R_m$	1812	1281	3384	4520	4539
$T_{20}N_m$	2959	1014	2416	3015	3290
$T_{20}F_m$	3570	1730	3305	4692	5201
$T_{20}R_m$	2311	1628	3254	4170	4670
LSD 5%	NS	NS	NS	NS	865
Mulch effects					
N_m	3004	1157	2381	2857	3120
F_m	3494	1837	3292	4454	5250
R_m	2008	1421	3310	4332	4580
LSD 5%	348	213	279	315	288

T_0: Zero tillage. T_{10}: Shallow tillage. T_{20}: Deep tillage. N_m: No mulch. F_m: Farmyard-manure. R_m: Rice straw.

Table 3
Sorghum and maize fodder yields (kg ha^{-1}), under normal fertility (NF), between 1989 and 1993 (adjusted means; abbreviations as for Table 2)

Treatment	Sorghum (kg ha^{-1})		Maize (kg ha^{-1})		Sorghum (kg ha^{-1})
	1989	1990	1991	1992	1993
N_m NF	4559	3786	3442	3856	5640
F_m NF	4899	5232	4495	5124	8050
R_m NF	4507	5112	4578	4846	7870
LSD 5%	NS	329	218	299	354

Normal fertility fodder yields for mulched treatments (F_m, R_m) were significantly higher ($P < 0.05$) than N_m treatments in all years except 1989 (Table 3). There were no statistical differences for high fertility fodder yields, except for 1993 when N_m (7500 kg ha^{-1}) was less ($P < 0.05$; 665 kg ha^{-1}) than F_m (8890 kg ha^{-1}) and R_m (8780 kg ha^{-1}).

The rate of canopy development, as determined by LAI, in N_m was significantly less ($P < 0.05$) than F_m and R_m treatments for up to 8 weeks after planting in 1991 and 1992. An example is shown in Fig. 2 for 1992. Final LAI was similar for all treatments. In 1989, R_m sorghum was significantly shorter than both F_m and N_m sorghum, while in 1990 there were no significant differences in sorghum plant height (data not shown). The addition of extra fertiliser in the high fertility subplots had no effect on plant height. In both early 1991 and all of 1992, N_m maize was shorter ($P < 0.05$) than either F_m and R_m maize, even when extra fertiliser was added. There was no effect of tillage.

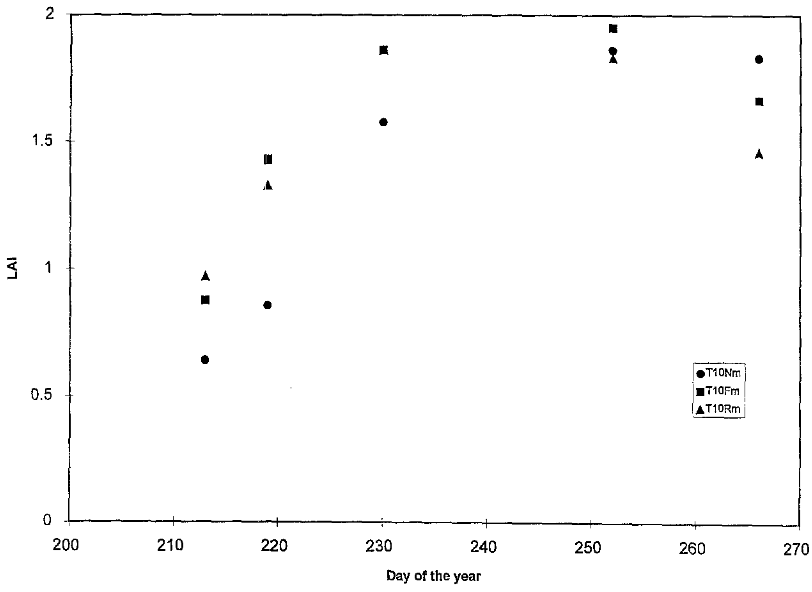

Fig. 2. Leaf area index (LAI) for shallow tilled (T_{10}) maize under three mulch regimes (N_m, F_m, R_m) in 1992 ($P < 0.05 = 0.23$ for sampling days 213, 219 and 230).

