# Soil structural form: the effect of irrigation water with varying SAR on several Vertosols

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## Abstract

This paper presents a comparison of four Vertosol surface horizons sampled from the irrigation furrow of cotton fields in the Bourke and Hillston regions of NSW. Five treatments of field water, 'clean' water and solutions of EC 0.5 dS $m^{-1}$ (SAR 0, 7.5 or 15) were each applied to duplicate soil columns (150 mm o.d. × 200 mm h.) in the laboratory. At the completion of six wet–dry cycles, columns were impregnated with fluorescent resin, allowed to dry and digital images collected at 10 mm depth intervals. Binary images were then prepared, and using Solicon v2.1 software, estimates of structural parameters obtained.

The structural from of Vertosol surface horizons was significantly influenced by the sodium content of the irrigating solution. In general, irrigation water of greater SAR increased the dimensions of soil solid attributes but decreased the estimated connectivity of macropore and solid elements. Total macroporosity showed few significant differences when soil was treated with either SAR 7.5 or 15 irrigation water, and pore surface area was less for treatments of greater SAR. Interestingly, irrigating using either 'clean' or field water led to structural attributes similar to those of soil treated with the SAR 7.5 solution. These results show that increasing the sodium contribution of irrigation water resulted in larger soil aggregates, with macropore space being less widely distributed and less connected.

## Key Words

Image analysis, macroporosity, surface area, pore star length, solid star length, pore genus, solid genus

## Introduction

In the Australian environment the availability of water for irrigated cotton (*Gossypium hirsutum*) production is becoming increasingly limited. Continued access to irrigation water from current sources is not assured and it is anticipated that cotton producers will become more reliant on supplies from alternative sources, potentially of lesser quality. This practice is likely to impact on the structural form of Vertosols (Isbell 1996), those soils most frequently used for irrigated cotton production, potentially exacerbating pre–existing sodicity problems. In turn, this will influence soil hydraulic properties and alter crop water use efficiency.

Many authors have defined soil structural form (e.g. Kay 1990; McGarry 1996) but not all account for the properties of vertic soils. Thus, for the purpose of this work we will consider soil structural form to represent the arrangement of solid and void space in a heterogeneous or discontinuous manner; this being the continual development of soil constituents (mineral, organic etc) into aggregates of increasing size and bound by zones of failure. In this context, the mechanics of structural development in Vertosols have been well documented (e.g. Probert *et al.* 1987; Dudal and Eswaran 1988) and summarized by McGarry (1996), who attributed the development of soil structural form to swelling and shrinkage, to climatic conditions and to the physico–chemical nature of each soil. Specifically, the ability of Vertosols to shrink upon drying causes an arrangement of cracks to develop, and the arrangement or pattern of cracking exhibited in a particular soil is a function of landuse and of soil physico–chemical properties, e.g. the size distribution of soil minerals, the quantity and forms of organic material present, and differences in cation concentrations in both exchange and solution phases.

The effect of altered water quality on a number of soil properties has been extensively studied both in the laboratory and the field. An early study by Quirk and Schofield (1955) investigated the effect of electrolyte concentration on the permeability of soil saturated with various exchangeable cations. Many others have followed (e.g. Curtin *et al.* 1994; Crescimanno *et al.* 1995) but the majority of these works were leaching studies using soil columns packed with ground aggregates, soil pastes or in combination with sands. Therefore, a dearth of literature exists describing the effect of solution composition on the structural form of intact Vertosols.

Several methods are available to characterise soil structural attributes. Lebron *et al*. (2002) used thin sections and scanning electron microscopy to identify changes in the characteristics of porosity and aggregation of two soils, a silty loam and a fine sandy loam. This method provides well–defined structural components but the process is time consuming. Alternatively, X–ray computed tomography (CT–scanning) is a rapid, non–destructive method which has been applied in a variety of ways; for example, Mooney (2002) applied CT–scanning to undisturbed soil, preparing 3D visualisations to quantitatively describe soil pore structure. Despite the advantages of this technique, access to scanners, resolution limitations and the associated costs restrict usage. The impregnation of soil columns with an epoxy–based resin and subsequent image analysis (e.g. McBratney *et al.* 1992) in contrast, provides a relatively rapid and inexpensive method of obtaining images of soil sections. Using stereology techniques, soil structural attributes can then be estimated from images of large soil samples.

