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The effect of sodicity severity and depth on irrigated cotton production at Hillston, New South Wales

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Abstract

Sodic soils have been highlighted as a major land degradation issue within the last decade, and currently affect a large proportion of Australia's arable land. Sodicity is known to produce yield declines, yet the failure to adequately identify the mechanisms responsible for reduced productivity, has limited the ability of landholders to target and improve the effectiveness of available amelioration strategies. In this study the direct (plant) and indirect (soil) effects of sodicity on irrigated cotton yield were examined. Twenty sites were selected in two individual fields of two farms in the Hillston district (32°28'S 145°32'E) of southwestern New South Wales, in which cotton yield varied. At each "high" and "low" yielding site, soil samples to a depth of 1.0 m and leaves from the youngest mature leaf stage were collected, with soil cores taken from topsoils and subsoils in a subset of the sampling locations.

Sodicity was not uniformly associated with yield declines across different sampling locations. Direct effects of sodicity on cotton plant nutrition did not appear to play a significant effect in yield reduction, with no significant difference in macro and micronutrient concentrations between high and low yield zones in both fields A and B. Sodicity-related soil parameters, such as ESP and aggregate instability were more severe at shallower profile depths in low yielding zones of field B, due to the influence of landforming processes. The proximity of these structurally altered layers to the root zone was therefore thought responsible for yield declines, as dispersed layers presumably reduced the water availability to the plant. In contrast, the upper 0.45 m of soil profiles at field A displayed similarly large ESP values across low and high yielding zones, yet exhibited a limited propensity for soil dispersion. In this case, yield differences are attributed to other factors such as variable irrigation rates. Where indirect effects of sodicity occurred the dataset was used to quantify 'critical' values or the point at which sodicity-induced changes impact on soil structural behaviour and crop production. Based on data compiled at field B, an ESP and ASWAT score greater than 6 in the top 0.45 m of the soil profile was strongly correlated with significant reductions in irrigated cotton yield. The ability to determine these benchmark figures could benefit landholders, allowing growers to assess the economic viability, via soil analysis, of crop production prior to sowing.

Keywords: Sodicity; sodic soils, irrigated cotton; cotton yield; Lachlan Valley

1. Introduction

Sodicity is defined as an excess amount of sodium on soil exchange sites and under Australian conditions, it is generally accepted that a soil may be regarded as ‘sodic’ if sodium occupies more than 6% of all exchanges sites. Current estimates indicate 30% of Australian agricultural soils are sodic, with nationwide distribution predicted at approximately 340 million hectares (Northcote and Skene, 1972; Rengasamy and Walters, 1994). Irrigated soils are particularly affected, with approximately 80% of the irrigated area subjected to sodicity-induced problems as a consequence of addition of sodium to soil profiles via irrigation water and inadequate drainage (Khan and Abdullah, 2003).

Irrigated cotton occupies approximately 320 000 hectares in Australia and is located primarily in the river valleys of north west New South Wales and south east Queensland (Surapaneni et al., 2002). Major cotton-growing soils include Vertosols (80%), and upland (15%) and alluvial (5%) texture contrast soils (Kurosols, Chromosols and Sodosols). The lower Lachlan Catchment is a relatively new contributor to irrigated cotton production, with expansion into the Hillston district in southwestern New South Wales occurring in the last 15 years. However, even with limited development of irrigation in the district prior to the introduction of cotton, anecdotal evidence is already emerging to suggest that yield losses are occurring as a result of sodicity.

While studies on the relationship between sodicity and crop yield are presently limited, existing research generally acknowledges that any increase in sodicity will be accompanied by yield declines (Ahmad and Makhdum, 1992; Ali et al., 1992). Sharma and Minhas (1998) demonstrated that application of sodic water produced yield losses as high as 30% in wheat rotations following five years of irrigation. Similarly, inference based studies illustrated the effect of sodicity through the application of ferrogypsum, which was shown to increase yield of grain and straw of rice by 23%; this result was attributed to declines in exchangeable sodium of up to 50% (Jagadeeswaran et al., 2002). Economic ramifications of the 20–30% reductions in crop yields are estimated at $1.3 billion in the form of losses to annual incomes for farmers (Hulugalle and Finlay, 2003). Yet despite these yield declines being observed, the relative importance of indirect (soil) or direct (plant) effects have not been properly assessed.

The indirect impacts of sodicity on plant growth are well recognised with typical outcomes including dispersion, swelling and slaking of the soil. This behaviour has been noted on Australian cotton-growing soils where increased sodicity accounted for soil structural deterioration on irrigated and dryland Vertosols (Hulugalle and Finlay, 2003). Sodicity-induced structural decline may lead to hardsetting and crusting, lower soil hydraulic conductivity, evaporation and infiltration rates

(Sumner, 1993), decreased levels of organic matter and reduced seed germination (McKenzie et al., 2002). Increasing the amount of exchangeable sodium from 3–7% was shown to decrease the rate of evaporation by 10% and onion seedling emergence by 50% in a loess soil (Rapp et al., 2000). Studies by Levy et al. (2002) revealed that an increase in sodicity of 8% induced a 25% reduction in hydraulic conductivity on Australian Vertosols.

Few existing studies have examined the effect of direct influences of sodicity, with the majority of current knowledge based on theoretical assumptions. It is understood that the majority of plants express sodium toxicity, with sodium acting only as an essential micronutrient in plants with either C_4 or Crassulacean Acid Metabolism (CAM) (Marschner, 1995). However, rudimentary results indicate that at heightened sodicity levels plants are less able to maintain selectivity mechanisms (K:Na channels), thereby impacting on plant growth and development (Porcelli et al., 1995). Despite the bulk of existing literature assuming reductions in crop productivity are a result of sodicity-induced soil structural problems, investigations by Porcelli et al. (1995) highlight the need for further investigation, as clearly the mechanisms involved in yield decline may be more complex.

Therefore, due to limited information on the effect of sodicity on cotton yield and an inability to currently identify the causes of yield losses, the aims of this research were: (i) to quantify the severity and depth of sodicity in Red Vertosols at Hillston and (ii) to determine whether observed sodicity is affecting cotton yield as a result of indirect and/or direct mechanisms.

2. Materials and methods

2.1. Sample site and experimental design

Two commercial irrigated cotton properties located 10 km north and 25 km north west of the Hillston township (32°28’S 145°32’E) were selected for study. The locations and approximate boundaries of the sampled properties are given in Fig. 1. Hillston is situated in southwestern New South Wales and physiographically, the district is dominated by low-lying topography, with outlying areas of the region comprised of extensive alluvial floodplains and source bordering dunes (Cameron, 1997). The climatic regime of the Hillston region is defined as temperate according to the Köppen system, with hot summers (maximum 32.4, minimum 17.6°C), cool winters (maximum 15.8, minimum 4.6°C) and an even distribution of rainfall (average 366 mm annually) (Bureau of Meteorology, 2005). Landuse in Hillston is primarily dictated by soil type and access to irrigation. Properties located north of the Lachlan River are located on fertile alluvial plains and have access to irrigation, resulting in a greater level of agricultural diversity, with common enterprises including cereal, oilseed, citrus and vegetable production. A lack of access to irrigation south of the Lachlan has ensured dryland cereal production is the dominant agricultural landuse.

Although no map of soils in the Hillston area currently exists, a provisional map sheet by Cameron et al. (2000) describing the dominant geological units (TQs, Qa and Qaf) has been found to largely correspond with the Quaternary alluvial soil types (Cay and Cattle, 2005). The major soils of the cotton-growing areas in Hillston are Red Vertosols (TQs), Grey Vertosols (Qa) and Grey Brown Vertosols (Qaf). Grey and grey brown Vertosols form the active alluvial landscape, while Red Vertosols are derived from old river sediments at higher elevations.