Table 4
Grain and fodder N concentration (N%) for normal fertility and high fertility plots for maize (1991 and 1992) and sorghum (1993) (adjusted means; abbreviations as for Table 2)

Treatment	Maize (N%)				Sorghum (N%)	
	1991		1992		1993	
	NF	HF	NF	HF	NF	HF
Grain						
N_m	1.56	1.73	1.44	1.54	1.62	1.30
F_m	1.51	1.69	1.47	1.44	1.53	1.43
R_m	1.35	1.65	1.19	1.27	1.38	1.45
LSD 5%	0.02	0.02	0.04	0.04	NS	NS
Fodder						
N_m	0.75	0.99	0.72	0.86	0.72	0.64
F_m	0.74	0.87	0.67	0.73	0.74	0.52
R_m	0.61	0.94	0.46	0.57	0.57	0.57
LSD 5%	0.07	0.06	0.04	0.07	NS	NS

A significantly lower grain N percentage ($P < 0.05$) occurred after mulching with rice straw (R_m) in 1991 and 1992, and this effect was not removed by the high fertility (HF) treatment (Table 4). Treatments mulched with rice straw (R_m) generally had lower fodder N percentages ($P < 0.05$) in all years.

3.3. Annual crops (following 4 years of perennials) 1992–1993

The following results are compared with T_0 treatments from the tillage by mulch factorial because the prior-perennial plots received no tillage but did receive a mulch of

Table 5
Low fertility (LF) yields (kg ha^{-1}) for maize and sorghum grown in prior-perennial treatments in 1992 and 1993, compared to T_0 treatments (adjusted means; abbreviations as for Table 2)

Treatment	Maize 1992 (kg ha^{-1})		Sorghum 1993 (kg ha^{-1})	
	Grain	Fodder	Grain	Fodder
T_0N_m	1498	2803	4099	5629
T_0F_m	3436	4957	3948	8360
T_0R_m	2892	3934	1509	5728
Pp	2151	3412	2776	8241
PpSt	3029	4585	3251	8483
PpCSt	2199	3761	2775	5859
C	908	2260	3499	7902
CSt	2537	4300	4151	9027
St	2545	4201	2718	7106
LSD 5%	1281	1310	NS	2142

Pp: Pigeon pea. C: *Cenchrus ciliaris* L. St: *Stylosanthes hamata* L.

Table 6
Normal fertility (NF) yields (kg ha^{-1}) for maize and sorghum grown in prior-perennial treatments in 1992 and 1993, compared to T_0 treatments (adjusted means; abbreviations as for Table 2Table 5)

Treatment	Maize 1992 (kg ha^{-1})		Sorghum 1993 (kg ha^{-1})	
	Grain	Fodder	Grain	Fodder
T_0N_m	2313	3655	2785	5198
T_0F_m	4407	5125	5517	8164
T_0R_m	4306	4794	4542	7966
Pp	4418	5226	5219	8498
PpSt	4859	6076	4742	7258
PpCSt	3568	4913	3781	6557
C	3972	4940	4902	8057
CSt	4869	5519	4957	7534
St	4754	5470	4568	7128
LSD 5%	944	897	865	1063

rice straw, except PpCSt which did not receive straw. Also, because there were no responses to tillage, the T_0 results are indicative of responses to mulch.

In the low fertility (LF) subplots, after 4 years of perennial crop and no applied N fertiliser, the lowest yielding maize followed C (Table 5). This was significantly lower ($P < 0.05$) than all other treatments except T_0N_m. Other maize yields following perennial treatments achieved yields similar to those from the tillage by mulch factorial. There were no significant differences for sorghum yields in 1993. In the normal fertility (NF) treatments, maize and sorghum grain yields after all perennial treatments were significantly higher than T_0N_m (Table 6). Yields after PpCSt were significantly lower than other S-based prior-perennial treatments for both maize and sorghum. For the high fertility (HF) comparisons, maize after all perennials except PpCSt had significantly higher grain yields than T_0N_m in 1992 (Table 7). There were no significant differences in 1993.

Table 7
High fertility (HF) yields (kg ha^{-1}) for maize and sorghum grown in prior-perennial treatments in 1992 and 1993, compared to T_0 treatments (adjusted means; abbreviations as for Table 2Table 5)

Treatment	Maize 1992 (kg ha^{-1})		Sorghum 1993 (kg ha^{-1})	
	Grain	Fodder	Grain	Fodder
T_0N_m	2910	4217	4780	8825
T_0F_m	4427	5451	5881	8973
T_0R_m	5774	5841	5512	8458
Pp	6241	6092	5990	9758
PpSt	5587	5761	6151	9039
PpCSt	4093	5027	4711	7133
C	4446	4657	5433	9255
CSt	4815	6212	5838	8177
St	5886	5586	5265	7516
LSD 5%	1452	NS	NS	1996

