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Changes in some soil properties due to tillage practices in rainfed hardsetting Alfisols and irrigated Vertisols of eastern Australia

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Abstract

Changes in soil physical and chemical properties were evaluated in several on-farm studies located in rainfed, hardsetting red Alfisols (Ferric Luvisols) and in irrigated, self-mulching Vertisols (Chromic Vertisols) of eastern Australia. The objective of the studies was to evaluate changes in soil physical and chemical properties with time under commercial farming situations where changes had been made to previously used farming systems (native pasture to wheat (*Triticum* sp.) cultivation in the hardsetting Alfisols; intensively tilled cotton (*Gossypium* sp.) monoculture to minimum tilled cotton monoculture and cotton–wheat sequences in the irrigated Vertisols). The soil physical and chemical changes in the Alfisols were caused by changing land use from native pasture to intensively tilled wheat cultivation with long fallow and stubble burning, whereas those in the Vertisols were caused by changing from intensive to minimum tillage in cotton-based cropping systems. Indicators of soil physical (tensile strength, structural stability, dispersion) and chemical (pH, electrical conductivity, organic C, total N) quality evaluated in the Alfisols indicated that a significant deterioration in soil quality, which was characterized by an increase in hardsetting behaviour and acidity, and a decrease in organic C, total N and aggregate stability had occurred. These changes were due to inappropriate tillage practices causing soil inversion and the rapid breakdown of organic matter which occurs when intensive tillage practices are imposed in previously untilled soils. In the Vertisols, however, indicators of soil physical (specific volume of air-filled pores in oven-dried clods, plastic limit, soil resilience) and chemical (pH, electrical conductivity, exchangeable sodium percentage, and soil organic C) quality indicated that while deterioration in physical quality (i.e., characterized by an increase in compaction) had occurred, chemical quality had improved. The latter was characterized by an increase in soil organic C and a decrease in exchangeable sodium percentage. These changes were due to replacing intensive tillage with minimum tillage. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Alfisol; Vertisol; Soil quality; Tillage systems; Cropping systems; Farming systems; Soil organic matter; Hardsetting

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1. Introduction

Indices used to evaluate soil quality differ between farming systems, soil types and land uses (MacEwan and Carter, 1996). Karlen et al. (1992) suggest that soil tilth (described by porosity, aggregation and other structural measures) is a useful index of soil physical quality, whereas possible chemical indicators of soil quality include pH, exchangeable cations and derived values, salinity and soil organic carbon. Physical properties which have proven useful in characterizing soil tilth include soil strength, aggregate stability and clay dispersion in hardsetting Alfisols (Mullins et al., 1990; Chan and Mullins, 1994; Chan, 1995). In comparison, air-filled porosity, specific volume, depth of water infiltration, aggregate stability, soil shrinkage characteristics, plastic limit, self-mulching behaviour, crack volume and depth, water infiltration and soil strength have been utilized to characterize Vertisols (McGarity et al., 1984; Daniells, 1989; Pillai-McGarry et al., 1995; Hulugalle and Entwistle, 1997). These physical properties are strongly influenced by chemical properties such as pH, exchangeable cations, sodicity, calcium carbonate concentration and soil organic carbon (Dalal, 1989; Little et al., 1992; Hulugalle and Entwistle, 1997; Hulugalle et al., 1997).

In the semi-arid areas of eastern Australia both Alfisols and Vertisols have been used extensively for crop production. Under conventional tillage practices, increasing degradation has been reported namely chemical fertility decline in Alfisols and Vertisols, and structural degradation characterized by increases in hardsetting problems for the Alfisols, and severe compaction and associated waterlogging for the Vertisols (State of the Environment Advisory Council, 1996). Furthermore, there is a paucity of information with respect to the likely changes in soil quality under alternative tillage and cropping practices in commercial farming systems.

The objective of the studies reported in this paper was to evaluate changes in soil physical and chemical properties with time under commercial farming situations where changes had been made to previously used farming systems (native pasture to wheat cultivation in hardsetting Alfisols; intensively tilled cotton monoculture to minimum tilled cotton monoculture and cotton–wheat sequences in the irrigated Vertisols). In this paper we present data on selected soil physical and chemical properties for the above-mentioned soil types and production systems.