To address the effect of irrigation water quality on the structural condition of Vertosols, this paper catalogues the degree of change to soil structural form when undisturbed samples are subjected to water of varying quality. Using large soil columns sampled from several cotton–producing fields of the Bourke and Hillston regions, images of structural form were collected and analysed according to Vervoort and Cattle (2003) for an array of attributes including total porosity, surface area and various other pore/solid descriptors.

## Materials and Method

### *Sites investigated*

The surface (0–0.2 m) of four Vertosols in the Bourke and Hillston cotton–growing regions of NSW were sampled. The Bourke cotton–producing area is located approximately 685 km northwest of Sydney, and two sites (B001 and B002) were investigated on the western side of the Darling River. At the time of sampling (March, 2002) cotton was being picked from field B001, while B002 was positioned in a field left in fallow for the following cotton season.

One of the southernmost areas of cotton production in NSW, the Hillston region is located in the lower Lachlan valley approximately 550 km west of Sydney. The two sampling sites (H001 and H002) had each been planted to cotton at the time of sampling (February, 2003).

### *Fundamental soil properties*

At each site, bulk soil was obtained for analysis of fundamental soil properties. The particle size distribution was determined by pipette and sieving (Gee and Bauder 1986) providing coarse sand (2–0.05 mm), fine sand (50–20 µm), silt (20–2 µm) and clay (<2 µm) fractions. Subsequently, the clay fraction was separated to provide a measure of coarse (2–0.2 µm) and fine fractions (<0.2 µm) (Jackson 1956). Soil pH was determined using a 1:5 soil to 0.01 M $CaCl_2$ ratio, while electrical conductivity (EC) and cations in soil solution were obtained using a 1:5 soil to water ratio. Exchangeable cations were extracted with 1 M $NH_4Cl$ at pH 8.5 (Rayment and Higginson 1992). The soil solution and exchangeable cations were quantified using atomic absorption spectroscopy, and effective Cation Exchange Capacity ($CEC_{eff}$) was calculated as the sum of exchangeable $Ca^{2+}$, $Mg^{2+}$, $Na^+$ and $K^+$. The Sodium Adsorption Ratio (SAR) was calculated from soil solution $Na^+$, $Ca^{2+}$ and $Mg^{2+}$, and the Exchangeable Sodium Percentage (ESP) determined from the ratio of exchangeable $Na^+$ and $CEC_{eff}$. Soil organic carbon was determined according to an adjusted Walkely and Black method (McLeod 1975).

### *Sampling, preparation and image analysis*

At each site, ten soil columns (150 mm o.d. × 200 mm h.) were excavated inside polyvinylchloride (PVC) cylinders from an irrigation furrow along a 5 m transect beginning at the tail drain. Columns were extracted and placed into sample bags, sealed and transported to the laboratory. Each column was prepared for irrigation by attaching a PVC cap (160 mm i.d.) to its base, in the centre of which a drainage hole (4 mm d.) had been inserted and covered by 0.2 mm gauze. In order to minimize water movement at the soil–PVC interface a silicone sealant was applied at the inner surface of each cap before being pressed onto each soil column. In addition, a section of PVC pipe (160 mm o.d.) was secured to the upper PVC edge of each column to allow irrigation solution to be ponded on the soil surface.

Soil columns were wetted slowly from the base, using water collected from irrigation sources at each site (FW001, FW002 or FW003); a description of which is given in Table 1. Once each column was wetted, and drained to field capacity, a 150 mm d. filterpaper was placed on the soil surface, and one of five water solutions was applied: FW00*i*, T1 (EC 0 dS/m SAR 0 $(\text{mmol}_{(+)}/\text{L})^{1/2}$) or a solution of EC 0.5 at an SAR 0, 7.5 or 15 (T2–T4). Solutions T2–T4 were prepared by combining $CaCl_2.2H_2O$, $MgCl_2.6H_2O$ and NaCl so that the ratio of Ca:Mg was 1:1 and the amount of $Na^+$ gave the required values of EC and SAR.

Approximately 1 L of irrigation solution was then poured carefully onto the soil surface and allowed to infiltrate over 72 hrs. Solution that remained on the soil surface was removed using suction and soil columns were placed in an oven to dry at 40 °C (Bresson and Moran 1995) for two weeks. After each column was irrigated through six of these wetting and drying cycles, they were placed in a drying room to further mature structural attributes over 7 weeks.