Table 8
Nitrogen percentages for normal fertility (NF) treatments in 1992 and 1993 (adjusted means; abbreviations as for Table 2Table 5)

Treatment	Maize 1992 (N%)		Sorghum 1993 (N%)	
	Grain	Fodder	Grain	Fodder
T_0N_m	1.32	0.79	1.61	0.82
T_0F_m	1.49	0.58	1.50	0.69
T_0R_m	1.20	0.43	1.42	0.57
$T_{10}N_m$	1.50	0.65	1.54	0.64
$T_{10}F_m$	1.43	0.63	1.59	0.83
$T_{10}R_m$	1.21	0.49	1.33	0.54
$T_{20}N_m$	1.52	0.72	1.71	0.68
$T_{20}F_m$	1.49	0.81	1.52	0.71
$T_{20}R_m$	1.15	0.45	1.40	0.61
Pp	1.16	0.46	1.51	0.59
PpSt	1.25	0.52	1.44	0.72
PpCSt	1.41	0.70	1.53	0.60
C	1.19	0.46	1.34	0.57
CSt	1.25	0.49	1.42	0.65
St	1.28	0.56	1.50	0.70
LSD 5%	0.13	0.11	0.18	0.13

For fertility sub-treatments, 100 seed weights (data not shown) for unmulched maize (N_m) were significantly lower ($P < 0.05$) than all prior-perennial treatments except maize after PpCSt. In addition for the NF treatment, 100 seed weights for the unmulched maize were not significantly lower than the C treatment. There were no differences across all treatments in 100 seed weights for sorghum grown in 1993. The response of fodder yields (Tables 5–7) to the treatments was generally similar to that of grain yields.

Table 9
Nitrogen removal (kg N ha^{-1}) in grain and fodder for maize and sorghum between 1991 and 1993 (mean and standard deviation; abbreviations as for Table 2)

Year	Crop	Treatment (kg N ha^{-1})			
		N_m	F_m	R_m	Pe
Low fertility					
1991	Maize	–	–	–	–
1992	Maize	43(4)	69(11)	38(7)	38(11)
1993	Sorghum	75(6)	116(24)	79(17)	94(16)
Normal fertility					
1991	Maize	64(1)	83(6)	72(8)	–
1992	Maize	69(9)	100(13)	74(6)	84(9)
1993	Sorghum	92(2)	141(7)	108(5)	116(11)
High fertility					
1991	Maize	89(5)	100(6)	108(22)	–
1992	Maize	91(6)	108(7)	87(19)	96(11)
1993	Sorghum	106(14)	126(6)	125(9)	126(13)

Pe: Perennials.