2. Methods and materials

2.1. Rainfed Alfisols

2.1.1. Comparison of cultivated and pasture soils

Soils were sampled from 61 sites on 30 commercial farms near Trangie in the semi-arid cropping zone of central-west New South Wales, Australia (31°57′S, 148°02′E). The area has an annual rainfall <500 mm which is highly variable and non-seasonal, and it experiences four distinct seasons with a mild winter and a hot summer. The hottest month is January (33°C) and the coldest is July (15°C). The soils sampled were hardsetting red Alfisols and classified as thermic, kaolinitic, Kandic Paleustalfs (Soil Survey Staff, 1994) or Ferric Luvisols (FAO/UNESCO, 1974). On each farm, samples were taken from fields under (a) pasture which had never been cultivated (referred to as "pasture"), and (b) cultivated with wheat (*Triticum aestivum* L.) for several years using conventional tillage (tillage to 0.1 m 3–5 times with disc or tyne implements) prior to sowing and 15–18 months long fallow (referred to as "cultivated"). In this system wheat stubble was burnt after harvest. At each site, composite soil samples (~10 sub-samples within an area of 100 m × 100 m) were collected from two layers, viz. 0.00–0.05 m and 0.05–0.10 m. Soil properties determined on air-dried soil (<2 mm) were: pH and electrical conductivity (1:5 soil:water); total soil carbon and total nitrogen using a Leco furnace (Rayment and Higginson, 1992); clay dispersion (Rengasamy et al., 1984); and tensile strength and structural stability. Tensile strength was evaluated on sub-samples (<6 mm) which were poured into perspex cylinders (25.8 mm diameter and 13 mm high) sitting in a shallow tray of de-ionized water. The soil disks were then dried at 40°C, placed on the side and the force required for failure determined by crushing between parallel plates, and tensile strength calculated (Chan, 1995). Soil structural (wet aggregate) stability was determined by wet-sieving 20 g of air-dried soil for 10 min using sieves of 2 mm and 0.25 mm aperture in a 2 l cylindrical container. After wet sieving, the container was inverted 10 times and the <0.05 mm fraction determined using a pipette sampling technique. Proportions of water stable aggregates >2 mm, 2−0.25 mm and <0.05 mm were calculated. Aggregate size distribution was expressed as mean weight diameter (MWD).

2.1.2. Undisturbed soil in a permanent pasture

Soil physical and chemical properties were evaluated at a single native permanent pasture site, which was dominated by native pasture species *Stipa spp.* and *Enteropogon acicularis*, and an adjacent 20-year old conventionally cultivated area on a Kandic Paleustalf. Composite soil samples (made up from 5–6 sub-samples) were collected from the permanent pasture area from three depths namely 0.00–0.02 m, 0.02–0.05 m and 0.10–0.15 m and from the 0.00–0.10 m depth of the cultivated area. The samples were analysed for organic carbon, and tensile strength as described previously over a range of water potentials (−1 kPa to −100 MPa). Ratio of tensile strength at −1 MPa to that at −0.1 MPa was taken as a measure of hardsetting potential of the soil. Structural stability of the surface soil (0–0.05 m) in both sites was assessed using the wet sieving method (as described above). In addition measurements of structural stability were made on soil sampled from a sub-plot within the cultivated area where a sown pasture of consol (African) lovegrass (*Eragrostis curvula* L.) had been established for 8 years.

2.2. Irrigated Vertisols

The sites were located on two commercial cotton (*Gossypium hirsutum* L.) farms: “Beechworth” in Merah North (30°11′S, 149°18′E) and “Glenarvon” in Wee Waa (30°13′S, 149°27′E), north-western New South Wales, Australia. The experimental sites have semi-arid climates (rainfall of 615 mm) and experience four distinct seasons with a mild winter and a hot summer. The hottest month is January (34°C) and the coldest is July (18°C). The soil at each site is a deep, uniform grey clay and is classified as a fine, thermic, montmorillonitic, Typic Haplustert (Soil Survey Staff, 1994) or a Chromic Vertisol (FAO/UNESCO, 1974). Details of soil properties at the commencement of the study (1993 at “Glenarvon” and 1994 at “Beechworth”) are summarized in Table 1.

