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The effect of sodicity on cotton: does soil chemistry or soil physical condition have the greater role?

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Abstract. Soil sodicity is widespread in the cracking clays used for irrigated cotton (*Gossypium hirsutum* L.) production in Australia and worldwide and sometimes produces nutrient imbalances and poor plant growth. It is not known whether these problems are due primarily to soil physical or to soil chemical constraints. We investigated this question by growing cotton to maturity in a glasshouse in large samples of a Grey Vertosol in which the exchangeable sodium percentage (ESP) was adjusted to 2, 13, 19, or 24. A soil-stabilising agent, anionic polyacrylamide (PAM), was added to half the pots and stabilised soil aggregation at all ESPs. Comparison of the effect of ESP on cotton in the pots with and without PAM showed that, up to ESP of 19, the soil physical effects of sodicity were mainly responsible for poor cotton performance and its ability to accumulate potassium. At ESP >19, PAM amendment did not significantly improve lint yield, indicating that soil chemical constraints, high plant sodium concentrations (>0.2%), and marginal plant manganese concentrations limited plant performance. Further research into commercial methods of amelioration of poor physical condition is warranted rather than application of more fertiliser.

Additional keywords: soil solution, Vertosols.

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Introduction

High exchangeable sodium percentage (ESP) in soil limits agricultural productivity in many parts of the world. In Australia, sodic soils (ESP $\geq$6, Isbell 2002) occupy ~23% of the total land area (McKenzie *et al*. 2004) and 80% of the irrigated agricultural area (Rengasamy and Olsson 1993). It has been estimated that ameliorating sodicity in Australian agricultural areas could add more than one billion Australian dollars to the value of agricultural output, which is five times more than ameliorating saline areas (Hajkowicz and Young 2005). Sodicity affects both physical and chemical fertility in soils and much research has documented these differing adverse effects on plant growth. This paper addresses the relative contributions of physical and chemical factors in reducing cotton growth; seeking to elucidate whether physical factors or chemical factors are of more significance at different soil ESP values. The negative effects on soil physical fertility of clay dispersion induced by high ESP are well documented (So and Aylmore 1993) and include poor infiltration and drainage, susceptibility to waterlogging and anoxia, high soil strength as soil dries, and a low plant-available water range. However, sodicity also affects soil solution chemistry. In a preliminary investigation of soil solutions of South Australian sodic soils, Naidu *et al*. (1995) found cases of low calcium (Ca) concentration relative to other cations, as well as low phosphorus (P) and micronutrient concentrations, sufficient to suggest potential nutrient deficiencies. In part, the poor chemical fertility of many sodic soils can be attributed to pedogenic factors including parent material and climate, as well as the inhibition of biological cycling due to their poor physical condition. However, there are also direct effects of ESP on soil solution chemistry, a necessary result of the chemical equilibrium developed between the exchangeable and solution ions.

Rochester (2010), in a series of field experiments at 30 sites in eastern Australia and over several growing seasons, observed that cotton (*Gossypium hirsutum* L.) crops grown on irrigated, sodic, cracking clay soils commonly have elevated concentrations of sodium (Na) and reduced concentrations of P and potassium (K) in their tissues. Dodd (2007) measured of the properties of cotton plants from different parts of an irrigated Vertosol field near Moree in New South Wales (NSW) that exhibited strong spatial variation in sodicity. Dodd (2007) found that as profile average ESP (0–0.6 m) increased from 1 to 31, there was a significant decrease in youngest mature leaf (YML) concentration of K and an increase for Na at both midseason and harvest. The YML P concentration decreased with ESP at harvest, although not at midseason, and YML Ca concentration was unaffected by ESP.

The mechanisms behind these patterns of nutrient accumulation are not understood, and arguably could result from either soil physical factors (dispersion and breakdown of aggregates, affecting bulk density and porosity, and restricting root extension and growth) or soil chemical factors (changes in soil solution composition resulting in changes in soil solution activity of P and K). One explanation is that low plant P and K concentrations result from poor soil structure, which impedes root growth, increases waterlogging, and restricts access to soil water and nutrients. An alternative explanation is that P and K uptake are directly affected by the chemical composition of the soil solution that is developed in response to the high ESP, for example, by competition between ions for uptake. Dodd *et al.* (2010*a*) investigated the second of these options and observed limited effects of soil solution composition on cotton growth. Separating the effects of chemical and physical effects on the growth of cotton in sodic soils has implications for management of crops. For example, low-yielding sodic areas are commonly supplemented with extra P and K fertiliser resources; however, were the effect predominantly physical, this would have limited beneficial effects on yield. This paper therefore aimed to quantify the relative contributions of adverse physical sodicity effects and changes in the soil solution composition on the growth and nutrient uptake of cotton plants in irrigated Vertosol soil systems.

