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Subsoil constraints in Vertosols: crop water use, nutrient concentration, and grain yields of bread wheat, durum wheat, barley, chickpea, and canola

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Abstract. Single or multiple factors implicated in subsoil constraints including salinity, sodicity, and phytotoxic concentrations of chloride (Cl) are present in many Vertosols including those occurring in Queensland, Australia. The variable distribution and the complex interactions that exist between these constraints limit the agronomic or management options available to manage the soil with these subsoil constraints. The identification of crops and cultivars adapted to these adverse subsoil conditions and/or able to exploit subsoil water may be an option to maintain productivity of these soils. We evaluated relative performance of 5 winter crop species, in terms of grain yields, nutrient concentration, and ability to extract soil water, grown on soils with various levels and combinations of subsoil constraints in 19 field experiments over 2 years. Subsoil constraints were measured by levels of soil Cl, electrical conductivity of the saturation extract (EC_{se}), and exchangeable sodium percentage (ESP). Increasing levels of subsoil constraints significantly decreased maximum depth of water extraction, grain yield, and plant-available water capacity for all the 5 crops and more so for chickpea and durum wheat than bread wheat, barley, or canola. Increasing soil Cl levels had a greater restricting effect on water availability than did EC_{se} and ESP. We developed empirical relationships between soil Cl, EC_{se}, and ESP and crop lower limit (CLL) for estimating subsoil water extraction by 5 winter crops. However, the presence of gypsum influenced the ability to predict CLL based on the levels of EC_{se}. Stronger relationships between apparent unused plant-available water (CLL – LL15; LL15 is lower limit at −1.5 MPa) and soil Cl concentrations than ESP or EC_{se} suggested that the presence of high Cl in these soils most likely inhibited the subsoil water extraction by the crops. This was supported by increased sodium (Na) and Cl concentration with a corresponding decrease in calcium (Ca) and potassium (K) in young mature leaf of bread wheat, durum wheat, and chickpea with increasing levels of subsoil constraints. Of the 2 ions, Na and Cl, the latter appears to be more damaging than the former, resulting in plant dieback and reduced grain yields.

Additional keywords: salinity, sodicity, chloride toxicity, crop lower limit, plant-available water capacity.

Introduction

Grain crops grown on Vertosols in Queensland depend on the stored soil moisture accumulated in the preceding fallow period. Low and variable rainfall, heat stress, and high rates of evaporation make stored soil water important during dry periods (Freebairn *et al*. 1990). Although many of these Vertosols are able to store 200–250 mm of water in the soil profile (Dalgliesh and Foale 1998), the presence of subsoil constraints such as salinity, sodicity, and Cl in many soils reduces effective rooting depth and increases crop lower limit (CLL) thereby reducing the amount of water and nutrients that plants can obtain from the soil (Sadras *et al*. 2003; Dang *et al*. 2006).

Subsoil constraints effect on root growth and function, and plant growth through several mechanisms. High salt concentrations in the soil solution (salinity) restrict water uptake, through increased osmotic potential (Shaw 1997), and toxic levels of Na and Cl can directly affect root and shoot growth (Greenway and Munns 1980). High sodicity often causes deterioration of soil physical properties, resulting in

 10.1071/AR05268 0004-9409/06/090983

poor soil–water and soil–air relations. Sodicity may also induce Ca and/or K deficiency (Naidu and Rengasamy 1993). The differences in salt tolerance within crop species are often correlated with differences in translocation of Na and Cl into the shoot, in particular to the youngest mature leaf (YML) (Marschner 1995; Xu *et al*. 2000). In general, variation in salt tolerance has been found to be associated with low rates of Na uptake and transport, and a high selectivity for K or Ca over Na (Marschner 1995) and/or restricted Cl translocation (Xu *et al*. 2000). Therefore, it is necessary to assess tissue ion concentrations against salt tolerance of crop species to identify whether exclusion of Na and Cl or selectivity of K or Ca, and/or ion imbalances is an appropriate selection criterion to identify plant tolerance to salinity and/or sodicity.

The variable distribution of subsoil constraints with depth and spatially within a paddock, and also across the landscape (Dang *et al*. 2006), often makes it difficult to identify the most limiting constraint and its interaction with other factors that limit crop yield. However, agronomic or management options to manage these subsoil constraints appear to be limited (Dang *et al*. 2006). Therefore, the identification of crops and/or cultivars adapted to adverse subsoil conditions and/or able to exploit subsoil water may provide a tangible solution to sustainably use the soils with subsoil constraints (Richards 2002).

The primary effect of complex and variable combinations of subsoil constraints is to reduce the plant-available water capacity (PAWC) and this effect is evident from increased CLL of available water (Sadras *et al*. 2003). Knowledge of the effect of subsoil constraints on increasing CLL will assist in identifying crops tolerant to the causal factors of subsoil constraints and development of decision support tools that will ultimately allow producers and advisors to make informed decisions about managing production systems where subsoil constraints are a limiting factor.

The objectives of this study were to (*i*) quantify the effect of a range of subsoil properties on the ability of 5 winter grain crop species to use stored soil water during the growing season; (*ii*) relate CLL to soil chloride concentration, exchangeable sodium percentage (ESP), and electrical conductivity of the saturation extract (EC_{se}); and (*iii*) identify the most limiting constraint implicit by examining the role of tissue ion concentration in plant adaptation to subsoil constraints.

Materials and methods

Experimental sites

The study area covered the south-west of Queensland's grain-growing region, located between 26° and 29°S, and 148° and 151°E (Fig. 1). The climate of this region is semi-arid with low (600–650 mm average annual rainfall) and variable (coefficient of variation 30%) rainfall, most of which falls during summer (Webb *et al*. 1997). The soils are mostly grey, brown, and red cracking (shrink-swell characteristics) clays (Vertosols) (Isbell 1996).