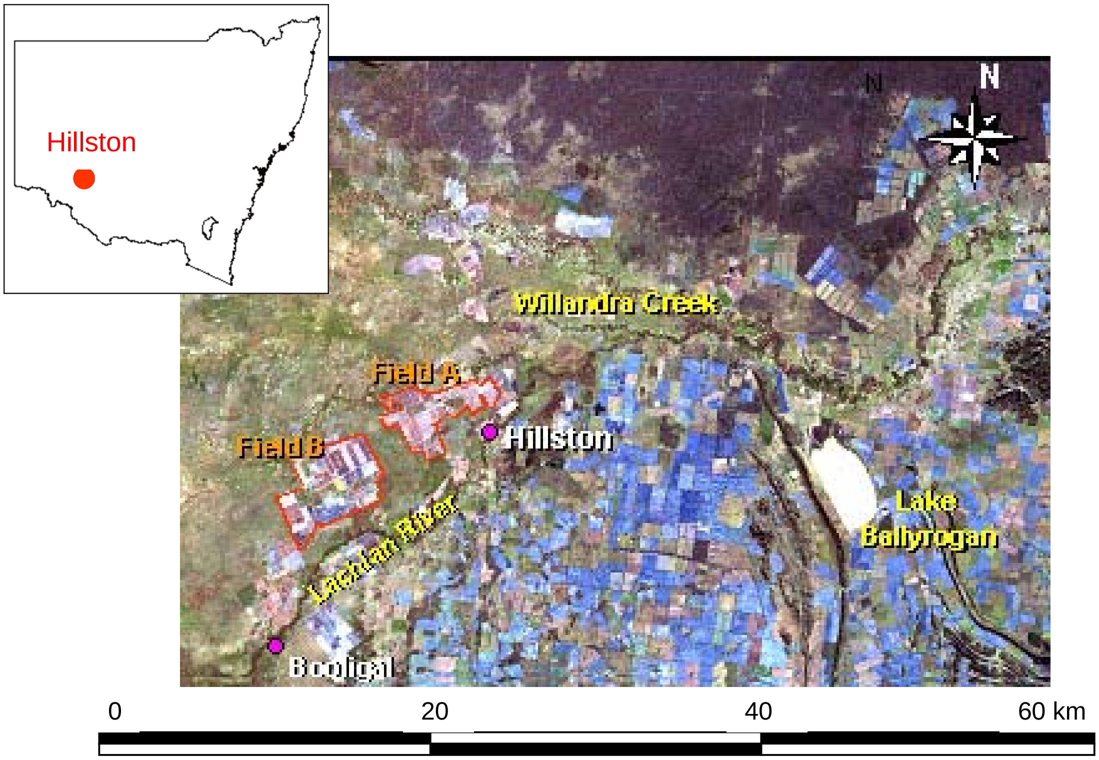
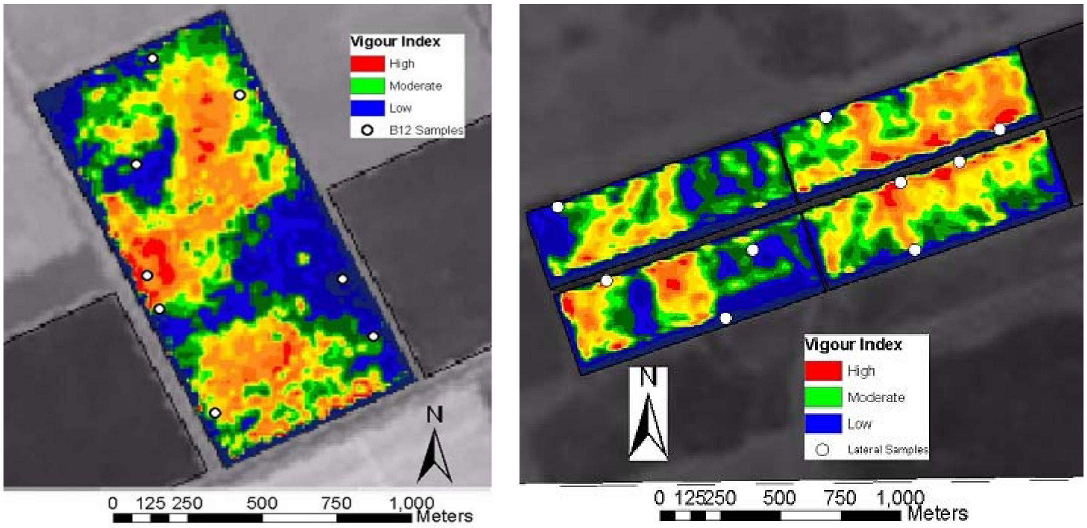


Fig.1. Area map and location of sampling sites. Red boundaries of properties indicate site margins.

In recent studies of soils of the Hillston area the Red Vertosols (TQs unit) have been identified as strongly sodic and strongly alkaline with the potential to impact on crop production (Cay and Cattle, 2005). Therefore, due to the recognised sodicity of the soil, sampling was targeted towards the Red Vertosol soil type.

A total of 20 sites were located, with each site representing a point in a commercial field in use for cotton production. Ten sites were sampled from each farm, with five replicates taken in both good and poor yielding areas. For the purpose of this report the two sampling locations shall hereafter be referred to as Field A and Field B. Normalised Difference Vegetation Index (NDVI) maps were used to identify zones of differential yield through variation in plant vigour, and allowed for a stratified random sampling pattern (Webster and Oliver, 1990) (Fig. 2). Final cotton yield data obtained from field B confirmed yield assumptions made from NDVI maps, with low and high yielding areas averaging 10.6 and 12.5 t/ha respectively. A final correlation between yield and crop vigour observed at field A could not be verified, however field observations during sample collection indicated a clear difference between areas of high and low yield. Therefore, it was assumed that there was a strong correlation between vigour and crop yield. General observations of crop yield and presence of disease and/or pest pressure were made during sampling. "Cut and Fill" maps were obtained from field B as auxiliary data.

At each site soil was hand augered (0.1 m diameter) to a depth of 1.0 m with soil collected at 0.1 m increments. Soil sampling was carried out within rows to minimise the influence of structural degradation from wheel traffic of heavy machinery. Additionally, around the immediate sampling area 30 leaves from the youngest mature leaf (YML) stage of cotton plants were also collected. The YML stage was chosen as it reflects nutrient levels stored in the plant, and is a commercial standard for nutrient analysis, providing data that may be directly applicable to growers. At selected sites soil cores were extracted at depths of 0.3–0.4 m and 0.7–0.8 m to allow for the determination of the water retention curve. Leaves and soil samples were air-dried, with soil mechanically ground to <2 mm.



(a) (b)

Fig. 2. Approximate sampling locations in cotton fields at (a) field A and (b) field B determined using Normalised Difference Vegetation Index maps.

2.2. Soil Properties

Soil samples from all 20 sites were assessed for a range of soil physico-chemical properties. Soil pH was determined using 1:5, soil: water extract (pH_w) and 1:5, soil: 0.01 M $CaCl_2$ extract (pH_{Ca}). Following agitation on a rotary shaker, solutions were allowed to stand for 5 minutes before measurement via a PHM 210 Meter Lab^{TM} pH meter with glass calomel electrode. Soil electrical conductivity (EC) was subsequently measured on the soil water extract using a CDM 210^{TM} conductivity meter.

The *A*ggregate *S*tability in *WAT*er test (ASWAT) was carried out according to Field et al. (1997), to qualitatively assess soil dispersion. The ASWAT scheme assigns a score between 0–16 based on the extent of aggregate dispersion, where 0=no dispersion and 16=maximum dispersion. Air-dry soil aggregates (3–5 mm) were placed in a petri dish of deionised water and assigned scores at 10 minute and 2 hour intervals. A score between 9–16 results from spontaneous aggregate dispersion, whereas scores of 0–8 are assigned to those soils which only disperse following remoulding, or application of mild amounts of stress.

Exchangeable base cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) were determined following removal of soluble salts using a 1 M NH_4Cl displacing solution (pH=8.5) according to Rayment and Higginson (1992). Pre-treatment involved three washes of the soil sample with 50 mL of 60% ethanol solution. Extraction was subsequently performed using 60 mL of 1M NH_4Cl over a 10-hour period, after which 40 mL of 0.5 M HCl was added and the extract solution made to 100 mL with 1M NH_4Cl. A mechanical leaching device (Holmgren et al., 1997) was used for both preparation and extraction of exchangeable cations. Concentration of cations in the extract solution were analysed via atomic absorption spectrometry and Effective Cation Exchange Capacity (ECEC) estimated as the sum of exchangeable basic cations. Exchangeable sodium percentage (ESP) was calculated according to Eq. (1).

$$ESP = \frac{Exchangeable\ Na}{ECEC} \times 100 \qquad (1)$$

Previous research has identified the inability of ESP to accurately predict structural instability (Sumner, 1993; Hulugalle and Finlay, 2003). Therefore, the Electrochemical Stability Index (ESI), which accounts for the flocculative effects of soluble salts, was calculated according to Eq. (2) (McKenzie, 1998):

$$\frac{EC_{1:5}}{ESP} \qquad (2)$$

where EC is the electrolyte concentration given in dS m^{-1}.