Methods

A glasshouse pot experiment was undertaken to assess the relative contributions of the physical and chemical limitations imposed by high ESP in a Vertosol on the growth and nutrient accumulation of cotton plants. Soils sampled from the field that differ in sodicity may also differ in other properties such as mineralogy, organic matter, nutrient status, and salinity, and these differences can confound investigations into the effects of ESP (Churchman *et al*. 1993; Sumner 1993). To overcome this problem, we took one soil and used a sodification technique, which raised its ESP while minimising changes in other soil chemical properties (Dodd *et al*. 2010*b*). In order to distinguish the physical from the chemical effects of ESP, half of the pots were treated with polyacrylamide (PAM), an anionic linear copolymer of acrylamide and sodium acrylate that increases aggregate stability (Wallace *et al*. 1986). Dodd *et al*. (2004) demonstrated that the addition of PAM to non-sodic and sodic cracking clays had no effect on soil solution nutrient concentrations, except for a slight decrease in P concentration.

Soil preparation

The soil (0–0.15 m) was collected from a cotton field at the Australian Cotton Research Institute, Myall Vale, NSW (150°E, 30°S), which had been used for irrigated cotton and wheat cropping for ~30 years. The soil is a fertile, dark greyish brown clay, classified as a fine, thermic montmorillonitic Typic Haplustert (Soil Survey Staff 2010) or a Haplic, Self-Mulching Grey Vertosol (Isbell 2002). Selected soil properties are presented in Table 1.

We prepared 250 kg soil for each of the four ESP levels chosen. A method developed by Dodd *et al*. (2010*b*) was used to create soils that varied primarily in their exchangeable Na and Ca content, with changes to other soil properties minimised. Four treatment solutions were prepared, varying in sodium adsorption ratio (SAR) (0, 45, 100, and 200), made from the chloride salts of the major nutrient cations at the following respective concentrations: Na 0, 25, 58, 122 mM; Ca 8.2, 0, 0, 0 mM; magnesium (Mg) 0.28, 0.31, 0.34, 0.37 mM; and K 0.08 mM for all. The soil was spread to a depth of 5 cm in calico-lined, stainless-steel trays (30 by 80 by 7.5 cm) with perforated bases. Each tray was immersed in a treatment solution for 4 h, allowed to drain for 1 h, and then partially dried in a fan-forced oven at 40°C for ~12 h. The immersing, draining, and drying cycle was repeated six times. Following equilibration with these four solutions, the saturation-extract electrical conductivity (EC_{se}) of the soils was adjusted to 2.7 dS m^{-1}. It was found that this could be achieved by immersing the soils in solutions containing the same K and Mg concentrations as the SAR 0, 45, 100, and 200 treatment solutions but with SAR values of 0, 35, 15, and 0, respectively. Each bulk soil sample was then oven-dried at 40°C, thoroughly mixed, and divided into two equal portions. One portion was spread in a large stainless-steel tray and PAM was applied in solution at a rate of 2.5 g kg^{-1} soil. The soil was then air-dried.

Soil chemical analyses

A sample of each soil was ground (<2 mm) and the effective cation exchange capacity (ECEC) and cation concentrations of each soil were measured using a method similar to that described by Tucker (1985). A 2-g sample of each soil was shaken end-over-end for 1 h with 40 mL of 1 M NH_4Cl (buffered to pH 8.5) and centrifuged for 15 min at 3000 rpm (2010*G*). The supernatant was filtered using Whatman No.1 paper and analysed for Ca, Na, K, and Mg using inductively coupled plasma-atomic emission spectroscopy (ICP-AES).

Soluble salts were measured as described by So *et al*. (2004). A 150-g sample of the soil was raised to field capacity (0.42 kg kg^{-1}) with de-ionised water, covered with wet paper towelling, and allowed to equilibrate for 48 h in a closed container. The soil solution was extracted by centrifuging the soil for 30 min at 4000 rpm (3580*G*) and filtered to 0.22 µm (Millipore, Merck Pty Ltd, Kilsyth, Vic.), and Ca, Na, K, Mg and micronutrient concentrations were determined using ICP-AES. Exchangeable cations were calculated as the difference between the NH_4Cl-extracted cations and soil solution cations.

Table 1. Selected soil properties of the surface 0–0.1 m of a Grey Vertosol from Narrabri, NSW

Soil type[A]	Site	Crop rotation	Clay[B] (g 100 g^{-1})	pH[C]	EC[D] (dS m^{-1})	ECEC[E] ($cmol_c$ kg^{-1})	ESP	Colwell P[F] (mg kg^{-1})	Carbonate[G] (g 100 g^{-1})
Grey Vertosol	25 km west of Narrabri	Cotton–cereal	52	7.35	0.7	38.0	2.5	42	0.05

[A]Isbell (2002). [B]Dispersion and sedimentation. [C]1 : 5 soil : solution ratio in H_2O.
[D]Saturation extract. [E]1.0 M NH_4Cl. [F]Colwell (1963). [G]Midwood and Boutton (1998).

Soil solutions were analysed for P using the method of Motomizu *et al.* (1983). A 1-mL aliquot of malachite green reagent was added to 3 mL of each soil solution, the colour was allowed to develop for 3 h, and the P concentration was measured using a spectrophotometer at 630 nm.

The pH and $EC_{1:5}$ of the soils were measured in a 1 : 5 water suspension. Soil pH was also measured in a mixed NaCl and $CaCl_2$ solution that matched the cation concentrations measured in the soil solution. To facilitate interpretation of any relationship between EC and plant growth, $EC_{1:5}$ was converted to EC_{se} by multiplying $EC_{1:5}$ by 7.5 as recommended by Slavich and Petterson (1993) for medium clays.