2.2.1. Tillage and cropping practice

In both sites land preparation prior to commencing the study consisted of disc-plowing to 0.2 m, chiselling to 0.3 m and reformation of ridges. Crop residues were burnt in situ. Deep ripping to 0.5 m was done every 3–5 years. After the study commenced land preparation consisted solely of ridge cultivation to 0.1 m followed by reforming the old ridges every year. All crop residues were slashed and incorporated into the ridges. There was no sub-surface tillage or burning of crop residues during the study period. Prior to this study both sites had been cropped continuously with cotton for a period of 15 years at “Glenarvon”

Table 1
Soil properties at experimental sites in New South Wales

Soil properties	Wee Waa[a] “Glenarvon”[b]		Merah North[a] “Beechworth”[b]		Trangie[a] –[b]	
	0–0.3 m	0.3–0.6 m	0–0.3 m	0.3–0.6 m	0–0.1 m	0.1–0.3 m
Clay (g kg^{-1})	540	550	620	650	160	300
Silt (g kg^{-1})	190	180	160	190	130	190
Sand (g kg^{-1})	270	270	220	160	710	510
Organic C (g kg^{-1})	10.5	9.1	8.0	5.7	8.7	5.0
Exchangeable sodium percentage	1.8	2.8	8.3	14.9	0.8	0.4
Electrical conductivity in 1:5 soil:water (dS m^{-1})	0.14	0.07	0.15	0.18	0.02	0.02
$CaCO_3$ (g kg^{-1})	25	29	62	68	Nil	Nil
Soil order	Vertisol		Vertisol		Alfisol	

[a] Location.

[b] Farm name.

and 6 years at "Beechworth". During the study the plots at "Beechworth" were cultivated continuously with cotton (cotton–winter fallow–cotton), whereas those at "Glenarvon" were cultivated with a cotton–winter wheat sequence (cotton–winter wheat summer and winter fallow–cotton). Individual plots (three at "Beechworth"; four at "Glenarvon"; all plots in each farm were located in the same field) consisted of 24 rows, spaced at 1 m intervals, which were 400 m long. In both sites commercial cropping practices (mechanized farm operations; aerial application of pesticides and defoliants etc.) used in local cotton production systems were followed, with all field operations being carried out by the co-operating cotton growers. The crops were irrigated by furrow irrigation at a rate of approximately 1 ML ha^{-1} when rainfall was insufficient to overcome evaporative demand.

2.2.2. Soil sampling and analysis

Soil was sampled with a spade from the 0.00–0.15 m, 0.15–0.30 m, 0.30–0.45 m and 0.45–0.60 m depths in rows adjacent to non-wheel-tracked furrows during June 1993 and 1996 at "Glenarvon", and May 1994 and 1996 at "Beechworth". Sampling was restricted to the central 12 rows of each plot, and encompassed a 60 m wide zone which centred on the spot which was 200 m from the head-ditch. A stratified random sampling design which used a grid of 20 m × 6 m was used to sample from six sites in each plot. One soil clod was taken from each depth interval in every sampling site in each plot. The rest of the soil was bulked to give a single composite sample for each depth interval in each plot. Soil physical properties evaluated were: specific volume of air-filled pores in soil clods (mean volume of 165×10^{-6} m^3) oven-dried to a temperature of 110°C after coating with a mixture of 1:7 saran resin:butanone (ethyl-methyl ketone) (Klute, 1986), plastic limit and soil resilience. Soil resilience, a measure of the self-mulching ability of the soil, was determined by puddling 25 g of sieved (<2 mm), air-dried soil and oven-drying thereafter at 40°C for 72 h. The size distribution of the aggregates formed (determined by dry-sieving on a nest of sieves with apertures of 9.5, 4, 2, 1 and 0.25 mm on a mechanical shaker) was expressed as the geometric mean diameter of the soil aggregates (Klute, 1986). Plastic limit was determined with a drop-cone penetrometer (Campbell, 1976) on 25 g samples (<2 mm) pre-wetted to different water contents and equilibrated over a two-day period in sealed plastic containers (25 cm^3). Indicators of soil chemical quality determined on air-dried soil (<2 mm) were: pH (in 1:5 soil: 0.01 M $CaCl_2$); electrical conductivity (1:5 soil:-water); and exchangeable sodium percentage (ESP) as: (exchangeable Na/cation exchange capacity) × 100. The cation exchange capacity was calculated as the sum of exchangeable Ca, Mg, K and Na determined after washing the soil with 60% aqueous alcohol and 20% aqueous glycerol to remove soluble salts and extraction with alcoholic 1 M NH_4Cl at a pH of 8.5 ("Tucker method") (Rayment and Higginson, 1992). Total soil organic carbon was determined on air-dried soil (<0.5 mm) by the wet oxidation method of Walkley and Black (Rayment and Higginson, 1992). All data were analysed with univariate analysis of variance to evaluate changes over time.