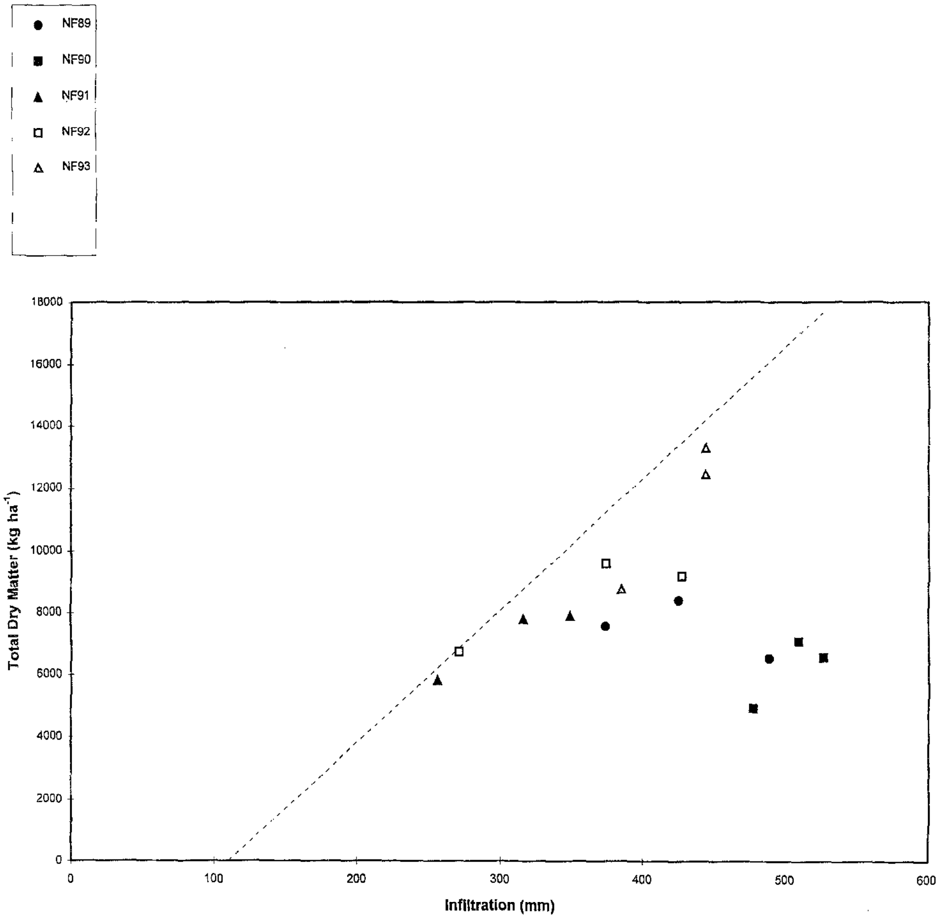

Fig. 3. Relationship between total yield and infiltration for all crops under normal fertility (NF) between 1989 and 1993.

The N concentration (%) of all straw mulched grain and fodder (R_m, and Pp, PpSt, C, CSt, St) in 1992 was lower (differences typically $P < 0.05$) than grain from non-mulched N_m and PpCSt treatments. The trend was continued in 1993 but the differences, although significant, were fewer (Table 8). Total removal of N in grain and fodder depended on the mulch treatment and N fertiliser application level (Table 9). Removal of N ranged between 38–116 kg N ha^{-1}, 64–141 kg N ha^{-1} and 87–126 kg N ha^{-1} per crop season for low, normal and high N applications between 1991 and 1993.

3.4. *Perennials yields (1989–1992)*

Total dry matter yields between 1990 and 1992 across perennial treatments ranged between 10.8 and 20.3 t ha^{-1} and indicated satisfactory growth (Pp, 14.4 t ha^{-1}; PpSt, 19.6 t ha^{-1}; PpCSt, 20.3 t ha^{-1}; C, 10.8 t ha^{-1}; CSt, 17.6 t ha^{-1}; St, 14.0 t ha^{-1}).

3.5. Interaction of soil management, water relations, nitrogen and yield

Total dry matter for normal fertility treatments exhibited a direct relationship with infiltration (Fig. 3) for all years, except 1990 and for R_m in 1989. In 1990, rain at planting caused waterlogging and a subsequent shootfly attack dramatically reduced yields. The equation for the linear relationship above the envelope of points was:

$$\text{Total dry matter yield} = 42.5(\text{Infiltration}) - 4672. \quad (1)$$

Inclusion of results from low and high fertility subplot treatments with the normal fertility results (Fig. 4) illustrates that yields improved to varying degrees with additional N in each year, but yields were still within the potential water use efficiency line defined by Eq. (1). The slope of the line viz. 42.5, is the potential water use efficiency in units of kg ha^{-1}/mm^{-1}.