Soil physical analyses

Prior to the pot trial, the effects of PAM on the physical condition of the soils were examined by determining the water-stable aggregation (WSA) and mean weight diameter (MWD) of the soils using a wet-sieving method described by Whitbread (1996). A tower of five 100-mm-diameter sieves with mesh screens of 125, 250, 500, 1000, and 2000 μm was used. A 15-g sample of air-dry soil was placed on the top of the sieves and immersed in distilled water at 22°C for 30 s before being sieved for 10 min through 17 mm amplitude at 30 cycles min^{-1}. The sieves were drained and dried at 40°C for 24 h before weighing. The WSA was calculated as the percentage of the soil aggregates >125 μm. The MWD was calculated as the average diameter of the retained soil aggregates, weighted by mass in each size fraction.

Further assessment of the efficacy of PAM in achieving uniform physical condition across the range of sodicity treatments was determined using a modification of the mini tension-infiltrometer method for hydraulic conductivity (HC) (McKenzie *et al.* 2002; Method 510.05). Three replicate cores of soil, 10 cm in both height and diameter, were taken from the soils of ESP 2 and 24 with and without PAM, following the experiment. The cores, without trimming, were immersed in a water bath by gradually increasing the water level. A sand bed was placed in a water bath and then placed inside a larger tray to allow excess water to overflow. The tension in the infiltrometer was set to equal the surface tension of the sand bed, by setting the infiltrometer to almost bubble when placed directly on the sand bed. The cores were placed on the sand bed and the mini tension infiltrometer was filled with deionised water and placed on top of the core. The mini tension infiltrometer was allowed to drain before being refilled until steady-state conditions were attained.

Glasshouse pot experiment

Large pots (0.75 m high by 0.3 m diameter, containing 40 kg soil) were used for the glasshouse experiment in order to allow the cotton plants to grow to maturity and express their full lint yield potential. The design comprised four soil ESP treatments (2, 13, 19, and 24), each with or without PAM addition (designated +PAM or –PAM), replicated three times with pots randomised within blocks.

Dry soil (40 kg) was packed evenly and gently to achieve the same height and therefore bulk density (1000 kg m^{-3}) in each pot. Before planting, fertilisers were incorporated into the top 20 cm of each pot. Amounts equivalent to 200 kg ha^{-1} of nitrogen (N) as urea, 20 kg ha^{-1} of P as $NH_4H_2PO_4$, and 2 kg ha^{-1} of zinc (Zn) as $ZnSO_4$ were applied. No K was applied. The base of each pot was sealed with a plastic bag to prevent leaching loss of salts, and deionised water was added to bring the pots to field capacity (0.42 kg kg^{-1}). Leaching and redistribution of solutes in the soil profile was assumed to be minimal due to the medium clay and high CEC soil, which was maintained at or below field capacity throughout. No salt efflorescence was observed on the pot surface throughout the trial. Ten seeds of cotton (cv. Sicot 289BR, CSD Ltd, Wee Waa, NSW) were planted into each pot, which was then covered with plastic to reduce evaporation. When the plants reached the two-leaf stage, the plastic was removed and the plants were thinned to one per pot.

The experiment was conducted in a glasshouse between October and February so that the cotton plants experienced normal summer daylength and light conditions, with the diurnal temperature range controlled to 20–35°C. Throughout this period, each pot was irrigated (by weight) to field capacity (0.42 kg kg^{-1}) when soil water content had declined to ~0.3 kg kg^{-1}. The plants were harvested after 18 weeks, when the plants reached maximum height and the fruit had matured.

Plant measurements

Early in the fruiting period ('squaring', 8 weeks after planting), the YML was taken from each plant. The nutrient content of the YML of cotton is commonly used as an indicator of midseason plant-nutrient status. At harvest, the plant tops were separated into shoots, fruit, and lint. Due to the large volume and shrink–swell nature of soil used in the experiment, we did not attempt to remove the total root mass of each plant from the soil, and only the main taproot (<20 cm) of each plant was harvested. This was separated from the tops at the point on the stem where the cotyledon leaves were located. Plant height, number of nodes, 5th internode length, number of fruiting positions, fruit number, and shoot, taproot, fruit, and lint dry weights were measured. The plant samples were dried at 80°C, ground (<2 mm), and digested with perchloric acid and hydrogen peroxide, using the sealed chamber method of Anderson and Henderson (1986). Concentrations of Ca, Na, Mg, K, P, boron (B), copper (Cu), iron (Fe), manganese (Mn), and Zn in the samples were determined using ICP-AES.

Statistical analyses

Analyses of variance were used to test the significance of treatment differences (at $P = 0.05$), with ESP, PAM amendment, and block as factors. Where significant interactions between ESP and PAM amendment were found, differences between individual treatment combinations were further evaluated by least significant difference (l.s.d. at $P = 0.05$). The GENSTAT program (Payne 1987) was used for all statistical analyses.