Analysis of particle size distribution (PSD) and aggregate instability was carried out on a subset of samples according to the observed behaviour of soil pH, EC and ASWAT. For both PSD and aggregate instability, soil was selected from 4 profiles in each field (field A and field B) with 2 replicates taken from both high and low yielding zones. PSD was carried out at 4 depths (0–0.1, 0.2–0.3, 0.5–0.6 and 0.9–1.0 m) with clay (<2 µm) content measured by the hydrometer method. Fine sand (53–212 µm) and coarse sand (212–2000 µm) was determined by sieving, and silt (2–53 µm) content calculated by difference. Aggregate stability via end-over-end disruption was used to further explore aggregate instability at greater energy levels at 3 depths (0–0.1, 0.5–0.6 and 0.9–1.0 m). Following the method of Field (2000), 6g of soil was placed in a centrifuge bottle and 100 mL of deionised water added. After shaking for 30 minutes at 30 r.p.m. the soil solution was transferred to a 500 mL measuring cylinder. Following the appropriate sedimentation period material, <2 µm and <20 µm was sampled and oven-dried to determine the mass of each fraction.

The water retention curve was determined using cores (73 mm diameter, 61 mm height) extracted at depths 0.3–0.4 and 0.7–0.8 m at 8 sites, with 4 samples taken from both field A and B. Two replicates were taken from high and low yielding zones. Cores were saturated from the base and allowed to equilibrate before desorption of soil was automatically recorded via the ku-pF machine (Umwelt-Gereate-Technik, Muncheberg, Germany), calibrated at potentials of 0 and –60 kPa. Tensiometers inserted into the soil core at depths of 15 mm and 45 mm, monitored changes in surface potential, with weight differences determined by balance. Changes in potential and weight were used to formulate a water retention curve according to Minasny and Field (2005).

2.3. Plant Properties

Cotton plant leaves were ground to a fine powder and analysed for both macro (Ca, K, Mg, P, S,) and micronutrient (Al, B, Cd, Co, Cr, Cu, Fe, Mn, Mo, Na, Ni, Pb, Se, Ti, Zn) concentrations using Radial CIROS Inductively Coupled Plasma Atomic Emission Spectrometry (ICPAES).

2.4. Data Analysis

The majority of data obtained was analysed using a general analysis of variance at P=0.05. While a score-based dataset, such as ASWAT would typically be analysed by ordinal regression, simplification of the scale was required to reduce the level of parameterisation, following which significance could not be accurately determined. Therefore, ASWAT was analysed via REML as the large range in scores allowed for the dataset to be classed as normally distributed. Statistical significance of aggregate instability, via end-over-end disruption, was determined using a regression analysis due to the non-orthogonal characteristics of the dataset. Prior to analysis data was examined for equal variance with some datasets requiring logarithmic transformation in order to reduce fanning of residuals.

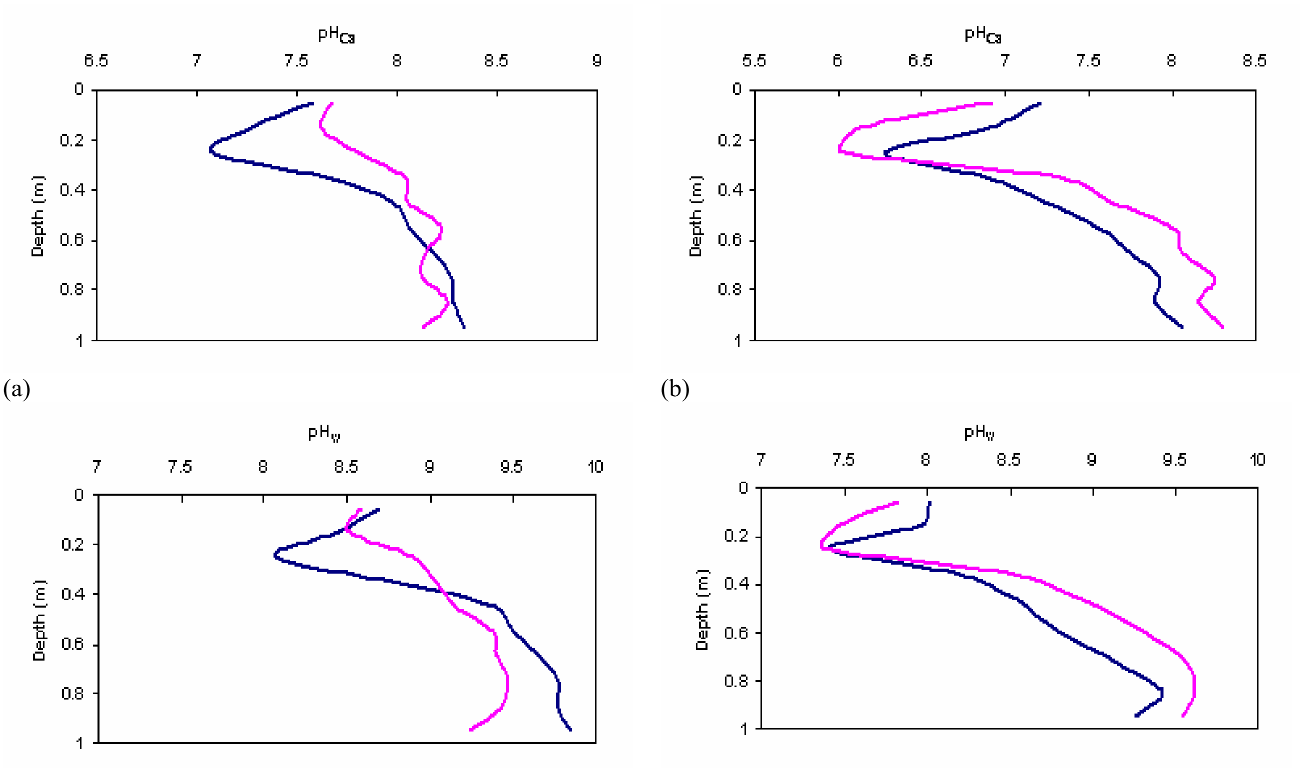
As the major objective of this study was to observe the significance of indirect and direct effects on cotton yield, mean values of soil and plant attributes were compared across yield zones (high and low yield) at various depths, within fields (field A and B). Blocking occurred between fields as management techniques, e.g. irrigation technique, was not uniform on the different farms, with lateral and furrow irrigation occurring at fields A and B, respectively.

3. Results

3.1. Soil Analyses

3.1.1. pH

Across the two sampling locations mean pH_{Ca} and pH_w values were consistently slight to moderately alkaline in the topsoil and strongly to moderately alkaline in the subsoil (mean pH_{Ca} ranging from 7.5–8.5), with mean pH_{Ca} and pH_w values increasing with depth (Fig. 3). There was a significant difference in soil pH occurring between yield zones, with significantly greater alkalinity occurring in low yielding areas (P=0.04, s.e. 0.04). Average profile pH_{Ca} values in low and high yielding zones for field A were 8.01 and 7.87 respectively. Field B was slightly less alkaline with mean profile pH_{Ca} 7.81 and 7.37 for low and high yielding zones, respectively. A comparison of depth trends between fields demonstrated a more gradual increase in pH_{Ca} at field A, increasing by only 1 pH unit down to a depth of one metre. A sharp decline in soil pH occurred at a depth of 0.2–0.3 m (0.94 unit decrease in pH_{Ca} at field B) and was observed both in high and low yielding zones, with field B displaying a particularly rapid reduction in pH. This pattern was more pronounced in pH_{Ca} (Fig. 3). Measurements of pH_{Ca} were approximately 1 pH unit lower than values recorded in water, and were used to draw conclusions on the resulting effect of pH on crop yield, as values are influenced to a lesser degree by soluble salts present and soil moisture content (Rayment and Higginson, 1992).



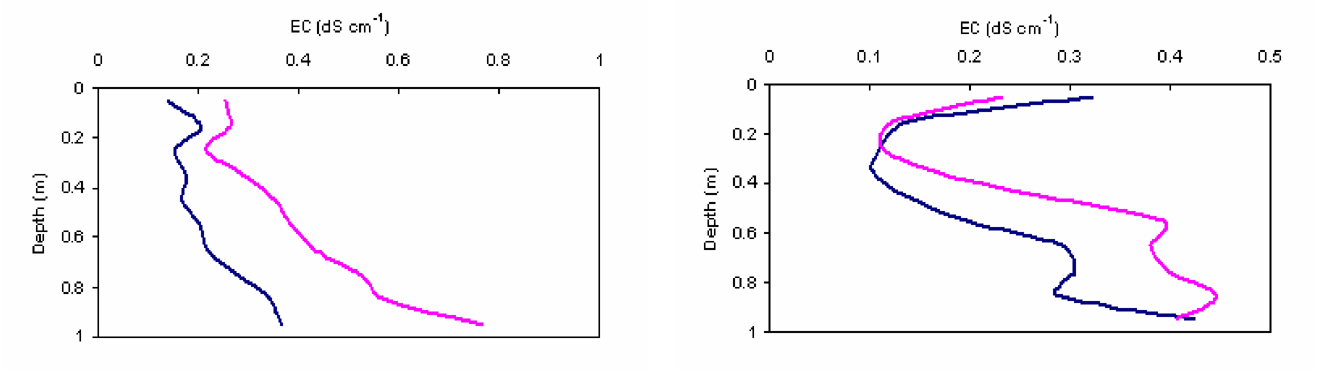
(a) (b)

(c) (d)

Fig. 3. Average soil pH$_{Ca}$ and pH$_w$ for high (▬) and low (▬) yielding zones at (a, c) field A and (b, d) field B respectively, as a function of depth.