**Table 1. Chemical attributes of field water (FW00*i*) used on Vertosol topsoils**

| | | E.C. | SAR | Cations $(\text{mmol}_{(+)}/\text{L})$ | | | |
|---|---|---|---|---|---|---|---|
| | Origin | (dS/m) | $((\text{mmol}_{(+)}/\text{L})^{1/2})$ | $Ca^{2+}$ | $Mg^{2+}$ | $K^+$ | $Na^+$ |
| FW001 | Darling river[a] | 0.98 | 4.69 | 1.14 | 1.14 | 0.11 | 5.02 |
| FW002 | H001 Bore[b] | 0.45 | 3.38 | 0.45 | 0.58 | 0.05 | 2.43 |
| FW003 | H002 Bore[b] | 0.31 | 3.44 | 0.27 | 0.37 | 0.04 | 1.94 |

[a] Water sampled from the Darling River, Bourke, at a time when the river had ceased to flow was used to treat B001 and B002.

[b] Water sampled from separate bores at two Hillston properties, where bore water was the principle water allocation for the 2002–2003 cotton crop.

Once drying was completed, columns were impregnated with a slow–curing resin mixture containing an ultraviolet (UV)–fluorescent yellow dye. The fluid components of this mixture were detailed by McBratney *et al*. (1992) and consist of resin, diluent, hardener and opacifier at a ratio of 34:34:32:1 (Vervoort and Cattle 2003).

Each column was left to cure for a minimum of 48 hrs, then ground using an angle grinder in 10 mm increments through the horizontal plane (Vervoort and Cattle 2003). At each depth, images of the exposed surface were captured using a *Canon G3 Powershot* digital camera under blacklight blue UV light. The distance between the camera lens and the surface of each core remained constant by raising the exposed face on a fixed surface. Furthermore, all images from individual columns were collected while maintaining a uniform orientation, allowing a comparison between sampling intervals to be made post–analysis.

Images, composed of yellow pore space and black solids, were downloaded to a computer and segmented to give black (pore space) and white (solid space) binary images with a single pixel representing approximately 0.12 mm. All pores detected can therefore be regarded as macropores (Beven and Germann 1982). Using Solicon v2.1 (Cattle *et al.* 2001), various pixel–counting procedures enabled the estimation of six structural parameters for each image in the horizontal plane; macroporosity (MP), surface area (SA), pore star length (PSL), solid star length (SSL), pore genus (PG) and solid genus (SG). These parameters have each been comprehensively defined by McBratney and Moran (1990) and by Vervoort and Cattle (2003). In addition, as resin was applied to the surface of each column, all structural attributes are indicative of surface–connected macroporosity.

Structural parameters were analysed after being prepared using square root and $\log_{10}$ transformations to normalise the data. To ascertain significant differences between soil types and treatments, One–Way Analyses of Variance (ANOVA) were applied. The Tukey–Kramer test (P=0.05) was used to indicate significant differences between means.

## Results

### *Fundamental soil properties*

Generally, soil physico–chemical properties (Table 2) differed little across the four sites investigated. The particle size distribution showed H002 to have a greater total sand content (>20 µm (%) = 50.5), than the other three soils. Correspondingly, this soil contained the least total clay (<2 µm (%) = 44.8), while B002 contained the greatest (<2 µm (%) = 52.9). With the exception of B001, the electrical conductivity of each soil was small. The B001 topsoil also had a much greater SAR (4.94) than each of the three remaining sites, and a markedly greater ESP than those of B002, H001 or H002 soils. The ESP of B001 was considerably larger than the critical ESP of 5, above which soils potentially become structurally unstable (McIntyre 1979). A second measure of potential instability, the electrochemical stability index ($EC_{1:5}$/ESP), indicated that the B001 and B002 samples are potentially dispersive (ESIs of $4.6\times10^{-2}$ and $3.9\times10^{-2}$ respectively), as the critical minimum ratio proposed for Vertosols is $5.0 \times10^{-2}$ (McKenzie 1998). The $CEC_{eff}$ was much less for H001 than that of the remaining soils. This Red Vertosol is known to contain a different mineral composition to the other sites, with a larger proportion of illite and comparatively less smectite than B001, B002 or H002. Organic carbon contents were uniformly small for these top soils.