Results

Soil chemical analysis

The sodification process used in this experiment had no detectable effect on the ECEC ($P = 0.23$) or EC ($P = 0.12$) but increased the ESP from 3 to 24 ($P < 0.001$) and decreased exchangeable Ca from 71 to 52% of cations present ($P < 0.001$) (Table 2), indicating that exchangeable Ca was replaced with exchangeable Na. There was no effect on the

Table 2. Effect of equilibration solution sodium adsorption ratio (SAR) on cation concentrations, effective cation exchange capacity (ECEC), pH, electrical conductivity (EC_{se}), and soil solution phosphorus (P) concentration of a Grey Vertosol

Values are means of three replicates. Exchangeable cations are also shown in parentheses as a percentage of ECEC

SAR	Na	Ca	Mg ($cmol_c\,kg^{-1}$)	K	ECEC	pH H_2O	pH Solution	EC_{se} ($dS\,m^{-1}$)	Solution P (μM)
0	1.1 (3%)	29.0 (71%)	9.1 (22%)	1.6 (4%)	40.8	7.6	7.3	3.5	0.11
45	5.2 (13%)	25.4 (62%)	8.8 (22%)	1.5 (4%)	40.8	8.2	7.6	3.5	0.12
100	8.1 (19%)	23.4 (57%)	8.4 (20%)	1.5 (4%)	41.4	8.5	7.8	3.6	0.14
200	9.8 (24%)	21.2 (52%)	8.3 (20%)	1.5 (4%)	40.8	8.7	7.9	3.6	0.18
P-value	<0.001	<0.001	<0.001	0.36	0.23	<0.001	<0.001	0.12	<0.001

exchangeable K concentration of the soil, and the Mg percentage only decreased from 22% to 20% of cations present ($P<0.001$). Soil pH rose from 7.6 to 8.7 in water and from 7.3 to 7.9 where soil solution Na and Ca concentrations were matched ($P<0.001$). The P concentrations of the soil solutions also increased with soil sodicity ($P<0.001$) (Table 2).

Soil physical analysis

Increasing ESP reduced WSA, MWD, and HC in the –PAM soils ($P<0.001$) (Table 3). For MWD, the decline was only significant between ESP 3 and ESP 13 (i.e. from non-sodic to sodic soil). In contrast, in +PAM soils, increasing ESP had no effect on WSA, MWD, or HC, demonstrating that PAM was effective in stabilising soil aggregation. At low ESP, addition of PAM had no significant effect on the WSA of the non-sodic soil but increased the MWD and decreased HC.

Table 3. Effect of exchangeable sodium percentage (ESP) and polyacrylamide (PAM) application on water-stable aggregates (WSA), mean weight diameter (MWD), and hydraulic conductivity (HC) of a Grey Vertosol

Values are means of three replicates. Within columns, means followed by different letters are significantly different at $P=0.05$

PAM application	ESP	WSA >125 μm (%)	MWD (mm)	HC ($mm\,h^{-1}$)
–PAM	3	86a	0.39a	15.4a
	13	65b	0.24b	
	19	50c	0.23b	
	24	33d	0.20b	0.0c
+PAM	3	91a	1.29c	4.1b
	13	90a	1.38c	
	19	91a	1.25c	
	24	90a	1.30c	4.1b
l.s.d. ($P=0.05$)		5.8	0.145	2.9

Plant nutrition

Nutrient concentrations in the YML at squaring, and in shoots and roots at harvest (mass of nutrient per unit plant dry matter), as well as plant nutrient contents (mass of nutrient per plant), are presented in Tables 4–6. Plant Na concentration and content both increased in all plant parts as soil sodicity increased ($P<0.05$) (Table 4). Amendment with PAM had no effect on concentration or content of Na in cotton. Cotton Ca concentrations were not significantly affected by either sodicity or PAM amendment (Table 4). Plant Ca content declined as soil sodicity increased ($P=0.01$, and plant Ca content was higher where PAM had been applied ($P=0.02$).

There was an interaction between ESP and PAM amendment on midseason YML K concentrations ($P=0.02$) (Table 5). In the –PAM pots YML K decreased substantially, from 1.85% at ESP 2 to 1.11% at ESP 24, whereas in the structurally stabilised +PAM pots there was no change in YML K with ESP. Similarly, a significant ESP × PAM interaction for shoot K ($P<0.001$) showed a decline in concentration with increasing ESP for the –PAM treatment, but no simple trend for the +PAM treatment. This was also reflected in taproot K concentration ($P=0.07$). Total plant K content declined significantly with increasing ESP ($P<0.001$), but in the +PAM treatment the decline was smaller and occurred at a higher ESP than in the –PAM treatment. The ESP had no significant effect on P concentration or content of any plant part, although taproot P concentration tended to increase with increasing soil ESP ($P=0.07$) (Table 5). Addition of PAM had no effect on the YML P concentration at squaring, taproot P concentration, or P content at harvest, but it did lower shoot P concentrations ($P=0.01$).

There were no ESP × PAM interactions for B. The YML B concentration at squaring was not affected by ESP but shoot B concentration and content were lower ($P<0.001$) in the higher sodicity treatments (Table 6). Taproot B concentration was affected by ESP ($P=0.03$), but there was not a simple increasing or decreasing trend. The total B content increased with PAM amendment ($P=0.01$). As with B, plant Mn measurements showed no ESP × PAM interaction (Table 6). Leaf and shoot Mn concentrations and total Mn content tended to decrease with increasing ESP, but there was no effect on taproot Mn. Cotton shoot Mn concentrations tended to be lower in the PAM-amended soils than in the –PAM treatment ($P=0.05$). The concentrations of Mg, Cu, Fe, and Zn in cotton were not affected by ESP or PAM amendment (data not shown).