3. Results and discussion

3.1. Rainfed Alfisols

3.1.1. Comparison of cultivated and pasture soils

The cultivated soils had significantly lower organic C and total N in the 0–0.05 m layer (Table 2). Mean organic carbon content of the cultivated soils was about half of that in the pasture soils. The cultivated soils also had significantly lower water stability (MWD) and higher tensile strength of aggregates (Table 2). The higher per cent of mechanically dispersible clay found in the cultivated soils compared to the pasture soils (Table 2) confirmed their increased hardsetting behaviour (Young and Mullins, 1991). The cultivated soils at 0.00–0.05 m also had significantly lower pH and electrical conductivity (Table 2). For the 0.05–0.10 m layer, while the organic carbon level was similar, the cultivated soils had significantly lower MWD, higher dispersible clay and higher tensile strength compared with the natural pasture soils.

Examining the depth effect, under natural pasture there is a decline in organic C with depth, and a corresponding increase in tensile strength and hardsetting potential (Table 3). Conventional tillage implements, such as disc plough, which pulverize and invert

Table 2

Changes in soil properties under conventional tillage/wheat-based cropping systems in hardsetting red Alfisols (values within the same column and depth which are followed by different superscripts differ significantly at the 95% level of probability)

Land use system	Depth (m)	Organic C (g kg^{-1})	Total N (mg kg^{-1})	pH	EC[a] (dS m^{-1})	DC[b] (g kg^{-1})	MWD[c] (mm)	Tensile strength (kPa)
Native pasture	0.00–0.05	28.1^{A}	0.20^{A}	5.5^{A}	0.08^{A}	29^{A}	5.1^{A}	44^{A}
Cultivated		13.8^{B}	0.13^{B}	5.1^{B}	0.07^{B}	39^{B}	3.4^{B}	89^{B}
Native pasture	0.05–0.10	13.6^{A}	0.11^{A}	5.3^{A}	0.04^{A}	37^{A}	3.8^{A}	75^{A}
Cultivated		12.2^{A}	0.10^{A}	4.9^{A}	0.04^{A}	46^{B}	2.1^{B}	143^{B}

[a] Electrical conductivity in 1:5 soil:water.

[b] Mechanically dispersible clay.

[c] Mean weight diameter.

Table 3

Soil profile characteristics under native pasture and cropped field in a hardsetting Alfisol (values within the same column and depth which are followed by different superscripts differ significantly at the 95% level of probability)

Landuse system	Depth (m)	Organic C (g kg^{-1})	Tensile strength (kPa)	Hardsetting potential
Native pasture	0.00–0.02	42.9^{A}	4^{A}	0.0^{A}
	0.02–0.05	20.0^{B}	49^{B}	1.3^{B}
	0.10–0.15	6.6^{C}	226^{C}	3.6^{C}
Cultivated field	0.00–0.10	8.7	99	2.3

soil, and lead to increased losses of organic C and exposure of the hardsetting sub-soil. Therefore, exacerbation of hardsetting problems occurs under cropping. The latter is thought to be related to the separation of fine materials (<63 μm) from the macroaggregates (Chan and Mullins, 1994) and as such might be irreversible. The above results highlight the importance of using appropriate tillage practices in managing these fragile soils. A novel dual depth non-inversion tillage implement is being developed for managing these soils (Mead and Chan, 1995).