**Table 2. Physico–chemical attributes of the irrigation furrow from where sampling occurred in the Bourke and Hillston cotton producing regions.**

| | B001 | B002 | H001 | H002 |
|---|---|---|---|---|
| Soil type | Grey Vertosol | Grey Vertosol | Red Vertosol | Brown Vertosol |
| Coarse sand >50 µm (%) | 23.0 | 20.7 | 21.4 | 32.5 |
| Fine sand 50–20 µm (%) | 14.3 | 17.2 | 17.2 | 18.0 |
| Silt 20–2 µm (%) | 11.5 | 9.2 | 10.4 | 4.7 |
| Coarse clay 2–0.2 µm (%) | 14.5 | 15.1 | 14.2 | 13.6 |
| Fine clay <0.2 µm (%) | 36.7 | 37.8 | 36.8 | 31.2 |
| pH (1:5 $CaCl_2$) | 7.2 | 7.2 | 7.2 | 7.9 |
| EC (1:5 water) (dS/m) | 0.37 | 0.14 | 0.20 | 0.20 |
| SAR ($(mmol_{(+)}/L)^{1/2}$) | 4.94 | 1.88 | 2.99 | 2.35 |
| $Ca_{exch}$ ($cmol_{(+)}/L$) | 20.42 | 26.85 | 18.58 | 24.71 |
| $Mg_{exch}$ ($cmol_{(+)}/L$) | 10.67 | 10.35 | 9.86 | 11.70 |
| $Na_{exch}$ ($cmol_{(+)}/L$) | 2.86 | 1.46 | 0.94 | 0.70 |
| $K_{exch}$ ($cmol_{(+)}/L$) | 1.53 | 1.85 | 1.43 | 1.11 |
| $CEC_{eff}$ ($cmol_{(+)}/L$) | 35.47 | 40.51 | 30.80 | 38.21 |
| ESP (%) | 8.06 | 3.60 | 3.05 | 1.83 |
| Organic Carbon (%) | 0.22 | 0.32 | 0.45 | 0.40 |

*Soil structural attributes*

Soil structural attributes were influenced by the SAR of the irrigation water. Estimates of soil macroporosity, surface area and pore connectivity (as determined by PG) were less for soil columns treated with a solution containing a large sodium content ($SAR_{T4}$ 15) than for those soil columns treated with water containing negligible sodium ($SAR_{T2}$ 0). Applying water of intermediate sodium content ($SAR_{T3}$ 7.5) generally resulted in similar estimates of macroporosity, surface area and pore connectivity to those columns irrigated with solution of $SAR_{T2}$ 0. Estimates of solid connectivity (as determined by SG) were also less for soil columns treated with a solution containing a large sodium content, while the estimated size of aggregates (assessed by SSL) tended to increase with increasing sodium content of the irrigation water.

However, the four topsoils investigated were influenced by the varying irrigation solutions to different extents. To illustrate this, Figure 1 shows depth functions for 3 structural attributes of topsoils B001 and H001, which have been subjected to irrigation solutions with SARs of 0, 7.5 and 15 (T2, T3 and T4). At the soil surface, macroporosity represented >0.95 $mm^3/mm^3$ of B001 and H001 and decreased rapidly with depth to 20 mm. With increasing depth below 20 mm, the macroporosity of H001 decreased at different rates, depending on the irrigating solution, whereas for B001 columns the macroporosity decreased at the same rate for all solution treatments. The subsurface macroporosity of H001 columns treated with a solution of T4 was distinctly less than that of H001 cores treated with solutions of T2 and T3. In contrast, estimates of B001 macroporosity for all irrigated treatments were similar at all depths. Estimates of surface area did not reflect the trends in macroporosity below 20 mm depth. The B001 columns irrigated with solutions T2 and T3 gave similar estimates of surface area, whereas those B001 columns treated with T4 solution yielded much smaller surface area values between 20 mm and 100 mm depth. In contrast, for topsoil H001 each increase in SAR resulted in decreasing estimates of surface area at depths below 20 mm. The average size of aggregates increased with increasing depth in both B001 and H001 columns. In general, irrigating B001 with solutions T2 and T3 resulted in aggregates of similar size, while irrigating with a solution of T4 increased the estimated size of aggregates only between 40 and 100 mm depth. In comparison, treatment of H001 showed a distinct increase in the average size of aggregates when the SAR of solutions was increased from 0 to 7.5 and then to 15 (T2, T3 and T4 respectively).