Plant growth

Sodicity and PAM amendment interacted to modify cotton taproot dry weight ($P=0.02$), lint dry weight ($P=0.03$), fruit numbers ($P=0.02$) and fruiting position numbers ($P=0.01$) (Table 7). In the –PAM treatment, three plant parameters related to reproductive growth (lint yield, fruit number, and fruiting position number) declined between the non-sodic and sodic soil, and increasing sodicity above 13% had little or no effect on these plant attributes. By contrast, for the +PAM soils these parameters were unaffected by sodicity until ESP reached

Table 4. Effect of exchangeable sodium percentage (ESP) and polyacrylamide (PAM) application on youngest mature leaf (YML), shoot, and taproot Na and Ca concentrations and accumulation in cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol

Values are means of three replicates. Within columns, means followed by the same letter are not significantly different at $P = 0.05$; n.s., no significant interaction between ESP and PAM treatments

PAM application	ESP	Na concentrations (%) and content (g plant^{-1})				Ca concentration (%) and content (g plant^{-1})			
		YML at squaring (%)	Shoot (%)	Taproot (%)	Total (g plant^{-1})	YML at squaring (%)	Shoot (%)	Taproot (%)	Total (g plant^{-1})
–PAM	3	0.03	0.06	0.10a	0.09	2.52	2.58	0.47	3.55
	13	0.06	0.13	0.28cd	0.12	2.60	3.00	0.46	2.57
	19	0.07	0.24	0.32de	0.21	2.39	2.99	0.43	2.03
	24	0.11	0.31	0.40e	0.27	2.09	1.88	0.47	1.41
+PAM	3	0.04	0.08	0.17ab	0.15	2.38	2.23	0.52	3.84
	13	0.05	0.12	0.19bc	0.17	2.64	2.40	0.48	3.16
	19	0.07	0.20	0.27cd	0.27	2.59	2.28	0.41	2.61
	24	0.09	0.25	0.30d	0.29	3.15	2.84	0.43	3.04
Interaction l.s.d. ($P = 0.05$)		n.s.	n.s.	0.09	n.s.	n.s.	n.s.	n.s.	n.s.
ESP *P*-value		<0.001	<0.001	<0.001	<0.001	0.47	0.73	0.39	0.01
PAM *P*-value		0.06	0.06	0.05	0.32	0.21	0.50	0.99	0.02

Table 5. Effect of exchangeable sodium percentage (ESP) and polyacrylamide (PAM) application on the youngest mature leaf (YML), shoot, and taproot K and P concentrations and accumulation in cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol

Values are means of three replicates. Within columns, means followed by the same letter are not significantly different at $P = 0.05$; n.s., no significant interaction between ESP and PAM treatments

PAM application	ESP	K concentration (%) and content (g plant^{-1})				P concentration (%) and content (g plant^{-1})			
		YML at squaring (%)	Shoot (%)	Taproot (%)	Total (g plant^{-1})	YML at squaring (%)	Shoot (%)	Taproot (%)	Total (g plant^{-1})
–PAM	3	1.85a	2.28a	2.26	3.33a	0.57	0.23	0.15	0.33
	13	1.48b	2.11ab	1.56	1.91c	0.66	0.27	0.19	0.24
	19	1.42b	2.12ab	1.76	1.77c	0.57	0.34	0.18	0.27
	24	1.11c	1.95bc	1.1	1.52c	0.59	0.29	0.17	0.22
+PAM	3	1.47b	1.87c	1.76	3.36a	0.49	0.17	0.15	0.30
	13	1.48b	2.10ab	1.84	2.96a	0.58	0.21	0.15	0.28
	19	1.50b	1.92bc	1.33	2.57b	0.63	0.21	0.17	0.25
	24	1.48b	2.29a	1.84	2.33b	0.46	0.23	0.19	0.26
Interaction l.s.d. ($P = 0.05$)		0.29	0.39	n.s.	0.37	n.s.	n.s.	n.s.	n.s.
ESP *P*-value		<0.001	0.61	0.24	<0.001	0.24	0.15	0.07	0.24
PAM *P*-value		0.16	0.20	0.90	<0.001	0.16	0.01	0.24	0.37

Table 6. Effect of exchangeable sodium percentage (ESP) and polyacrylamide (PAM) application on the youngest mature leaf (YML), shoot, and taproot B and Mn concentration and accumulation in cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol

Values are means of three replicates; n.s., no significant interaction between ESP and PAM treatments