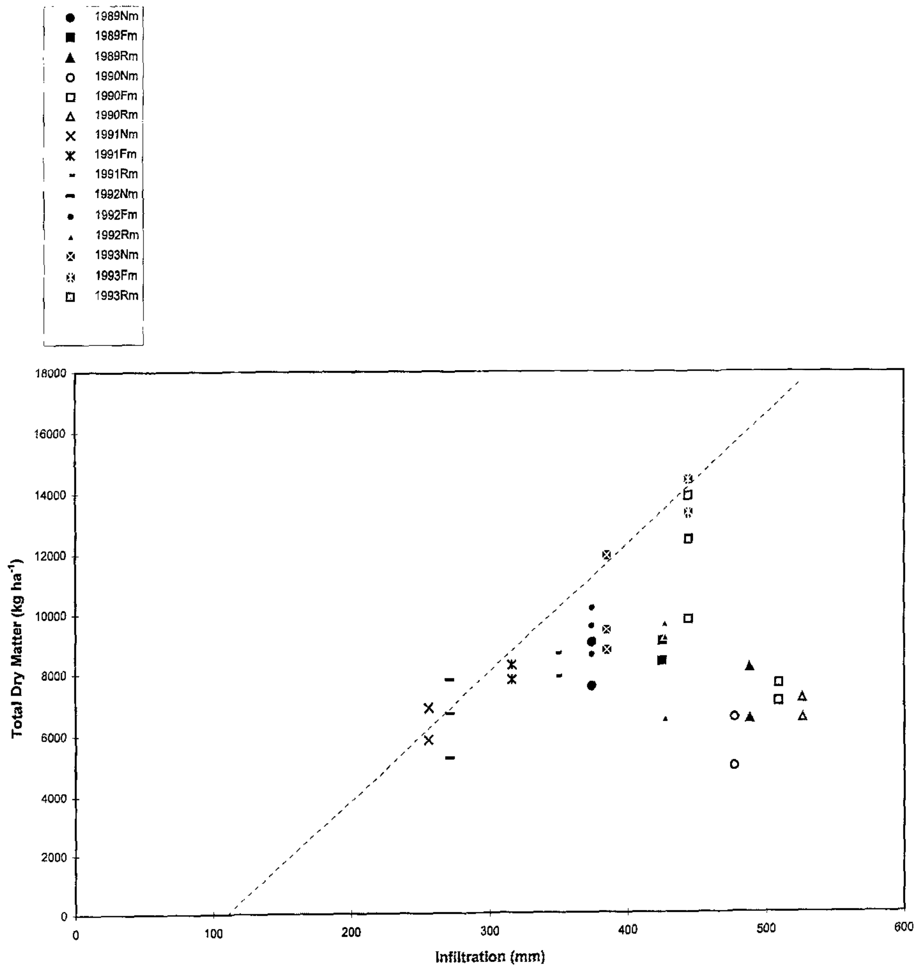

Fig. 4. Relationship between total yield and infiltration for all crops under low, normal and high fertility between 1989 and 1993.

4. Discussion

4.1. Annual cereals (tillage by mulch factorial) 1989–1993

Grain yields from F_m and R_m treatments were between 16 and 59% higher than from N_m treatments (Table 2). These yield increases for mulched crops are attributed to increased availability of water from improved soil management, as shown by Yule et al. (1991). Although mulching may have provided improved nutrient availability, we believe the dominant influence was increased water supply. Supporting evidence comes from the lack of a yield response to high fertility on F_m treatments which suggests that yields under the equivalent normal fertility regime in F_m were not limited by N, P or K. Similarly, the increase in R_m treatments was only marginal (Table 2) following the high fertility fertiliser applications, although yields in N_m did respond to higher fertility. While there may have been a nutrient contribution from the rice straw, we consider that the contribution from the annual application would have little effect on nutrient availability in the current year, given the low N percentage of the straw (0.7% N). The low grain and fodder N concentrations in R_m crops support this. We therefore suggest that improved infiltration in F_m and R_m treatments was the major reason for increased yields and that further fertiliser addition to R_m treatments would have consistently achieved yields similar to F_m.

Plant growth rate was greater in mulched crops as shown by greater LAI (Fig. 2) and plant height in sorghum and maize from F_m and R_m treatments. Lower 100 seed weights for N_m treatments provide further support for poorer growth under unmulched conditions. A delay in plant growth in a soil and water conservation context impacts on the speed at which the crop can provide soil surface protection from raindrop impact. Hence, benefits of mulching (as shown in F_m and R_m) to the soil surface as cover and organic matter for aggregate stability (Cogle et al., 1995b), interact with faster crop canopy development to provide improved water conservation.

The yield increases show the strong potential for increased production using mulches. The increased fodder production provides support for the contention (Unger et al., 1991; Gupta and Moncreif, 1994) that management practices using mulching can be implemented using straw derived from the increased on-farm production (i.e., applying a proportion of the fodder produced in any year). In many countries, including India (Kelley et al., 1993), straw has considerable financial value and increased fodder production is crucial for acceptance of management practices, that promote organic matter retention. Similarly, farmyard-manure has alternative uses (fuel, construction, mulching) but is perceived as beneficial to soil structure by Indian farmers (Motivalli and Anders, 1991) and increased grain and fodder production obtained from F_m mulching will further enhance its value as a mulch. However, farmyard manure does vary in quality depending on its source and its method of collection (Probert et al., 1992; Motivalli and Anders, 1991) and this may affect crop and soil response in any one year. It should be noted, that to maximise the benefit of mulching, farmyard-manure should be applied as a mulch and should not be incorporated into the soil.

While our results show no benefit of tillage, weed control was achieved using herbicides and hand weeding, which is a form of interrow cultivation. Where weed control in farmers fields involves interrow cultivation, which may break surface crusts, infiltration may be greater than in our experiment. Such tillage incurs short and long term costs. Our results show the potential benefits of soil structural modification by mulches, either from surface soil protection or the development of a favorable soil structure (macropore development, surface aggregate stability) (Cogle et al., 1995b), and presumably soil water environment for root proliferation, when mulches are used.