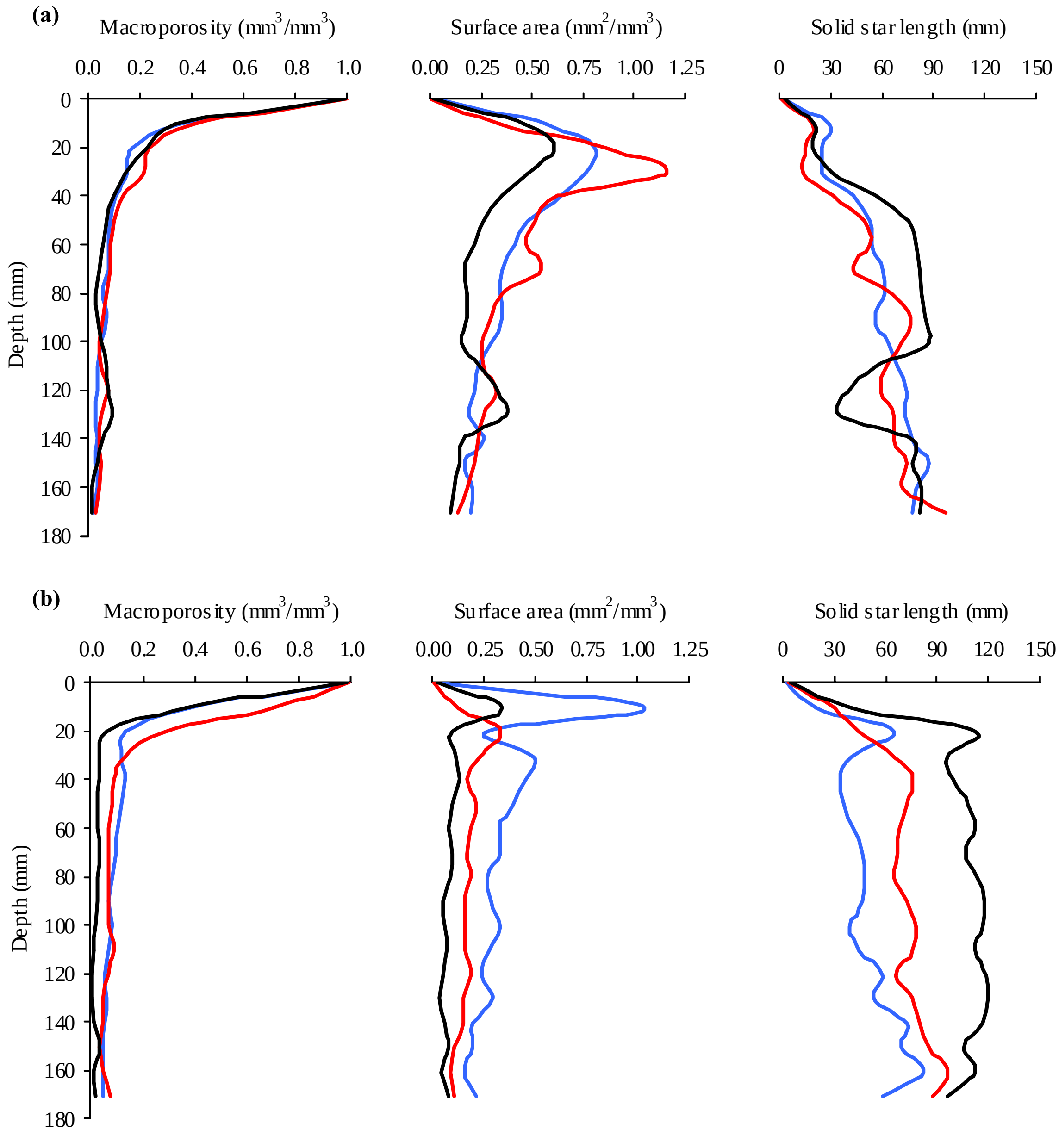

**Figure 1Response of selected soil structural parameters (MP, SA and SSL) at sites B001 (a) and H001 (b) to three treatments of $SAR_{T2}$ 0 (—), $SAR_{T3}$ 7.5 (—) or $SAR_{T4}$ 15 (—) at EC 0.5 dS/m.**

The greatest differences in structural attributes of soil columns subjected to different irrigation solutions tended to occur between depths of 50 and 100 mm. Above a depth of 20 mm, surface heterogeneity tended to confound any treatment effects, while beneath 100 mm treatment effects tended to become less distinct. Hence, to test the significance of water quality effect on soil structural form, means of estimated structural attributes between 50 and 100 mm were compared for each topsoil (Table 3). In general, irrigating soil columns with FW00*i* or T1 resulted in similar estimates of structural form for each topsoil. Only in H002 soil was the macroporosity significantly smaller after treatment with FW00*i*, compared to T1–treated soil. The estimated surface area of H002 was significantly less when soil was irrigated with FW00*i* and reflected the significant decrease in macroporosity. In contrast, the pore surface area of topsoil B002 was significantly greater when treated with FW00*i* than when treated with T1. In comparison to topsoils treated with T1, the estimated size of soil aggregates was significantly less when B002 and H001 were irrigated with FW00*i*, while the size of soil aggregates for topsoil H002 were significantly larger after application of FW00*i*.