3.1.2. Electrical Conductivity

Electrical conductivity (EC) was found to be significantly different between yield zones in both field A and B, with low yielding regions containing larger mean EC values at field A ($P<0.001$, s.e. 0.04) and field B ($P=0.005$, s.e. 0.13). As expected, recordings for EC increased with depth (Fig. 4). Low yielding zones generally exhibited larger EC values at shallower profile depths, a characteristic which was particularly evident at field A. Mean topsoil EC (0–0.4 m) was 0.16 dS m^{-1} in areas of high yield and 0.21 dSm^{-1} in low yielding zones. Subsoil EC (0.7–1.0 m) mean values were 0.32 dS m^{-1} and 0.51 dS m^{-1}, for high and low yielding zones, respectively. These are classified as low levels of salinity in the topsoil and moderate in the subsoil, according to Shaw (1999). It is noted that this may not be an accurate representation of actual salinity levels, as dispersed clay present in the soil suspension could contribute to charge and therefore may lead to a elevated concentration of salts (Shaw, 1999). Differences between the two field locations were quite pronounced with field A showing dissimilar profile trends to field B (Fig. 4). The difference occurring between fields is highlighted by larger mean subsoil EC in field A (0.44 dS m^{-1}) than field B (0.38 dS m^{-1}). Trends in depth functions were different between fields with field A exhibiting a linear increase in EC with depth, whereas field B displayed less variation between high and low yielding zones. Field B reflected a similar pattern to pH depth functions, with a sharp decline in EC at depths of approximately 0.2 and 0.4 m at low and high yielding regions, respectively.



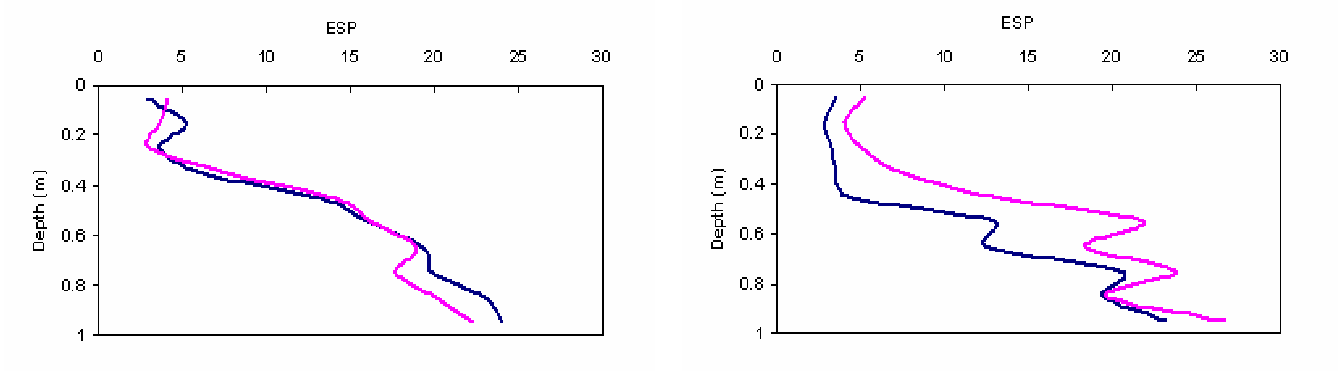
(a) (b)

Fig. 4. Average soil EC for high (▬) and low (▬) yielding zones at (a) field A and (b) field B as a function of depth.

3.1.3. ESP

ESP was found to increase throughout the profile, reaching a maximum of 22–26% at a depth of one metre at both fields A and B. However, as indicated in Fig. 5 the ESP depth functions at field A and field B were quite different, with field A possessing a uniform increase in ESP down the profile at both high and low yielding zones. This is illustrated by soils being similarly classed as 'sodic' (mean ESP>6) at a depth of 0.35 m across areas of high and low yield. ESP values at field A were not significantly different with high yielding zones demonstrating a larger mean ESP (10.0%) than low yielding zones (9.1%) ($P=0.26$, s.e. 0.06). In contrast, the disparity between high and low yielding areas was more pronounced at field B, with a greater severity of sodicity occurring at shallower depths in low yielding areas (mean profile ESP values at high yield=7.4%, low yield=11.5%) ($P>0.01$, s.e. 0.13). For example, at a depth of 0.45 m mean ESP in field B was 4.3 and 12.8 in areas of high and low yield, respectively. As was observed with mean EC, field A and B demonstrated a characteristic decline in ESP at a depth of approximately 0.25 m, averaging a reduction in ESP of 1.2 in high yielding and 0.91% in low yielding zones from surface soils (0–0.1 m).

Mean ESI values for topsoil and subsoil depths across yield states are presented in Table 1. Significant differences in ESI values were demonstrated in topsoils at field B ($P=0.04$, s.e. 0.01) and subsoils at field A ($P=0.01$, s.e. 0.003). According to McKenzie (1998) a soil with an ESI of less than 0.05 will exhibit structural instability. Based on this critical ratio, topsoils were classified as structurally stable in low yielding areas at field A and high yielding zones at field B. All subsoils were structurally unstable, behaviour deemed undesirable for cotton-growing soils.



(a) (b)

Fig. 5. Average soil ESP for high (▬) and low (▬) yielding zones at (a) field A and (b) field B as a function of depth.

Table 1.
Average sodicity in topsoil (0–0.4 m) and subsoil (0.7–1.0 m) expressed as the exchangeable sodium percentage (ESP) and electrochemical stability index (ESI) in high and low yielding zones.

		Field A		Field B	
	Yield	Low	High	Low	High
Topsoil	ESP	4.65	4.50	5.42b	3.29a
	ESI	0.10	0.04	0.03c	0.06d
Subsoil	ESP	19.75	21.56	22.13f	18.93e
	ESI	0.03h	0.01g	0.02	0.02

ESI given as $EC_{1:5}$/ESP where EC is measured in dS m^{-1}

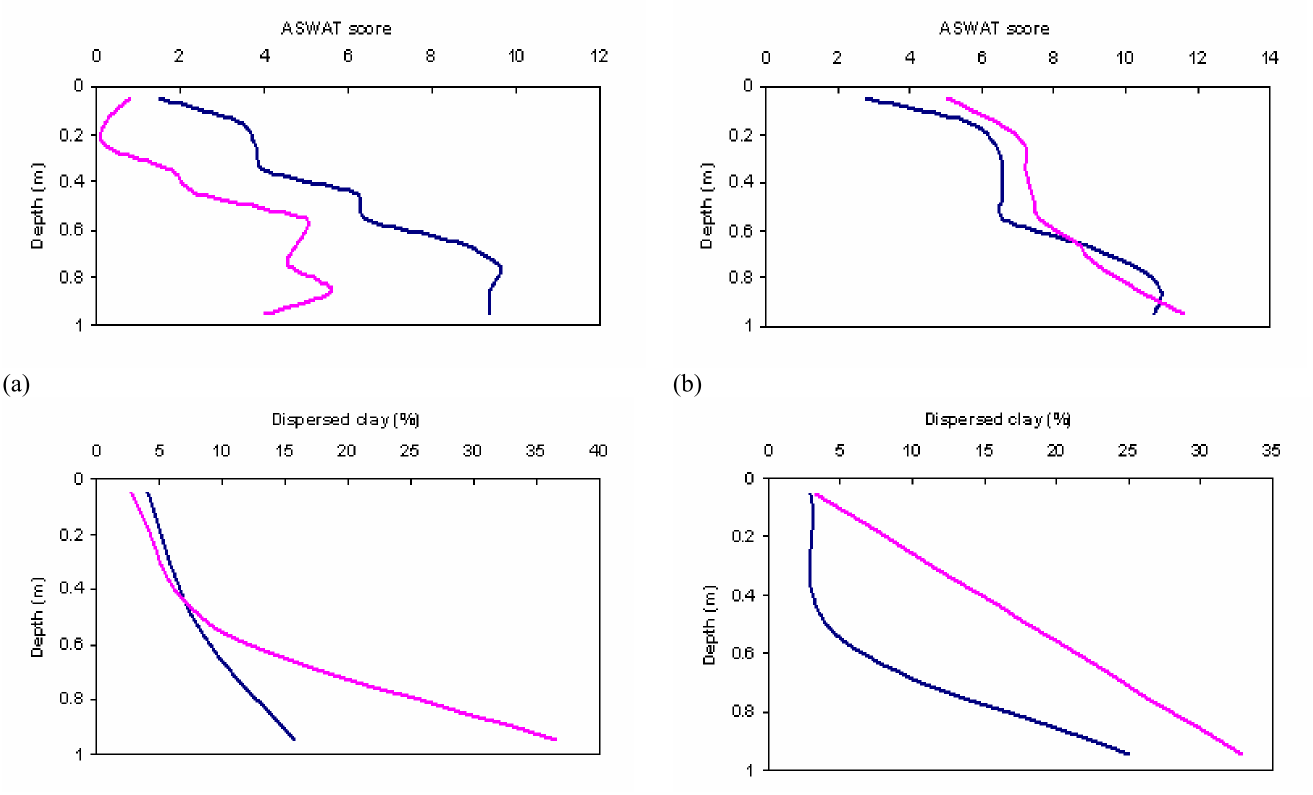
For each field, different letters (a, b) in a row denote where values are significantly different ($P<0.05$).