4.2. Annual cereals (following 4 years of perennials) 1992–1993

Grain yields of maize grown in prior-perennial treatments yielded between 14 and 81% more than the unmulched treatment (N_m), with one exception. The exception was maize from the low fertility C treatment which showed a yield depression, probably due to severe nutrient deficiency caused by exploitation of the soil nutrient reserve by the only non legume perennial, *C. ciliaris*; and perhaps an immobilising effect caused by slowly decomposing grass roots and remaining tops.

The grain yield benefit in prior-perennial treatments which were unmulched during the maize crop was between 19 and 25% for normal and high fertility treatments over the N_m treatment. The important aspect of this result is that the treatment (unmulched prior-perennial-PpCSt) which would be more likely to be adopted as an innovation in farm situations still yielded more than the treatment most resembling farmer practice. As shown in other papers (Littleboy et al., 1996; Smith et al., 1992; Yule et al., 1991; Cogle et al., 1996), benefits would also apply to resource protection and hence the pasture/crop rotation has potential in regions where grazing animals are part of the agricultural system.

The N contribution of perennials to the first subsequent cereal crop can be examined by comparing maize grown in Pp, PpSt, C, CSt, and St with T_0R_m; and maize grown in PpCSt with T_0N_m (and similarly for sorghum for the second subsequent crop). There was no yield improvement for maize grown after perennials, if straw was applied, indeed N levels were similar for all straw mulched maize regardless of the prior crop; similarly for sorghum in 1993. Maize yields from PpCSt plots were significantly higher ($P < 0.05$) than T_0N_m in normal fertility treatments, however there was no difference at other fertility levels or in the second year when sorghum was grown. Further, the N% of maize and sorghum from PpCSt plots was little different to F_m and N_m treatments. This provides further evidence that increased water availability was the main contributing factor in yield improvement following mulching or perennial/annual crop rotations, and that N from prior-perennial crops was not a large yield contributor.

4.3. Interaction of soil management, water relations, N and yield

The potential water use efficiency (WUE) of 42.538 kg ha^{-1} mm^{-1}, defined by the slope of the arbitrary line relationship between NF yield and infiltration, is in the range reported by other authors (Perry, 1987). As discussed previously, increased yield is positively related to improved crop water supply. Our arbitrary line drawn at the top of the envelope of points, similar to that of French and Schultz (1984), shows that some treatments were yielding substantially below their yield potential. The straw mulched treatment (R_m) was noticeable in this regard and perhaps produced below its potential due to an N limitation, as implied by the lower grain N percentages. The WUE relationship also showed the unmulched treatments (N_m) were growing almost to their potential WUE, even though the N_m treatments responded the most in percent yield terms to the HF treatment. Difficulties with the sorghum pest, shootfly, help explain the poor WUE relationships for the 1989 data.

Inclusion of all fertility treatments (LF, NF, HF) (Fig. 4) illustrates that an yield improvements occurred to a certain degree with added nutrition in yield, although they were generally not significant ($P < 0.05$). Notably, but the same line enclosed the expanded set of data, which indicates either that nutrition was adequate or that other nutrients beside N were limiting. While we are more confident with the NF yield compared to the LF and HF yield vs. infiltration data, due to smaller plot sizes for the latter, this is an important finding in so much as it emphasises that yield increases were due principally to improvements in water availability, via soil management, rather than nutritional effects. Further investigations to confirm our findings should consider the influence of different N rates, and other nutrients on full size plots to provide a better understanding of the water and nutrient interactions that influence yield in this situation.

5. Conclusion

Our aim in analysing the interactions between soil management, water relations, and N was to broadly identify the driving factors for yield improvement in Alfisols in the SAT environment. This analysis suggests that water availability, as influenced by mulch treatment through reduced run-off, was the critical factor. The effect of three N rates (0, 100, and 186 kg N ha^{-1}) were also considered, although only the effect of 100 kg N ha^{-1} rate could be linked to water availability due to run-off plot size. Further investigations should consider the influence of different N rates, and other nutrients, on the development of the crop canopy and consequent water conservation for different mulches to provide a fuller understanding of the water and nutrient interactions that influence yield. These investigations should consider a broad range of N levels, both below and above 100 kg N ha^{-1}. In the Indian situation, the effects of differing levels of residue retention need to be determined to place a monetary value on retention to compare to the market value as fodder. Experimentation is also needed to determine optimum mixtures of retention, nutrition and mulching and the timing of the mulch effect viz it is possible to remove mulch for other purposes sometime during the crop cycle.