**Table 3 Mean structural parameters derived for each site investigated (50–100 mm)**

| | FW00*i* | T1 | T2 | T3 | T4 |
|---|---|---|---|---|---|
| | | EC 0 dS/m | EC 0.5 dS/m | | |
| | | SAR 0 ((mmol$_{(+)}$/L)$^{1/2}$) | SAR 0 ((mmol$_{(+)}$/L)$^{1/2}$) | SAR 7.5 ((mmol$_{(+)}$/L)$^{1/2}$) | SAR 15 ((mmol$_{(+)}$/L)$^{1/2}$) |
| *Site B001* | | | | | |
| MP ($mm^3/mm^3$) | 0.11*ab* | 0.14*a* | 0.07*bc* | 0.08*bc* | 0.05*c* |
| SA ($mm^2/mm^3$) | 0.39*a* | 0.53*a* | 0.38*a* | 0.41*a* | 0.20*b* |
| PSL (mm) | 3.27 | 2.94 | 2.50 | 2.16 | 2.85 |
| SSL (mm) | 50.93*bc* | 36.90*c* | 57.79*ab* | 59.34*ab* | 81.77*a* |
| PG ($\times 10^{-2}$ $mm^2$) | 0.62*ab* | 0.66*a* | 0.58*ab* | 0.96*a* | 0.24*b* |
| SG ($\times 10^{-2}$ $mm^2$) | 6.25*ab* | 8.58*a* | 10.31*a* | 8.75*a* | 3.90*b* |
| *Site B002* | | | | | |
| MP ($mm^3/mm^3$) | 0.10 | 0.09 | 0.10 | 0.11 | 0.09 |
| SA ($mm^2/mm^3$) | 0.49*a* | 0.31*b* | 0.46*a* | 0.38*ab* | 0.41*ab* |
| PSL (mm) | 3.78 | 3.09 | 3.42 | 4.34 | 3.38 |
| SSL (mm) | 39.31*c* | 70.09*a* | 42.95*bc* | 55.67*ab* | 43.18*bc* |
| PG ($\times 10^{-2}$ $mm^2$) | 0.62*b* | 0.36*c* | 0.93*a* | 0.79*ab* | 0.55*bc* |
| SG ($\times 10^{-2}$ $mm^2$) | 11.78*a* | 5.02*c* | 10.70*ab* | 7.45*bc* | 9.79*ab* |
| *Site H001* | | | | | |
| MP ($mm^3/mm^3$) | 0.09*ab* | 0.07*b* | 0.09*a* | 0.07*ab* | 0.03*c* |
| SA ($mm^2/mm^3$) | 0.25*ab* | 0.19*bc* | 0.32*a* | 0.18*c* | 0.08*d* |
| PSL (mm) | 4.55 | 3.98 | 3.42 | 4.68 | 3.47 |
| SSL (mm) | 55.34*cd* | 75.46*b* | 42.72*d* | 70.50*bc* | 112.16*a* |
| PG ($\times 10^{-2}$ $mm^2$) | 0.39*ab* | 0.22*b* | 0.50*a* | 0.27*ab* | 0.08*c* |
| SG ($\times 10^{-2}$ $mm^2$) | 4.06*ab* | 2.81*b* | 6.05*a* | 2.50*bc* | 1.40*c* |
| *Site H002* | | | | | |
| MP ($mm^3/mm^3$) | 0.04*c* | 0.08*ab* | 0.10*a* | 0.06*b* | 0.07*ab* |
| SA ($mm^2/mm^3$) | 0.15*c* | 0.25*b* | 0.37*a* | 0.17*bc* | 0.18*bc* |
| PSL (mm) | 2.49*c* | 3.30*bc* | 3.27*bc* | 3.98*ab* | 4.75*a* |
| SSL (mm) | 92.74*a* | 57.54*bc* | 50.03*c* | 89.13*a* | 70.48*ab* |
| PG ($\times 10^{-2}$ $mm^2$) | 0.22*b* | 0.29*b* | 0.87*a* | 0.25*b* | 0.24*b* |
| SG ($\times 10^{-2}$ $mm^2$) | 2.72*bc* | 4.00*ab* | 5.99*a* | 1.97*c* | 2.59*bc* |

Within the rows significant differences are represented by the letters *a*, *b*, *c* and *d*.