3.1.4. Aggregate Stability

Fig. 6 shows the aggregate stability as a function of depth according to ASWAT and the proportion of dispersed clay. ASWAT values differed between sampling locations and mirrored trends previously observed in ESP and EC data. Aggregate stability decreased with depth, with mean ASWAT values ranging from 3 in the topsoil (0–0.4 m) to 9 in the subsoil (0.7–1.0 m). Low yielding zones at field A were shown to possess significantly greater mean aggregate stability (av. ASWAT score=3) than higher yielding areas (av. ASWAT score=6) ($P<0.001$, s.e. 0.72). According to Field et al. (1997) soils where ASWAT scores are below 8 are not susceptible to spontaneous dispersion, but may exhibit aggregate failure with remoulding (application of force). Therefore, soils at field A are, on average, unlikely to experience spontaneous dispersion in ponded conditions and with adequate management, such as avoiding the use of heavy implements on wet soils, will not exhibit structural degradation.

Field B exhibited greater aggregate instability than field A with mean ASWAT scores 1.3 to 2.7 times larger. There was no significant difference between mean profile ASWAT scores in high and low yielding zones (P=0.15, s.e. 0.37). However, higher yielding zones demonstrated a significantly greater mean level of aggregate stability in topsoils (P=0.03, s.e. 1.63), a difference most pronounced down to a depth of 0.6 m. The similarity in ASWAT scores beyond 0.6 m at field B is a reflection of the comparable mean ESP levels occurring at subsoil depths across differential yielding zones (Fig. 5). Mean ASWAT scores at field B for low yielding zones were approximately 8, indicating strongly dispersive soil profile characteristics (Field et al., 1997). ASWAT did not assess the response of soil to slaking, however a scheme devised by Cass (1999) was used to interpret soil slaking behaviour. As air-dry aggregates sank and slaked rapidly upon placement in deionised water, soil at both field A and B was deemed to possess unstable macrostructure, lower than optimum organic matter content, and hardsetting behaviour after rainfall (Cass, 1999).

Due to the qualitative nature of the ASWAT test, end-over-end disruption was used to further quantify aggregate stability. The proportion of dispersed clay increased with depth, and was significantly greater at all profile depths in regions of low yield (P=0.04, s.e. 2.3) (Fig. 6). Similarly, the proportion of the silt fraction dispersed increased with depth. While results measured at field B were consistent with results obtained via ASWAT, field A displayed a substantial difference in the mean aggregate stability, with lower yielding zones exhibiting an increased proportion of dispersed clay at depths greater than 0.5 m (17.2% dispersed clay) when compared to areas of high yield (12.1%). Proportions of dispersed clay were interpreted using the classification scheme by Hulugalle and Finlay (2003). Topsoils (0–0.1 m) were ranked as very good across areas of high and low yield, and subsoils (0.5–1.0 m) poor to very poor for cotton production.



(a) (b)

(c) (d)

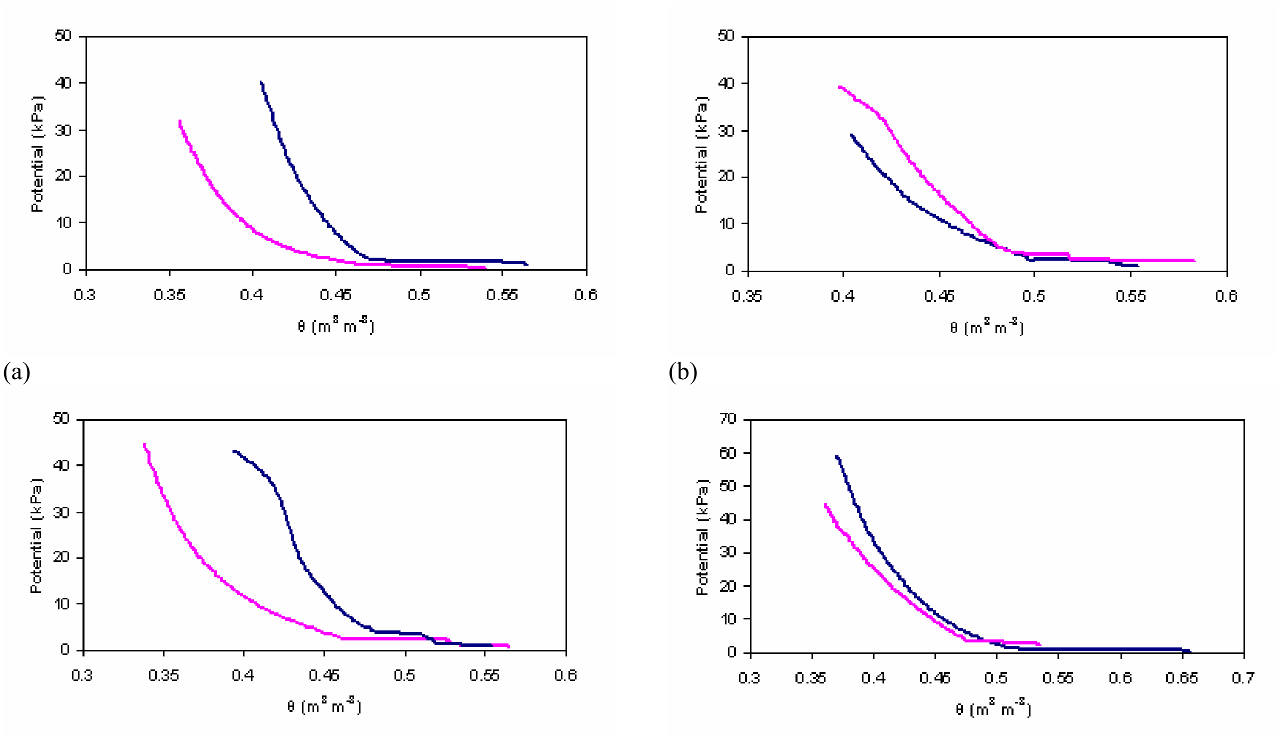
Fig. 6. Soil aggregate stability depth functions including the mean ASWAT score and percentage dispersed clay at (a, c) and (b, d) for field A and field B respectively in high (▬) and low (▬) yielding zones.

3.1.5. Water retention curve

Pore size could not be approximated from the curve as shrinkage occurring with desorption decreases effective pore size in clay soils and therefore cannot accurately represent porosity (Townend et al., 2001). However, in subsoil depths (0.7–0.8 m) (Fig. 7c and 7d) less water was removed at smaller (more positive) values of matric potential, indicating that pores with smaller diameters are expected to occur with decreasing profile depth.

Field A displayed a more pronounced difference between yielding zones with low yielding regions having smaller mean available water at field capacity (-10 kPa) (139 mm root zone, 308 mm subsoil) than high yielding zones (157 mm root zone, 345 mm subsoil). Minor variation in available water at the upper (wet) limit occurred at field B with a 1 mm (root zone) and 9 mm (subsoil) difference between high and low yielding zones.

In general, the reduction in water content with increasing matric potential was more rapid in lower yielding zones, as indicated by the shape of the water retention curve. The exception to this trend were the field B topsoils (0.3–0.4 m) where lower yielding zones demonstrated a more gradual decline in water content with increasing matric potential (Fig. 7).



(a) (b)

(c) (d)

Fig. 7. High-energy moisture characteristics in high (▬) and low (▬) yielding zones at a depth of 0.3–0.4 m for (a) field A and (b) field B and 0.7–0.8 m for (c) field A and (d) field B.