PAM application	ESP	B concentration (mg kg^{-1}) and content (mg plant^{-1})				Mn concentration (mg kg^{-1}) and content (mg plant^{-1})			
		YML at squaring (mg kg^{-1})	Shoot (mg kg^{-1})	Taproot (mg kg^{-1})	Total (mg plant^{-1})	YML at squaring (mg kg^{-1})	Shoot (mg kg^{-1})	Taproot (mg kg^{-1})	Total (mg plant^{-1})
–PAM	3	79.7	108.9	91.5	15.7	69.8	53.2	21.2	7.4
	13	102.6	94.7	46.9	8.3	60.6	41.3	10.4	3.6
	19	99.1	64.9	61.2	5.4	51.7	41.7	11.0	3.3
	24	88.6	55.1	106.0	5.0	63.6	33.7	12.4	2.6
+PAM	3	106.5	88.2	47.4	15.6	81.5	46.7	14.1	8.1
	13	93.9	90.7	79.9	12.8	61.1	28.5	16.0	5.2
	19	67.7	56.9	42.3	6.8	54.9	31.3	14.8	3.7
	24	60.0	75.4	82.0	8.7	52.2	32.8	16.5	3.6
Interaction l.s.d. ($P = 0.05$)		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
ESP *P*-value		0.24	<0.001	0.03	<0.001	0.04	0.02	0.43	<0.001
PAM *P*-value		0.21	0.57	0.17	0.01	0.85	0.05	0.47	0.06

Table 7. Effect of exchangeable sodium percentage (ESP) and polyacrylamide (PAM) application on the plant height, shoot dry weight, taproot dry weight, fruit dry weight, lint dry weight, total fruit number, and total number of fruiting positions at harvest of cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol

Values are means of three replicates. Within columns, means followed by the same letter are not significantly different at $P = 0.05$; n.s., no significant interaction between ESP and PAM treatments

PAM application	ESP	Plant height (cm)	Shoot weight	Taproot weight (g)	Fruit weight	Lint weight	Total no. of fruit fruit	Total no. of fruiting positions
–PAM	3	143.3	134.9	10.8cd	27.2	78.8a	31.0a	61.0a
	13	132.4	84.2	8.7cde	20.3	53.8bc	17.0b	33.0bc
	19	129.9	76.5	8.0e	18.3	41.8c	15.3c	33.0bc
	24	131.4	72.9	8.0e	18.7	40.5c	17.0b	30.7c
+PAM	3	151.4	168.0	14.3a	40.5	83.7a	32.3a	65.3a
	13	141.3	130.1	13.7ab	34.5	79.0a	31.7a	60.3a
	19	140.5	112.8	11.2bc	34.4	76.4ab	31.0a	59.7a
	24	126.8	106.0	8.6de	27.9	51.9c	23.3b	42.7b
Interaction l.s.d. (P = 0.05)		n.s.	n.s.	2.55	n.s.	17.70	7.01	9.70
ESP *P*-value		0.034	<0.001	0.003	<0.001	<0.001	0.001	<0.001
PAM *P*-value		0.159	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

24. At an ESP of 24, there was no significant difference between the –PAM and +PAM soils for any of the plant parameters except fruiting position number. Taproot weight was unaffected by sodicity in the –PAM soils but declined at an ESP of 19 in the +PAM soils. No significant interactions were apparent between sodicity and PAM on plant height, cotton shoot dry weight, and fruit weight. There was no significant effect of sodicity or PAM on the number of nodes or 5th internode length of the plants at harvest (data not shown).

Discussion

Effectiveness of experimental approach

In order to investigate the relative roles of soil physical and chemical factors in the adverse effects that sodicity induces in cotton, we adopted two experimental approaches. First, a sodification method was used to create soils varying principally in ESP, so that differences in the growth and nutrition of cotton plants grown on the soils could be attributed to ESP without being confounded by differences in extraneous soil properties. Second, the effect on soil and plant of increasing ESP was contrasted between soil treated with PAM to stabilise aggregates and unamended soil. The effect on cotton of increasing sodicity in the unamended (–PAM) soils could include both physical and chemical factors, whereas in the PAM-amended (+PAM) soil, changes with increasing ESP would not be attributable to physical factors resulting from declining aggregate stability. Clearly, the validity of the conclusions depends on the effectiveness of the two experimental approaches.

The sodification procedure we used allowed us to produce four soils with ESP values up to 24. This is consistent with the range of ESP of 2–25 generally found for Australian Vertosols used for cropping (Norrish *et al*. 2001; Dang *et al*. 2004). Importantly, in our sodified soils, soil K concentrations and EC remained consistent between treatments, and therefore, any change in the nutrient uptake of cotton cannot be attributed to these factors. Although the exchangeable Mg percentage decreased slightly as ESP increased, it did not fall below 20%, a level considered sufficient for cotton growth (Peverill *et al*. 1999), and Mg deficiency is rarely reported in cotton crops grown on Grey Vertosols (Rochester *et al*. 1998).

We also sought to minimise the confounding of sodicity with pH, but found that pH measured in water and in a solution matrix similar to that of the soil solution increased by 1.1 and 0.6, respectively, between ESP 3 and 24. Our soil had trace amounts of free lime (Table 1), which is often the case with alkaline sodic soils (Guerrero-Alves *et al*. 2002). For calcareous soils, the thermodynamics of chemical equilibria dictate that if the partial pressure of carbon dioxide and the total salt concentration remain constant, then raising the soil ESP must also raise the pH. This is because as ESP rises, the Ca : Na ratio in the soil solution falls, and if the total salt concentration in the soil solution is kept constant, then the Ca concentration must fall. This allows calcium carbonate to dissolve and so increases the concentration of dissolved carbonate ions. At pH below the acidity constant for bicarbonate (~10.3), most of the carbonate will convert to bicarbonate, consuming hydrogen ions thereby raising the pH (Butler and Cogley 1998). In our soils, the soil-solution P concentration also increased with sodicity (Table 2), which is consistent with the findings of Curtin *et al*. (1992) and Gupta *et al*. (1990), and may be related to the release of co-precipitated phosphate as calcium carbonate dissolved or desorption of phosphate as the pH rose.