A comparison of topsoils treated with T1 and T2 solutions also showed some significant differences in estimated structural parameters. For example, topsoil B001 had significantly less porosity when irrigated with solution T2, and a concomitantly larger aggregate size. In contrast, topsoils of B002, H001 and H002 treated with solution T2 had a much greater surface area and both pore and solid connectivity was increased. Increased pore attributes for B002, H001 and H002 were reflected in decreased estimates of soil aggregate size.

In general, increasing the sodium content of irrigation water (T2, T3 and T4) did not significantly decrease macroporosity between the depths of 50 and 100 mm. However, pore surface area and connectivity estimates were significantly less when topsoils were irrigated with solutions of greater SAR. In addition, the estimated size of the solid phase for topsoils B001 and B002 were not significantly influenced by irrigating with solutions of greater sodium content. This contrasted with estimates of the solid structural attributes for topsoils H001 and H002, both of which showed a significant increase with more sodic irrigation solutions.

## Discussion

In this work, the irrigation of four Vertosols with 3 solutions of increasing sodium content (T2, T3 and T4) generally resulted in decreased pore surface area and connectivity (pore and solid) and an increase in the estimated size of solids. Increases in the values of macroporosity and surface area and a decrease in the value of solid star length are seen as indicators of structural repair (Pillai and McGarry 1999), therefore the most desirable structural form achieved in this study resulted from the irrigation of soil with solution T2. Commonly, the soil samples treated with T2 solution contained more macropores of smaller size, as indicated by a greater pore surface area than other samples, but similar values of macroporosity. In addition, these soils had greater connectivity of pore and solid elements and estimates of solid size were much less than those obtained after irrigation with solutions T3 or T4. The structural attributes of T3 and T4–treated soil correspond to less desirable soil physical conditions restricting plant growth and limiting water movement (e.g. Crawford 1994).

In contrast to the impact of irrigation using solutions of SAR 0, 7.5 and 15, irrigating topsoils with FW00*i* and clean water (T1) did not consistently yield differences in estimated structural parameters. In general, the estimated structural attributes resulting from FW00*i* and clean water irrigation were most comparable to those obtained from topsoils irrigated with an intermediate sodium solution (T3); compared to those topsoils treated with solution T2, the FW00*i* and T1–treated topsoils commonly showed minor reductions in desirable structural attributes.

The effect of irrigation sodicity (T2, T3 or T4) was not equally reflected by each of the 4 Vertosols investigated. The Bourke soils changed least with increasing irrigation water sodicity (B002<B001); pore and solid connectivity and pore surface area become significantly less only when the sodium content of irrigating solution was increased from SAR 7.5 to SAR 15 (T3 and T4 respectively). In contrast, the Hillston topsoils were affected quite distinctly with increasing irrigation water sodicity (H002<H001). When the sodium content of solution was increased (T2 to T3), H002 yielded significantly reduced macroporosity, while both H002 and H001 contained significantly less pore surface area and connectivity of each phase and a significant increase in estimates of solid size. The estimated structural parameters of H002 were not significantly different when comparing the T3 and T4 solution treatments. However, H001 showed further significant reductions in macroporosity, pore surface area and pore connectivity and a corresponding increased in estimated solid size, when comparing the T4–treated samples to the T3 treated samples.

The extent to which each soil (B001, B002, H001 and H002) responded to irrigation solutions of increased sodicity (T2, T3 and T4) corresponded to fundamental differences between each cotton–producing region and to differences in soil physico–chemical properties within each district. In general, the structural form of B001 and B002 was influenced much less by solution sodicity than H001 and H002; it is anticipated that this will relate to differences between the clay mineral composition of Bourke and Hillston cotton districts. In comparison, differences between estimated structural parameters for soils from Bourke and for soils from Hillston are accounted for by variation in soil physico–chemical properties. The sites B002 and H002 each exhibited only minor changes in structural attributes, when treatments T3 and T4 were compared to treatment T2, whereas topsoils B001 and H001 exhibited more pronounced differences. This corresponds to differences in soil chemistry; specifically, B002 and H002 have lower values of EC, SAR and ESP and larger values of $CEC_{eff}$ than B001 and H001, respectively. Significantly, organic carbon, commonly believed to have a positive influence on soil structural stability, was much less for each of the Bourke topsoils than for those topsoils from Hillston, although values for both regions are very small. This is a likely reflection of the arid climate at both locations.