These results provide key data for the development of simulation models so that predictions can be made of the long term impact of soil management on crop yields and economic returns. Initial attempts were made by Cogle and Rao (1994), but further development is necessary using models calibrated both for soil management and N nutrition. The development of these types of models requires greater emphasis for SAT environments as both water and N are major limiting factors. Studies such as those by Littleboy et al. (1992, 1996) and Carberry et al. (1992) provide the necessary basis for these developments.

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References

Carberry, P.S., Cogle, A.L., McCown, R.J., 1992. An assessment of the cropping potential for land marginal to the Atherton Tablelands of north Queensland. Final Report of Project CSC-16A, Rural Industries Research and Development, Brisbane, 70 pp.

Cogle, A.L., Rao, K.P.C, 1994. Water conservation in soils of the semi-arid tropics. In: Virmani, S.M., Katyal, J.C., Eswaran, H., Abrol, I.P. (Eds.), Stressed Ecosystems and Sustainable Agriculture. Oxford and IBH Publishing Pvt., New Delhi, pp. 241–251.

Cogle, A.L., Bateman, R.J., Heiner, D.H., 1991. Conservation cropping systems for the semi-arid tropics of north Queensland, Australia. Aust. J. Exp. Agric. 31, 515–523.

Cogle, A.L., Littlemore, J., Heiner, D.H., 1995a. Soil organic matter changes and crop responses to fertiliser under conservation cropping systems in the semi-arid tropics of north Queensland, Australia. Aust. J. Exp. Agric. 35, 233–237.

Cogle, A.L., Reddy, M.V.R., Rao, K.P.C., Smith, G.D., McGarry, D., Yule, D.F., 1995b. The role of biological practices and the soil biota in management of sealing, crusting and hardsetting soils. In: So, H.B., Smith, G.D., Raine, S.R., Schafer, B.M., Loch, R.J. (Eds.), Sealing, Crusting and Hardsetting Soils: Productivity and Conservation. Aust. Soc. Soil Sci., pp. 305–324.

Cogle, A.L., Littleboy, M., Rao, K.P.C., Smith, G.D., Yule, D.F., 1996. Soil management and production of Alfisols in the semi-arid tropics: III. Long term effects on the resource base and production. Aust. J. Soil Res. 34 (1), 113–125.

Dalal, R.C., Strong, W.M., Weston, E.J., Gaffney, J., 1991. Sustaining multiple production systems: II. Soil fertility decline and restoration of cropping lands in sub-tropical Queensland. Trop. Grassl. 25, 173–180.

El-Swaify, S.A., Pathak, P., Rego, T.J., Singh, S., 1985. Soil management for optimized productivity under rainfed conditions in the semi-arid tropics. Adv. Soil Sci. 1, 1–63.

French, R.J., Schultz, J.E., 1984. Water use efficiency of wheat in a Mediterranean-type environment: I. The relation between yield, water use and climate. Aust. J. Agric. Res. 35, 743–764.

GENSTAT 5 Committee, 1993. GENSTAT 5 Release 3 Reference Manual. Clarendon Press, Oxford, p. 796.

Gupta, S.C., Moncreif, J.P., 1994. Tillage and land management as a means to mitigate stresses constraining sustainable agriculture. In: Virmani, S.M., Katyal, J.C., Eswaran, H., Abrol, I.P. (Eds.), Stressed Ecosystems and Sustainable Agriculture. Oxford and IBH Publishing Pvt., New Delhi, pp. 355–367.

Hoogmoed, W., 1995. Methods of managing problems in crusting and hardsetting soils. In: So, H.B., Smith, G.D., Raine, S.R., Schafer, B.M., Loch, R.J. (Eds.), Sealing, Crusting and Hardsetting Soils: Productivity and Conservation, Aust. Soc. Soil Sci., pp. 259–278.

Jones, R.K., Dalgleish, N.P., Dimes, J.P., McCown, R.L., 1991. Sustaining multiple production systems: IV. Ley pastures in crop–livestock systems in the semi-arid tropics. Trop. Grassl. 25, 189–196.