Unlike soils in which aggregation is maintained primarily by organic binding agents (fungal hyphae, humic substances, etc.) the shrink–swell behaviour of Vertosols enables aggregation and soil physical fertility to regenerate though wetting and drying cycles (Pillai and McGarry 1999). This is illustrated by the standard remediation practice for cotton fields on Vertosols where structure has been damaged by wet trafficking, in which the soil is dried by means of a deep-rooted crop such as wheat (McKenzie 1998; Hulugalle and Scott 2008). The sodification process used here took the soil through seven wetting and drying cycles, and for the non-sodic soil generated stable aggregation, with most (86%) of the soil present as macro-aggregates (>125 μm) after wetting (Table 3). As expected, the

WSA decreased because of dispersion in the sodic soils, down to 33% at an ESP of 24. The HC of the non-sodic soil and its decline to <0.1 mm h^{-1} at an ESP of 24 are typical for cracking clay soils (Hamblin 1985; So and Aylmore 1993). The decline in HC in a clay soil with increasing ESP is attributable primarily to swelling and dispersion (Quirk and Schoefield 1955).

The PAM-amended soils maintained their structural integrity and HC as sodicity increased (Table 3). Hence, any effects of sodicity on plant growth or nutrition in the +PAM treatment can be attributed to soil chemical (i.e. high solution Na concentrations and ion interactions affecting nutrient uptake), rather than physical limitations. In the non-sodic soil (ESP = 3), addition of PAM had no effect on WSA, but increased their size (MWD), suggesting that in addition to decreasing dispersion, PAM also decreased the degree of aggregate slaking, or size reduction. The HC of the non-sodic soil was also decreased by PAM, an observation consistent with Lentz (2003) and Malik and Letey (1992), who attributed these reductions to an increased viscosity of soil water in PAM-amended soils, associated with the charge on the PAM material. Therefore, there was some difference in physical condition between the +PAM and –PAM treatments, even in the absence of sodicity. The approach to interpreting the effect of soil chemistry *v.* soil physics on the plants in this experiment was therefore to compare the changes that resulted from increasing ESP in the –PAM treatment (chemical + physical factors) to the changes that occurred as ESP increased in the +PAM treatment (only chemical factors). This will be discussed first for plant nutrient status, and then for the overall effect on cotton growth and yield.

Plant nutrition

Sodium

Most commercial cotton cultivars are Na-acquiring plants, and one of their central mechanisms to tolerate high Na concentrations is to sequester Na within plant structures (Lauchli and Stelter 1982; Leidi and Saiz 1997). Soil physical condition can also affect plant Na accumulation, as Na uptake in cotton plants is increased under waterlogging following flood irrigation (McLeod 2001). This is caused by the breakdown of the Na-exclusion mechanisms in the plant roots as anoxia interferes with energy-dependent ion transport processes (Drew and Dikumwin 1985; Drew and Lauchli 1985). Hence, less structurally stable pots without PAM had higher root Na concentrations than PAM-treated pots with better aeration. This is discussed in more detail below.

Calcium

Calcium nutrition was not affected by soil sodicity in this experiment. All of the plants had YML Ca concentrations above the critical level of 1.9% Ca (Reuter and Robinson 1986). Carter and Webster (1990) suggested that a soil Ca : total cation ratio of <0.15 in saturated paste indicates that Ca deficiency may limit plant growth. However, analysis of the soil solution used in this experiment revealed that the Ca concentration was 2.15 mM in the ESP 24 treatment and that the Ca : total cation ratio was only 0.06.

Potassium

The contrasting effect between +PAM and –PAM treatments of ESP on midseason YML K concentration indicates the importance of soil physical condition on K uptake. In the structurally stabilised PAM pots, there was no effect of ESP on YML K concentration, with the values close to the critical value for cotton suggested by Reuter and Robinson (1986) of 1.5%. However, in the absence of PAM, the decline in YML K with increasing ESP led to a possibly limiting value of 1.11% at an ESP of 24. This contrasting effect in the presence and absence of PAM indicates the importance of soil physical conditions on K uptake.

Phosphorus

Soil-solution P increased with soil sodicity (Table 2), consistent with the observations of Gupta *et al.* (1990) and Curtin *et al.* (1992), who showed that P availability increases in sodic soils due to the dissolution of Ca–P compounds and the release of sorbed P. Therefore, crop P nutrition should be improved with increased soil P availability, contrary to the field observations of reduced P concentration in cotton grown on sodic soils. Our experiment found no significant effect of sodicity on cotton P uptake or concentration. The soil had a relatively high P status, with Colwell-P (a widely used index of soil P availability in Australian cropping soils) of 42 mg kg^{-1} (Table 1). Cotton crops respond to P fertiliser when soil Colwell-P concentrations are 6–8.5 mg kg^{-1} (Dorahy *et al.* 2002). Concentrations of YML P at squaring ranged from 0.46 to 0.66%, well above the critical value of 0.28%. We suggest that the high soil P status masked any effect of sodicity on P uptake.