## Conclusions

In general, irrigating with solutions of increased sodicity increased the estimated size of aggregates, decreasing pore surface area and connectivity, and resulting in less desirable soil structural form. However, each of the four Vertosols investigated in this study reflected the influence of solution composition differently. These differences were attributed to regional differences and to specific soil physico–chemical attributes, such as the soil solution components and soil exchangeable cations.

## References

Beven K, Germann P (1982) Macropores and Water flow in soils. *Water Resources Research* **18**, 1311–1325.

Bresson LM, Moran CJ (1995) Structural change induced by wetting and drying in seedbeds of a hardsetting soil with contrasting aggregate size distribution. *European Journal of Soil Science* **46**, 205–214.

Cattle SR, Farrell RA, McBratney AB, Moran CJ, Roesner EA, Koppi AJ (2001) © Solicon–PC Version 2.1. In. (The University of Sydney and Cotton Research and Development Corporation)

Crawford JW (1994) The relationship between structure and the hydraulic conductivity of soil. *European Journal of Soil Science* **45**, 493–502.

Crescimanno G, Provenzano G, Iovino M (1995) Influence of salinity and sodicity on soil structural and hydraulic characteristics. *Soil Science Society of America Journal* **59**, 1701–1708.

Curtin D, Steppuhn H, Selles F (1994) Clay dispersion in relation to sodicity, electrolyte concentration and mechanical effects. *Soil Science Society of America Journal* **58**, 955–962.

Dudal R, Eswaran H (1988) Distribution, properties and classification of Vertisols. In 'Vertisols: Their distribution, properties, classification and management'. (Ed. LP Wilding, Puentes, R.) pp. 1–22. (Texas A&M University Printing Center: College Station)

Gee GW, Bauder JW (1986) Particle–size Analysis. In 'Methods of Soil Analysis'. (Ed. A Klute). (Madison: Wisconsin, USA)

Isbell RF (1996) 'The Australian Soil Classification.' (CSIRO Publishing: Collingwood, Victoria)

Jackson ML (1956) 'Soil Chemical Analysis–Advanced course.' (Published by the Author, Department of Soils, University of Wisconsin: Madison 6, Wisconsin)

Kay BD (1990) Rates of change of soil structure under different cropping systems. *Advances in Soil Science* **12**, 1–52.

Lebron I, Suarez DI, Schaap MG (2002) Soil pore size and geometry as a result of aggregate-size distribution and chemical composition. *Soil Science* **167**, 165–172.

McBratney AB, Moran CJ (1990) A rapid method of analysis for soil macropore structure: II. Stereological model, statistical analysis, and interpretation. *Soil Science Society of America Journal* **54**, 509–515.

McBratney AB, Moran CJ, Stewart JB, Cattle SR, Koppi AJ (1992) Modifications to a method of rapid assessment of soil macropore structure by image analysis. *Geoderma* **53**, 255–274.

McGarry D (1996) The structure and grain size distribution of Vertisols. In 'Vertisols and technologies for their management'. (Ed. N Ahmad, Mermut, A.) pp. 231–259. (Elsevier: Amsterdam)

McIntyre DS (1979) Exchangeable sodium, subplasticity and hydraulic conductivity of some Australian soils. *Australian Journal of Soil Research* **17**, 115–120.

McKenzie DC (Ed.) (1998) 'SOILpak for cotton growers (3rd edn).' (N.S.W. Agriculture: Orange, N.S.W.)

McLeod S (1975) Studies on wet oxidation procedures for the determination of organic carbon in soil. In 'Notes on Soil Techniques' pp. 73–79. (CSIRO Division of Soils)

Mooney SJ (2002) Three–dimensional visualization and quantification of soil macroporosity and water flow patterns using computed tomography. *Soil Use and Management* **18**, 142–151.

Pillai VP, McGarry D (1999) Structure repair of a compacted Vertisol with wet–dry cycles and crops. *Soil Science Society of America Journal* **63**, 201–210.

Probert ME, Fergus IF, Bridge BJ, McGarry D, Thomson CH, Russell JS (1987) 'The Properties and Management of Vertisols.' (CAB International: Wallingford, U.K)

Quirk JP, Schofield RK (1955) The effect of electrolyte concentration on soil permeability. *Journal of Soil Science* **6**, 163–178.

Rayment GE, Higginson FR (1992) 'Australian Laboratory Handbook of Soil and Water Chemical Methods.' (Inkata Press: Sydney)

Vervoort RW, Cattle SR (2003) Linking hydraulic conductivity and tortuosity parameters to pore space geometry and pore–size distribution. *Journal of Hydrology* **272**, 36–49.