3.1.6. Particle Size Analysis

Field texture grades were estimated to be heavy clays throughout the profile in field B and medium to heavy clays in field A. In general, the proportion of clay increased with depth, with a substantial increase in clay content occurring at a depth of 0.2–0.3 m at field B (Table 2). The sand fraction ranged from 32–40% of the soil solids, consisting of 76 and 83% fine sand at field A and field B, respectively. The silt fraction (2–53 µm) remained relatively constant throughout all profile states. Previous research has demonstrated a large correlation (R^2=0.65) between NDVI and variation in clay content, due largely to the influence of clay on the water holding capacity of the soil (Iqbal et al., 2005). Therefore, in order to ensure that differences in yield were not occurring as a result of different water holding capacities, the statistical significance of clay content was assessed. Clay content was shown to not differ significantly between yield zones (P=0.72, s.e. 1.18); consequently, it was assumed that yield differences were occurring as a result of factors other than clay content, and associated ‘normal’ variation in water holding capacity.

Clay mineralogy at field A and B was approximated using the ECEC-to-clay ratio proposed by Shaw et al. (1998). The two sampling fields demonstrated mixed clay mineralogies with a large proportion of montmorillonite (swelling 2:1 phyllosilicates), throughout the profile. Classification in the subsoil at field A showed a minor difference in mineralogy due to an increase in ECEC, with a slight dominance of montmorillonite and the possibility of feldspars. This is in agreement with the results of Vervoort et al. (2003), who indicated a similar dominance of smectitic (montmorillonite) secondary clay minerals, and subordinate kaolinite and illite clays in Red Vertosols of the lower Lachlan.

Table 2
Mean clay content in high and low yielding zones for locations field A and field B

	Clay content (%)			
	Field A		Field B	
Depth (m)	Low Yield	High Yield	Low Yield	High Yield
0–0.1	57	46	53	55
0.2–0.3	47	51	64	61
0.5–0.6	46	55	57	58
0.9–1.0	55	53	58	60

3.2. Plant Analysis

For leaf samples taken from both farms, and from high and low-yielding zones, macronutrient concentrations were found to lie within the adequate to critical range in terms of plant nutrient status (Reuter et al., 1997). Concentrations of macro-elements were shown to be similar between sampling locations with the greatest degree of inter-field variation occurring in sulfur concentrations, averaging 0.89% at field A and 1.43% at field B (Table 3). In general there was no significant effect of yield on leaf elemental concentrations ($P>0.05$). The exception to this was phosphorus, where lower yielding sites had significantly lower mean P concentrations (0.22%) than higher yielding zones (0.26%) ($P<0.01$, s.e. 0.005). However, when examining elemental levels present in leaf samples, phosphorus concentrations were at similar levels at both high and low yielding fields, showing little variation around the critical concentration range suggested for P (0.25–0.28%) (Reuter et al., 1997). Therefore, any impact on growth and development of cotton would occur similarly between yielding zones. Sulfur concentrations were well above recommended guidelines for cotton, which should not typically exceed 0.4% (Hearn, 1981).

Table 3
Average macronutrient concentration (% dry matter) at the youngest fully mature leaf stage for high and low yielding zones at fields A and B.

Element (%)	Yield	Mean Field A	Mean Field B	Nutritional Status
Phosphorus	Low	0.22a	0.23a	Marginal
	High	0.25b	0.27b	Critical
Sulfur	Low	0.80	1.43	Elevated
	High	0.97	1.44	Elevated
Magnesium	Low	0.88	0.78	Adequate
	High	0.76	0.80	Adequate
Calcium	Low	3.26	3.48	Adequate
	High	3.18	3.84	Adequate
Potassium	Low	1.54	1.46	Critical
	High	1.36	1.44	Critical

Critical and elevated values represent elemental concentrations where no symptoms occur and yield is at 95% of the maximum. Adequate ranges do not cause changes to growth or production and may also be referred to sufficient or satisfactory (Reuter and Robinson, 1997).

For each element and individual field, different letters (a,b) in a column indicate where values are significantly different ($P<0.05$).

Average leaf micronutrient concentrations were found to be greater at field B across the microelement suite (Table 4). Micronutrient nutrition largely demonstrated no significant differences between high and low yielding zones ($P>0.05$). Nutritional status for commonly reported plant nutrients are given in Table 4, with leaf micronutrient concentrations ranging from poor to elevated (Reuter et al., 1997). Boron was determined to be at elevated concentrations, with mean boron levels at 128 mg kg^{-1} and 140 mg kg^{-1} for high and low yielding zones, respectively. Reuter et al. (1997) suggest adequate concentrations for boron range between 20–80 mg kg^{-1} for plants in the stage of flowering to boll development. Zinc was below recommended concentrations 25–80 mg kg^{-1} at field A (mean field concentration 21.6 mg kg^{-1}) (Reuter et al., 1997). Sodium concentrations were found to be above average for Australian conditions (350 mg kg^{-1}), yet were adequate for crop nutrition, suggesting the absence of sodium toxicity. Non-essential heavy metals

(Ni, Pb, Cd, Co) lay below the upper limit of normal values assigned to heavy metal concentrations in plants and therefore were not thought responsible for any yield decline as a result of heavy metal contamination (Tam and Singh, 2004). Results for aluminium, chromium and titanium were not presented, as the nitric/hydrochloric acid digest used in analysis did not give a full recovery of element concentrations in the leaf, and consequently, was only used as a potential indicator for contamination during the sampling procedure. Contamination in analysis of leaf samples was deemed to be of minor importance.

Table 4
Average micronutrient concentration (mg/kg) at the youngest fully mature leaf stage for high and low yielding zones at Field A and B.

Element (mg/kg)	Yield	Mean Field A	Mean Field B	Nutritional Status
Copper	Low	6.17	6.87	Critical
	High	6.91	7.03	Critical
Zinc	Low	20.6	27.1	Poor
	High	22.6	27.9	Poor
Manganese	Low	72.6	96.0	Adequate
	High	71.7	109	Adequate
Iron	Low	174	236	Adequate
	High	221	240	Adequate
Sodium	Low	2328	2300	Adequate
	High	2006	2070	Adequate
Boron	Low	127	152	Elevated
	High	108	149	Elevated
Molybdenum	Low	1.31	1.29	Adequate
	High	1.35	2.25	Adequate
Selenium	Low	<10	<10	Adequate
	High	<10	<10	Adequate
Nickel	Low	1.02	1.44	Adequate
	High	1.24	1.64	Adequate
Lead	Low	<3	<3	Adequate
	High	<3	<3	Adequate

Cadmium	Low	<0.2	<0.2	Adequate
	High	<0.2	<0.2	Adequate
Cobalt	Low	<0.6	<0.6	Adequate
	High	<0.6	<0.6	Adequate

4. Discussion

4.1. Indirect effects of sodicity on crop yield

Soil physico-chemical attributes at the two individual locations (field A and B) were considerably different, with substantial dissimilarities taking place in electrical conductivity, exchangeable sodium percentage and aggregate stability (ASWAT) mean depth functions. In order to assess the implications of physico-chemical attributes, the upper 0.45 m of the soil profile was examined, as 80% of all cotton roots occur within this zone (Hodgson et al., 1990) and as such is considered to be of primary importance for irrigated cotton production. Consequently, characteristics of topsoils and subsoils were treated separately, to reflect the differing importance of different profile depths on crop productivity.

4.1.1. Topsoil

Across low and high yielding zones, topsoils ranged from slight to moderately alkaline. As topsoil pH_{Ca} was not significantly different between yield zones in field B alkaline soil conditions could not account for lower crop productivity. In contrast, low yielding zones in field A exhibited significantly greater mean pH_{Ca} (7.8), exceeding the optimal soil pH_{Ca} of 5.5–7.0 for cotton production, and may cause yield implications (McKenzie, 1998).

Widely reported effects of excessive concentrations of salt include reduced stomatal conductance (Moreno et al., 2001), staple length, fibre maturity and fibre strength (Ashraf and Ahmad, 2000). However within the upper 0.45 m of all fields and yielding zones, measurements of electrical conductivity were small and were considerably below the 1.2 dS m^{-1} ($EC_{1:5}$) threshold salinity level recommended for cotton (Shaw, 1999). Therefore even with significantly greater concentrations of topsoil soluble salts in field A, existing crops would not be experiencing reduced growth as a result of osmotic influences of salinity. Topsoil depths in field B displayed a greater amount of soluble salts at surface layers, as highlighted by Fig. 4. The accumulation of salts is thought to be a result of application of irrigation water containing soluble salts, which has lead to a concentration of salts at the surface.