3.1.2. *Effectiveness of pasture phase in structural amelioration: evidence of irreversibility*

The highest water stability was found in the native pasture soil which had the highest >2.00 mm and 0.25–2.00 mm fraction, and the lowest <0.05 mm fraction (Fig. 1). As expected, the cultivated soil has the lowest stability as indicated by the lowest >2 mm fraction and the highest <0.05 mm fraction. For the 8 year pasture soil, while the >2 mm is as high as the native pasture, the <0.05 mm was not significantly different from the cultivated soil, i.e., it was significantly higher than that of the native pasture soil. This suggests that while the pasture phase was effective in promoting macroaggregates, it had little effect on the microaggregate stability. Organic carbon level of the 8 year old sown pasture soil was 14.0 g kg^{-1}, and therefore actually higher than that of the native pasture (12.5 g kg^{-1}) and cultivated (9.0 g kg^{-1}) soils. Hence, the structural breakdown could be irreversible despite the organic carbon increase.

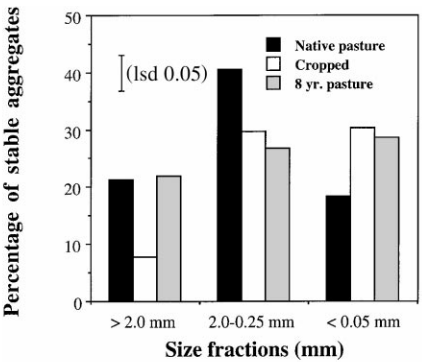

Fig. 1. Water stability of a hardsetting Alfisol under different management practices.

3.2. Irrigated Vertisols

Compaction had increased in both sites; i.e., specific volume of air-filled pores in oven-dried clods had decreased (Table 4). The increases at ''Glenarvon'' had occurred throughout the measured profile and may be due to the fact that wheat was harvested and stubble incorporated in 1995 under wet conditions. However, the increase at ''Beechworth'' occurred only in the 0.15–0.30 m depth, and is probably due to the cumulative effects of mechanized traffic from 1993 to 1996. High and increasing compaction in this layer is common in irrigated cotton monoculture in eastern Australia (McGarity et al., 1984; Daniells, 1989; Constable et al., 1992; Pillai-McGarry et al., 1995). Amelioration of soil compaction and maintenance of the soil in a less compacted state may require other management strategies such as the strict application of controlled traffic principles at these sites (Yule and Tullberg, 1995). However, it should be noted that soil faunal populations are decimated by the low air-porosities frequent in irrigated Vertisols (Tisdall and Hodgson, 1990) and by the high rate of agro-chemical application (Hulugalle et al., 1997). Past studies of minimum tillage in dryland Vertisols have suggested that improvements in soil physical properties associated with soil tilth, an indicator of soil physical quality (Karlen et al., 1992) in minimum tilled soil is largely attributable to increases in soil faunal activity (Holt et al., 1993; Radford et al., 1995). In the absence of soil faunal activity a significant proportion of the potential benefits of minimum tillage may not be realized. Soil resilience had increased at ''Glenarvon'' but decreased in depths >0.3 m at ''Beechworth'', and may be associated with more intense drying in the former site. Profile water content measurements indicated that sub-soil water extraction at ''Glenarvon'', particularly during the wheat phase, frequently resulted in soil water content values close to the wilting point, whereas this did not occur at ''Beechworth'' (Hulugalle and Entwistle, unpublished data; J. Quinn, personal communication). Plastic limit increased in both sites and may be related to increases in soil organic matter and decreases in pH (Table 4), which cause decreases in $CaCO_3$ and increases in exchangeable Ca (Little et al., 1992; Chorom and Rengasamy, 1997).