Boron

The adsorption of B onto clay minerals is reduced by soil solution Na and increased by soil solution Ca, where pH >8 (Keren and Gast 1981), which may lead to B toxicity in sodic systems (Cartwright *et al.* 1986). However, in our experiment, shoot B concentrations decreased as ESP increased. Nevertheless, the midseason YML concentrations (60–107 mg kg^{-1}) were adequate (Reuter and Robinson 1986). The lack of significance of the PAM × ESP interaction indicates that stabilising soil structure did not change the response to ESP, so that the effects of ESP on plant B are due to changes in soil chemistry rather than soil physical condition.

Manganese

Manganese deficiency has been widely reported in crops grown on sodic soils (Northcote 1988; Williams and Raupach 1983). Manganese availability in soil is strongly affected by the reduction of insoluble Mn(IV) to soluble Mn(II), which decreases as pH rises, reaching a minimum at pH 9 (Lindsay 1979), and increases under anoxic conditions (Ponnamperuma 1972). As was the case for B, the lack of a PAM × ESP interaction suggests that the decline in midseason YML and harvest shoot Mn concentration with increasing ESP was mainly an effect of soil chemical change. All of the plants in this experiment had sufficient YML Mn concentrations at squaring, but the Mn concentrations in the YMLs of the two most sodic +PAM treatments and of the ESP 19 –PAM treatments were marginal (Reuter and Robinson 1986).

Plant growth

Letey (1985) pointed out that four soil physical properties could directly affect plant growth: soil water, aeration, soil strength, and temperature. In our pot trial with water and temperature controlled, soil physical constraints were most likely to arise from high soil strength as the soil dries, impeding root access to water and nutrients, or from anoxia due to poor aeration after irrigation. No attempt was made here to assess the relative contribution of these two factors. Although care was taken not to over-irrigate the pots (water was added by weight to a nominal field capacity), given the low HC of the sodic –PAM pots, the possibility of transient waterlogging and restriction of aeration in the pots with poor aggregation cannot be excluded. High soil strength is common in Australian sodic subsoils (Curtin and Naidu 1998) and has the effect of thickening and shortening plant roots, reducing the soil volume that can be explored and hence exploited for nutrients. These restrictions on root growth may result in plants that are growing in soil that should have high enough nutrient levels to sustain plant growth showing evidence of nutrient deficiency through failure to extend through high soil-strength conditions to exploit those resources. We believe this to be the dominant mechanism in this experiment reducing plant growth where soil physical conditions were not ameliorated with PAM.

Increasing sodicity decreased plant growth and yield and there was an interaction between the effects of PAM application and ESP for root weight, lint weight, fruit number, and number of fruiting positions. In the PAM-treated soils these plant parameters tended to be fairly stable up to the higher ESP levels, with a decline mainly observed between ESP 19 and 24, and with the values at ESP 24 mostly showing no significant difference between the +PAM and –PAM treatments. This suggests that chemical effects of ESP on these cotton plant properties are minor up to ESP 19. By contrast, in the –PAM pots, the major effect on plants tended to be between the non-sodic soil (ESP 2) and the lowest sodic treatment (ESP 13), with little change after that, suggesting that physical effects (aeration and/or soil strength) predominate at low sodicity levels. This is consistent with the unpublished results of a later experiment on the interaction between ESP and waterlogging (Dodd 2007). In sodified batches of the same soil, it was shown that recovery of plant root function after a waterlogging event, as indicated by the commencement of ^{32}P uptake, was significantly delayed in sodic (ESP 12–25) compared with non-sodic (ESP 2) soil.

Therefore, we suggest that strategies to overcome sodicity resulting in poor P and K nutrition of cotton (i.e. increased fertilisation with P and K) that do not address soil physical condition are unlikely to be of significant value to producers. We also suggest that the minimal effect of increased sodicity on Ca nutrition of cotton reduces the impact of arguments in favour of gypsum amelioration of sodic soil physical condition on the basis of ameliorating potential plant Ca deficiency. Hence, further research is warranted into delivery and application methods of anionic PAM, or similar structural ameliorants, in sodic Vertosols.

Conclusion

This study found that, despite the soil chemical and plant nutrient changes that accompanied increasing ESP in a calcareous Vertosol, up to ESP 19 the effects of sodicity on cotton growth and yield were predominately related to poor aeration and root extension due to dispersion rather than Na toxicity or interference with uptake of important nutrients. At an ESP of 24, however, stabilising soil structure did not prevent a decline in lint yield, suggesting that soil chemical fertility was responsible. Soil chemical constraints at high ESP could include high plant Na concentrations (>0.2%) and marginal plant Mn concentrations, but this needs further investigation. The results of this experiment agree with a hydroponic study of the effect of sodic nutrient solutions on cotton growth, which showed little effect on cotton growth up to concentrations similar to those found in a Grey Vertosol with an ESP of 22 (Dodd *et al*. 2010*a*).

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