Kampen, J., Burford, J.R., 1980. Production systems, soil related constraints and potentials in the semi-arid tropics with special reference to India. In: Priorities for Alleviating Soil Related Constraints to Food Production in the Tropics. Los Banos, Laguna, Philippines, IRRI, pp. 141–165.

Kelley, T.G., Parthasarathy Rao, P., Walker, T.S., 1993. The relative value of cereal straw fodder in the semiarid tropics of India: implications for cereal breeding programmes at ICRISAT. In: Dvorak, K.A. (Ed.), Social Science Research for Agricultural Technology Development—Spatial and Temporal Dimensions. CAB International UK, pp. 88–105.

Lal, R., 1989. Conservation tillage for sustainable agriculture: tropic vs. temperate environments. Adv. Agron. 42, 85–197.

Laryea, K.B., Pathak, P., Klaij, M.C., 1991. Tillage systems and soils of the semi-arid tropics. Soil Tillage Res. 20, 201–218.

Littleboy, M., Freebairn, D.M., Hammer, G.L., Silburn, D.M., 1992. Impact of soil erosion on production in cropping systems: II. Simulation of production and erosion risks for a wheat cropping system. Aust. J. Soil Res. 30, 775–788.

Littleboy, M., Cogle, A.L., Rao, K.P.C., Smith, G.D., Yule, D.F., 1996. Soil management and production of Alfisols in the semi-arid tropics: I. Modelling the effects of surface cover and tillage on runoff and erosion. Aust. J. Soil Res. 34 (1), 91–102.

McCown, R.L., Jones, R.K., Peake, D.C.I., 1985. Evaluation of a no-till, tropical legume ley farming strategy. In: Muchow, R.C. (Ed.), Agro-Research for the Semi-arid Tropics: NW Australia. University of Queensland Press, pp. 450–469.

Motivalli, P.P., Anders, M.M., (1991). Management of farmyard manure in India's semi-arid tropics: farmer perceptions and practice. Resource Management Program Production Agronomy Progress Report 1. ICRISAT, Patancheru, India, 101, pp.

Mullins, C.E., MacLeod, D.A., Northcote, K.H., Tisdall, J.M., Young, I.M., 1990. Hardsetting soils: behaviour, occurrence and management. Adv. Soil Sci. 11, 37–99.

Perry, M.W., 1987. Water use efficiency of non-irrigated field crops. In: Proceedings of 4th Australian Agronomy Conference La Trobe University, Melbourne, pp. 88–99.

Probert, M.E., Okalebo, J.R., Simpson, J.R., Jones, R.K., 1992. The role of boma manure for improving soil fertility. In: Probert, M.E. (Ed.), A Search for Strategies for Sustainable Dryland Cropping in Semi-Arid Eastern Kenya. ACIAR Proceedings No. 41, pp. 63–70.

Rao, K.P.C, Cogle, A.L., Yule, D.F., Smith, G.D., Srinivasan, S.T., 1992. Development of sustainable management systems for Alfisols: a biological approach. In: Narain, Prem (Ed.), Proceedings First Agricultural Science Congress—1992. National Academy of Agricultural Sciences, Indian Agricultural Research Institute, New Delhi, pp. 261–270.

Reddy, M.V., Yule, D.F., Ravinder Reddy, V., George, P.J., 1992. Attack on pigeonpea (*Cajanus cajan* (L.) by *Odontotermes obesus* (Rambur) and *Microtermes obesis* Holmgren (Isoptera: Microtermitinae). Trop. Pest Manage. 38 (3), 239–240.

Smith, G.D., Coughlan, K.J., Yule, D.F., Laryea, K.B., Srivastava, K.L., Thomas, N.P., Cogle, A.L., 1992. Soil management options to reduce runoff and erosion on a hardsetting Alfisol in the semi-arid tropics. Soil Tillage Res. 25, 195–215.

Unger, P.W., Stewart, B.A., Parr, J.F., Singh, R.P., 1991. Crop residue management and tillage methods for conserving soil and water in semi-arid regions. Soil Tillage Res. 20, 219–240.

Venkateswarlu, J., 1987. Efficient resource management systems for drylands of India. Adv. Soil Sci. 7, 165–221.

Vittal, K.P.R., Vijayalakshmi, K., Rao, U.M.B., 1983. Effect of deep tillage on dryland crop production in red soils of India. Soil Tillage Res. 3, 377–384.

Yule, D.F., Cogle, A.L., Smith, G.D., Rao, K.P.C., George, P.J., 1991. Soil management of Alfisols for water conservation and utilization. J. Indian Water Res. Soc. 11, 10–13.