Across high and low yielding zones in field A, amounts of exchangeable sodium remained relatively uniform in the topsoil. In contrast, field B demonstrated significantly greater ESP values in low yielding zones, with an increased severity of sodicity at shallower profile depths. The greater severity and shallower occurrence of sodicity in low yielding zones is thought to be a result of “cut and fill” practices, commonly used in the district. “Cut and fill” processes involve the removal of topsoils at high elevations (cut) and deposition of soil (fill) in areas of lower elevations, and is frequently practiced to improve irrigation efficiency. Greater ESP as a result of exposure of sodic subsoils by landforming processes was recently reported by Cay and Cattle (2005) in Red Vertosols at Hillston and previously in the Macquarie Valley by Jessop et al. (1985). Comparison of NDVI and “cut and fill” maps indicated that low yielding zones were typically located in cut areas. Other effects of landforming on topsoil characteristics were additionally observed in all physico-chemical depth functions via the common inflection at 0.2–0.3 m in pH, EC and to a lesser extent ESP, in both high and low yielding zones at fields A and B. As highlighted in Fig. 3–5, these alterations to topsoil attributes were generally more severe in low yielding zones, with more alkaline pH, greater electrolyte concentrations, and larger ESP (in field B) occurring at shallower profile depths.

In field B, ESP exhibited similar trends to pH, electrical conductivity and aggregate stability (ASWAT and proportion of dispersed clay). That is at 0.4 m, lower yielding fields demonstrated a significantly larger ESP (7.4%), resulting in a greater propensity for soil dispersion (mean ASWAT score=6). Aggregate instability is attributed to sodium increasing the thickness of the diffuse double layer, decreasing forces of attraction and resulting in destruction of inter-aggregate bonds. However, aggregate behaviour in low and high yielding topsoils of field A indicated the proportion of sodium on soil exchange sites was not the sole factor controlling structural instability, as although low yielding zones displayed a similar mean ESP level (7.7%) to field B, soil did not exhibit spontaneous dispersion (mean ASWAT score=1). Differences in the upper 0.45 m of physico-chemical depth functions highlighted that enhanced structural stability may be attributed to the flocculative properties of greater concentrations of soluble salts in low yielding zones (mean EC=0.27 dS m^{-1}). These assumptions are in agreement with the findings of So and Aylmore (1993) who noted a decrease in dispersion of west Australian kaolinitic clays, following EC increasing beyond 0.17 dS m^{-1}. Increases in soluble salts reduce the forces of the diffuse double layer, allowing operation of van der Waal attractive forces, and flocculation of clay particles. Apart from increases in electrolyte concentration, propensity towards aggregate breakdown has additionally been associated with soil texture, pH, organic matter and clay mineralogy. However, as clay mineralogy and pH are similar between yielding zones in the topsoil at field A, EC is viewed as the primary mechanism controlling aggregate stability.

Calculation of the ESI, which considers both the role of exchangeable sodium and electrolyte concentration in soil structural behaviour, confirmed the importance of the flocculation effect, with low yielding zones at field A shown to maintain structural integrity (McKenzie, 1998). Based on the physical behaviour of aggregates, yield differences occurring at field B may be a result of significantly greater mean aggregate instability in low yielding zones. Decreased water movement, root germination and inhibition to root growth are potential causes of yield decline, as detrimental effects on these soil properties have been observed under deteriorated soil structure (ASWAT scores>6) (McKenzie, 1998). As aggregate stability scores and the proportion of dispersed clay were relatively small at field A, it is unlikely that soil structure would impose any indirect limitations to cotton production. This is supported by evidence of significantly greater aggregate instability in high yielding zones (mean ASWAT score=3), with no ramifications to crop productivity.

The effect of significantly worse soil structure on topsoils in field B was demonstrated in water retention curves, where lower yielding zones showed a more gradual decline in water content with increasing matric potential. Similarly, where increased aggregate stability occurred in low yield regions of topsoils in field A, soil demonstrated a more rapid decline in water content with increasing matric potential, indicating the draining of larger pores. Decreased water content and similar trends in water retention curves as a result of sodicity-induced destabilisation has also been reported by Malik et al. (1992) in montmorillonite clays of the Sudan. Despite the greater water content (at field capacity) in lower yielding zones of field B, this should not translate to an increase in water availability, as in sodium dominant montmorillonite clays, water will remain between clay sheets and smaller interparticle pore spaces, and be largely unavailable for crop production (Malik et al., 1992). The interpretations derived from the water retention curve should be accepted with caution, as shrink/swell behaviour could be of greater importance to water retention and transport than structural deterioration. Additionally, inherent uncertainty may occur in the dataset used to derive the water retention curve, as Vogel (2000) suggested that a different pore size distribution can produce a similar water retention curve. Therefore, the ability to accurately predict the influence of water storage in the topsoil may be improved through monitoring of soil shrinkage during desorption and pedotransfer functions (Minasny and Field, 2005).

4.1.2. Subsoil

In both fields A and B subsoils exhibited significantly greater alkalinity, electrolyte concentration, ESP and aggregate instability due to a uniform increase in physico-chemical attributes with depth. Consistently larger pH_{Ca} in subsoils was presumably due to an accumulation of sodium, calcium and magnesium carbonates, and is subsequently responsible for strongly alkaline conditions as a consequence of sodium hydrolysis. The progressive increase in soil alkalinity with depth increases the possibility of yield impacts from altered micronutrient availability. However, the potential for yield implications was only demonstrated in field B, as in contrast to the topsoil, pH_{Ca} was not significantly greater in low yielding zones of field A at depth.

Climatic conditions (low rainfall) have inhibited salts from being adequately flushed from the profile, causing a concentration of soluble salts at subsoil depths. Subsoils at both fields A and B, in the same manner as topsoils, did not exhibit direct limitations to cotton production as a result of salinity.

The interplay between electrolyte concentration and ESP on aggregate stability occurring in topsoils was equally observed in subsoils. However, as ESP increased substantially beyond 0.5 m depth, values of aggregate stability indicated that concentrations of soluble salts were no longer sufficient to suppress soil dispersion. With the exception of low yielding sites at field A, subsoils in areas of high and low yield exhibited strongly dispersive characteristics, potentially causing dense or hardpan layers which may restrict infiltration below one metre, and impact on crop growth and development. These changes are thought not to be responsible for observed yield declines as in contrast to the root zone (upper 0.45 m); no significant difference occurred between high and low regions at field B according to ASWAT. Reasons for this similarity in structural degradation relate to the significantly greater concentration of soluble salts at subsoil depths, which would prevent further aggregate instability. Similarly, as high yielding zones at field A exhibited significantly greater aggregate instability than low yielding zones, subsoil structural decline is unlikely to contribute to observed yield differences.

The evaluation of ESI subsoil values also indicated a strong correlation with ASWAT values, confirming the role of electrolyte concentration in flocculation of the soil. Comparison of structural instability between ASWAT and end-over-end disruption, in contrast to observed topsoil behaviour, showed a poor correlation with subsoil data, with significantly greater aggregate instability inferred in end-over-end results at both fields in low yielding zones. This discrepancy between techniques may be attributed to the more disruptive methodology employed by end-over-end, where total energy applied involves kinetic energy (aggregate collision) and shear pressure (Raine and So, 1997). Additionally, the linearity observed in dispersed clay depth functions are ascribed to sampling techniques which focused on only 3 profile depths.

In the same way as topsoils, the nature of aggregate stability impacted on water retention at subsoil depths, with lower yielding zones exhibiting a more rapid decrease in water content with increasing suction. This remains consistent with the greater structural stability observed at fields A and B in areas of low yield. However, as with topsoil interpretations these assumptions should be accepted with caution due to the shrink/swell behaviour of smectitic medium to heavy clays.

4.2. Impact of sodicity on plant nutrient status

4.2.1. Macronutrients

Analysis of macronutrient nutritional status identified critical concentrations of phosphorus and potassium and elevated levels of sulfur as potential sources of yield decline (Table 3). The response of P is unexpected, as previous studies have found that structural degradation, commonly associated with sodicity, frequently leads to greater soil phosphorus concentrations (Naidu and Rengasamy, 1993). These increases in P are attributed to a reduction in ferric phosphate compounds and alterations to the adsorption/desorption balance; causing $NaHCO_3$-P to become more labile and enhancing P availability for plants (Curtin et al., 1992; Naidu and Rengasamy, 1993). The absence of a similar response in observed plant tissues is likely to be a result of P occurring in soil as NaOH-P or HCl-P, as these represent more strongly adsorbed compounds, and consequently result in reduced P availability for plants. Alternatively, Marcus-Wyner and Rains (1982) have suggested that in the presence of large soil calcium concentrations, phosphorus is complexed as an insoluble precipitate and may be less available for plant uptake. The latter reason appears most likely as calcium occurred in larger concentrations at both field A and B, suggesting an abundance of calcium in the soil (Table 3).

As sulfur toxicities have not been reported in the field and excess amounts of available sulfur are readily leached, it is thought that elevated concentrations in the leaf may be occurring as calcium sulfate complexes (Marcus-Wyner and Rains, 1982). The absence of sulfur toxicity symptoms, such as molybdenum deficiencies, further supports this assumption. Lower concentrations of potassium recorded in leaf tissue are attributed to the earlier maturing varieties currently being grown at both fields. Reduced density of cotton root systems and faster growth rate of new varieties may have affected the ability of the plant to provide adequate K (Fageria et al., 1997).