Increases in soil organic carbon and electrical conductivity, and decreases in pH and ESP occurred in both sites (Table 4). The sub-soil (0.15–0.60 m) increases in soil organic carbon were unexpectedly high in both sites, with the intensity of the changes being greater at ''Glenarvon''. Higher concentrations of soil organic carbon in deeper soil horizons than in shallower horizons have been previously reported in Vertisols (Dalal, 1989; Sjkemstad et al., 1997). Radiocarbon dating of the organic C in the latter study (Sjkemstad et al., 1997) also suggested that the soil organic carbon in the deeper horizons was of more recent origin than that in the shallower horizons. The increase in soil organic carbon in our study may be due to a combination of several factors:

(a) The relatively high C/N ratios of cotton stubble (40–80) and root material (80–180) results in very slow decomposition of cotton crop residues (Hulugalle et al., 1998). Consequently, the soil organic carbon measured at any one time in a cotton-based cropping system is related to crop residue inputs from up to 5 years earlier, and not merely from the two preceding cropping season. (As a general guide, total crop residues incorporated at ''Glenarvon'' during the study period were 23 Mg ha^{-1} above-ground and 12 Mg ha^{-1} (estimated) below ground, and 6 and 3 Mg ha^{-1} above- and below-ground (estimated), respectively, at ''Beechworth''.) The unusually warm (daytime maximum temperatures $\geq 25°C$) and frequent rainfall (of the order of 160 mm) during spring (September–November) 1995 combined with irrigation is likely to have facilitated decomposition of these accumulated crop residues.

(b) Decomposition rates of soil organic matter are lower with minimum tillage and residue retention, and consequently organic carbon content increases over time (Loch and Coughlan, 1984; Dalal, 1989; Hulugalle and Entwistle, 1997; Hulugalle et al., 1997). The reduction of tillage intensity reduces disruption of clay coatings and microaggregates which protect soil organic matter from microbial degradation (Sjkemstad et al., 1997).

(c) Dissolved organic carbon and organic carbon associated with sediments being transported in infiltrating water moving through large cracks into the sub-soil, and organic carbon associated with dry soil falling down the large cracks (Dalal, 1989; Sjkemstad et al., 1997). Crop residues may also fall down cracks and decompose, further increasing soil organic matter content at depth. Formation of large cracks due to soil

Table 4

Comparison of changes in soil properties with depth over time under minimum tillage in irrigated Vertisols (values within the same column for any one site and index which are followed by different superscripts differ significantly at the 95% level of probability)

Soil property	Cotton–winter wheat sequence at "Glenarvon"					Continuous cotton at "Beechworth"				
	Year	0.00–0.15 m	0.15–0.30 m	0.30–0.45 m	0.45–0.60 m	Year	0.00–0.15 m	0.15–0.30 m	0.30–0.45 m	0.45–0.60 m
pH in 1:5 soil:0.01 M $CaCl_2$	1993	7.3^{A}	7.3^{A}	7.3^{A}	7.4^{A}	1994	6.8^{A}	6.7^{A}	7.2^{A}	7.2^{A}
	1996	6.7^{B}	6.9^{B}	6.9^{B}	7.0^{B}	1996	6.6^{B}	6.7^{A}	6.5^{B}	6.4^{B}
EC in 1:5 soil: water (dS m^{-1})	1993	0.17^{A}	0.10^{A}	0.05^{A}	0.08^{A}	1994	0.14^{A}	0.14^{A}	0.15^{A}	0.20^{A}
	1996	0.16^{A}	0.23^{B}	0.17^{B}	0.16^{B}	1996	0.09^{B}	0.11^{B}	0.11^{B}	0.25^{B}
Plastic limit (g $100g^{-1}$)	1993	16.1^{A}	15.6^{A}	12.9^{A}	13.7^{A}	1994	14.0^{A}	13.3^{A}	14.2^{A}	13.0^{A}
	1996	16.3^{A}	15.3^{A}	16.1^{B}	15.8^{B}	1996	16.7^{B}	17.2^{B}	16.0^{B}	15.8^{B}
Total soil organic C (g kg^{-1})	1993	10.9^{A}	8.1^{A}	8.4^{A}	7.4^{A}	1994	8.6^{A}	8.2^{A}	6.5^{A}	5.1^{A}
	1996	12.9^{B}	11.8^{B}	12.8^{B}	10.2^{B}	1996	10.1^{B}	9.1^{B}	9.0^{B}	6.7^{B}
Exchangeable sodium percentage	1993	1.8^{A}	1.8^{A}	2.4^{A}	3.1^{A}	1994	7.3^{A}	8.3^{A}	13.5^{A}	16.1^{A}
	1996	1.0^{B}	1.3^{B}	2.0^{B}	2.5^{B}	1996	4.7^{B}	6.8^{B}	9.2^{B}	12.5^{B}
Specific volume of air-filled pores in OD soil clods (m^3 $100Mg^{-1}$)[a]	1993	–	10.3^{A}	11.5^{A}	12.1^{A}	1994	–	7.9^{A}	10.7^{A}	9.6^{A}
	1996	–	5.4^{B}	7.5^{B}	8.0^{B}	1996	–	2.6^{B}	8.4^{A}	10.6^{A}
Soil resilience (mm)	1993	6.3^{A}	7.5^{A}	8.1^{A}	8.8^{A}	1994	5.6^{A}	6.1^{A}	6.0^{A}	5.8^{A}
	1996	5.9^{B}	7.1^{B}	7.4^{B}	7.0^{B}	1996	6.0^{A}	6.0^{A}	7.3^{B}	8.4^{B}