While leaf concentrations of macronutrients were often found not to lie within the boundaries deemed adequate for cotton nutrition, in general these could not account for yield decline, due to no significant difference occurring between high and low yield zones. The exception to this was phosphorus, with significantly poorer concentrations of P occurring in low yielding zones. Therefore, phosphorus may be the only potential soil nutrient contributing to yield losses.

4.2.2. Micronutrients

As pH_{Ca} levels greater than 7.6 are associated with various ion deficiencies e.g. zinc and manganese, and increased availability or toxicity of soil micronutrients e.g. boron, copper and molybdenum (Sparks, 2003), it is possible that differences in yield may be attributed to changes in soil macro-and micronutrient availability due to the alkalinity occurring across sampling locations. In examining micronutrient status of the leaves it appears that the strongly alkaline soil environment has directly impacted on plant nutrition.

Elevated levels of boron and zinc deficiencies (Table 4) indicate a correlation between soil and plant observations. Boron, when recorded at elevated concentrations, causes reduced vigour due to an increased production of boron anions ($B(OH)_4^-$), stimulated by pH_{Ca} increasing above 8. Therefore, based on the observed pH_{Ca} at the 'root zone', it appears depths beyond 0.45 m may be involved in nutrient uptake, as field B demonstrates larger boron concentrations, yet fails to exceed a pH_{Ca} of 8 until a depth of 0.55 m. The relationship between sodic soils and boron toxicity has previously been noted by Cartwright et al. (1986), and while symptoms of born toxicity were not observed in the field, it should be recognised that excessive boron concentrations represent a potential cause of future yield reductions.

Pedogenic carbonate observed at 0.5–0.7 m in profiles of the Red Vertosols, and similarly noted by Cay and Cattle (2005) elsewhere in the district, may have contributed to a reduced availability of zinc. Naidu and Rengasamy (1993) noted that it was only following removal or dissolving of these concretions and nodules that zinc becomes available for nutrient uptake. Alternatively, or in addition to the effects caused by pedogenic carbonate, laser-levelling may be responsible for the increased incidence of zinc deficiencies, as zinc is typically higher in surface soils and therefore can be removed with "cut and fill" operations (Marcus-Wyner and Rains, 1982). Application of $ZnSO_4$ has been shown to improve zinc availability and represents a possible management option for growers. The trend and effects of alkalinity was not observed throughout the microelement suite, with copper and molybdenum, typically thought to display increased availability under alkaline conditions, failing to show elevated concentrations in plant tissue at both field A and B.

Although sodicity may have been responsible for some aspects of leaf nutrition, no significant impact on micronutrient concentration was observed between zones of high and low yield at the different sampling locations. Based on these results it is likely that sodicity-induced alkalinity did not directly contribute to yield declines.

4.3. Importance of direct and indirect sodicity effects on cotton yield

Based on observed soil physico-chemical behaviour the relative importance of direct and indirect effects on cotton yield is different between the fields. Field B exhibited significantly greater sodicity and structural deterioration in the root zone of low yielding regions. Despite a greater severity of sodicity at subsoil depths, no significant differences occurred in ESP between yielding zones, indicating that the proximity of excessive levels of sodium to the root zone is of critical importance when examining yield implications. It is therefore assumed that the lower yields are a result of soil dispersion, and the associated consequences of structural change on movement and availability of water in the profile. Yield losses as a result of sodicity induced structural decline were also reported by McKenzie et al. (2002). The study, conducted in the Lachlan Valley, found that an ESP of 10.7 produced a 50% reduction in soybean yield. Data from this study indicated that at field B a 15% reduction in yield occurred with an ESP of 7.4 in the root zone. The smaller reduction in yield observed in this study may be a result of the clay mineralogy, which was dominated by montmorillonite and is therefore less sensitive than mixed clay mineralogies to the effects of sodicity (Shaw et al., 1998).

In contrast, differences in yield occurring at field A could not be ascribed to sodicity, as soil profiles exhibited uniform ESP levels throughout the profile, and higher yielding zones typically displayed greater aggregate instability. Significantly larger pH values in topsoils of low yielding zones of field A alluded to potential problems of micronutrient availability, however strongly alkaline soil conditions did not lead to significantly different impacts on micronutrient status in regions of high and low yield. In both fields A and B macronutrient concentrations indicated a significant difference in phosphorus status between zones of high and low yield. However, on the basis of existing literature (Curtin et al., 1992; Naidu and Rengasamy, 1993) it was concluded that differences in P could not be accounted for by the effects of sodicity, and were most likely a result of insufficient inorganic P. As such it can be intimated that yield differences at field A are caused by factors other than sodicity. Management techniques such as variable rates of irrigation, pest and disease pressure are possible cause of yield differences, however in the absence of pathogenic effects, observed during fieldwork, irrigation differences were thought to be accountable. As field A used lateral irrigation this may cause a greater potential for non-uniform irrigation application.

Across sampling locations there was no evidence in the data to suggest that sodicity was impacting directly on cotton production. This may be a consequence of insufficient concentrations of soil sodium to induce toxicity or deficiency symptoms, or the inhibitory effects of calcium which can restrict sodium uptake (Davenport et al., 1997).

When considering the data from field B, general recommendations could be proposed to farmers in this district, whereby if:

Alkalinity occurs (pH_{Ca} greater than 7)
ESP is greater than 6
$EC_{1:5}$ is greater than 0.2 dS m^{-1}
ASWAT is greater than 6

in the upper 0.45 m of the profile, the indirect effects of sodicity will be significant, causing substantial yield reductions. This is an empirical result and represents a guideline which is only directly applicable to field B. However, it is expected that the implications of sodicity may be similarly observed in other areas of irrigated cotton, as Nelson and Ham (2000) and McKenzie et al. (2002) likewise reported yield reductions in sugarcane and soybeans, respectively, attributed to the indirect effects of sodicity. These guidelines therefore could act as a framework for the current grower, and with future studies facilitate informed decision-making of landholders, via the assessment of soil conditions prior to planting. The formation of the 'critical' values concept could be extended with further research, with potential to create a database to encompass other regions of irrigated crop production, and include changes in critical values following soil amelioration. This could enable the formulation of a cost benefit analysis, potentially allowing growers to determine the economic viability of amelioration strategies and crop production.

5. Conclusions

Soil physico-chemical attributes and plant nutrition were assessed on two irrigated cotton properties near Hillston, New South Wales, to determine the effect, and importance of, sodicity on crop yield. At each location (field A and field B) a comparison of soil and leaf attributes was made between zones of high and low yield. Significant effects of sodicity were not similarly identified at both field A and field B, with considerable differences in electrolyte concentration, exchangeable sodium percentage, and aggregate stability (ASWAT and end-over-end disruption) occurring between locations and within high and low yielding zones.

Alkaline soil conditions commonly associated with excess levels of exchangeable sodium were thought responsible for the occurrences of some elevated (boron) and poor (zinc) micronutrient concentrations, detected across sampling locations. However, there was no evidence in the data to implicate any direct (plant) effects of sodicity on cotton production, due to the similarity in macro and micronutrient concentrations observed in both high and low yielding zones.

In topsoils of field B, low yielding zones exhibited significantly larger exchangeable sodium values at shallower profile depths, attributed to the raising of sodic subsoil layers via the process of landforming. Subsoils showed a greater severity in ESP, but as these soil layers were not in close proximity to the root zone, they were not thought accountable for yield differences. The large concentrations of ESP in topsoils displayed a strong correlation with aggregate instability in low yielding zones. It was therefore assumed that indirect (soil) effects of sodicity were responsible for yield reductions, as increased amounts of dispersed clay presumably reduced water availability to the plant. The location of these structural changes was important as the proximity of structural deterioration to the root zone lead to greater implications for crop growth and development.

Alternatively, field A failed to indicate sodicity-induced yield declines. Severity of sodicity paralleled levels observed in field B, yet this did not translate to a similar level of aggregate instability. The failure of low yielding zones to demonstrate soil dispersion was ascribed to the flocculative properties of a significantly greater electrolyte concentration. Therefore, in field A, variation in irrigation application was the more likely cause of yield reduction as there was no evidence of pest or disease pressure.

As indirect effects were shown to produce implications for crop development, a series of benchmark figures were determined from the dataset of field B, as this may assist landholders in the immediate area to assess whether yield reductions may occur as a result of sodicity. An ESP and ASWAT score greater than 6, when combined with small electrolyte concentrations and alkalinity, were associated with substantial decline in irrigated cotton yield. The ability to determine these critical values could allow growers to determine the viability of cotton production prior to sowing.

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