[a] Specific volume of air-filled pores in 0–0.15 m was evaluated by different methods during 1993–1994 and in 1996. Comparison between years is, therefore, not possible. OD = oven-dried.

shrinkage is a characteristic feature of Vertisols (McGarity et al., 1984). Furthermore due to the more frequent wetting and drying cycles which occur in irrigated Vertisols than in dryland Vertisols, and hence, more frequent water infiltration and cracking, it is likely that organic carbon movement into the sub-soil would take place at a faster rate than in dryland soils.

(d) Differential swelling and shrinking in different soil horizons leads to redistribution of soil organic matter from surface to sub-soil horizons (Sjkemstad et al., 1997). Due to the more frequent wetting and drying cycles which occur in irrigated Vertisols soil inversion may take place at a faster rate than in dryland Vertisols.

The intensity of the changes observed in soil organic carbon has not been reported previously for furrow irrigated Vertisols primarily due to the paucity of detailed information with respect to soil chemical changes over depth and time. Increases of soil organic carbon in the surface horizon are, however, similar to those reported by Loch and Coughlan (1984) and Dalal (1989) for a dryland Vertisol after 8 years. The combination of irrigation and hence, frequent wetting and drying cycles, and minimum tillage suggests that soil processes such as cracking, residue decomposition and mineralization, soil mixing and inversion, and consequent effects on soil properties such as soil organic carbon take place at a faster rate than in dryland farming systems. Both furrow irrigation (Pillai-McGarry et al., 1995) and minimum tillage (Loch and Coughlan, 1984) are reported to maximize depth of wetting and crack volume in Vertisols.

4. Conclusion

Degradation in soil physical and chemical properties of red Alfisols have occurred under existing farming systems, i.e., intensive tillage using conventional implements and continuous wheat cropping. Exacerbation of hardsetting can be caused by using tillage implements which cause soil inversion.

Imposition of minimum tillage to two irrigated Vertisols sown with cotton-based farming systems resulted in improvements in indicators of soil chemical quality but was unable to reduce increases in soil compaction. Long-term management options for these sites would, therefore, require inclusion of the following practices: (i) minimum tillage systems which avoid deep tillage, (ii) controlled traffic where farm machinery is restricted to previously determined furrows, adjusting axle length and wheel width may further assist in keeping traffic off the planting zone (i.e., ridges), (iii) crop residue retention, and (iv) irrigation strategies which permit saturation of the soil profile to depths of at least 1 m, followed by intensive drying. Many cotton farmers do not permit their sub-soil to dry out.

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