Field experiments

Nineteen field experiments were established on farmers' fields in the winter cropping seasons of 2003 and 2004, on soils with a range of EC_{se}, ESP, and Cl concentrations. Treatments consisted of

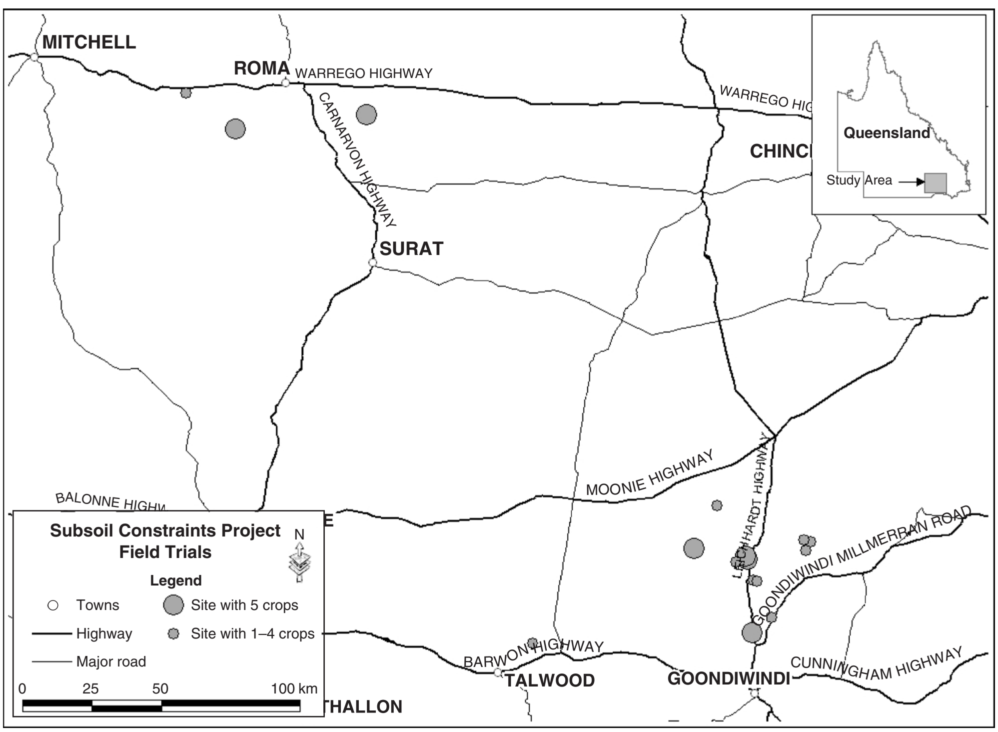

Fig. 1. Location of trial sites in south-western Queensland.

various combinations of different crop species: durum wheat (*Triticum turgidum* cv. Yallaroi), bread wheat (*Triticum aestivum* cv. Baxter), barley (*Hordeum vulgare* cv. Mackay), chickpea (*Cicer arietinum* cv. Jimbour), and canola (*Brassica napus* cv. Hyola 43). At 5 sites, 5 crop species were sown in a complete randomised block design with 3 replications (Fig. 1). At 6 other sites, 2–4 of the crop species were sown in a complete randomised block design with 3 replications. On the remaining 8 sites, commercial crops were monitored at 3 points at a distance of 2–3 m in each plot and results were averaged for the plot. Altogether, 19 bread wheat cv. Baxter; 13 chickpea cv. Jimbour; 12 barley cv. Mackay; 10 canola cv. Hyola 43; and 10 durum wheat cv. Yallaroi crops were monitored in 2 years. At all the experimental sites, rainfall was measured with a manual rain gauge located within 500 m of the experimental plots. All sowing and crop management operations were carried out using farmer equipment, and agronomic management followed the accepted district practice. All crops were supplied with 40–50 kg mono-ammonium phosphate (MAP) blended Zn fertiliser (9.3% N, 20.3% P, 2.6% S, 2.5% Zn). All crops were well managed and no significant weeds, pests, or diseases were observed.

Crop growth

At crop maturity, plant samples from quadrats (2 m by 1.0 m) were taken randomly from 2 places from each plot to determine total biomass and grain yield. Samples were oven-dried at 70°C to constant weight and weighed. Grain was threshed using a stationary thresher with negligible losses, and weighed. Grain yield was expressed at 12% moisture. Relative crop yields were obtained as grain yield at a given site/maximum grain yield achieved across the trial sites in the present study. Harvest index was calculated as the ratio of grain weight to total above-ground (grain + straw) weight at maturity.

Soil sampling and analysis

In April–May each year, 3–6 soil samples were taken per site, depending on the size of the experimental area, using a 50-mm diameter tube and a hydraulic sampling rig. Samples were separated into 0–0.10, 0.10–0.30, 0.30–0.50, 0.50–0.70, 0.70–0.90, 0.90–1.10, and 1.10–1.30 m intervals, dried at 40°C in a forced-draught oven, and ground to pass a <2-mm sieve.

Soil pH, EC, Cl, and NO_3-N were determined in 1 : 5 soil : water suspension (Rayment and Higginson 1992). Electrical conductivity of saturated extracts (EC_{se}) was calculated from EC (1 : 5 soil : water suspension), soil Cl, and clay concentration using the method of Shaw (1999).

Cation exchange capacity (CEC) and exchangeable cations (K, Na, Mg, Ca) were measured using 1 M NH_4Cl extracting solution (pH 8.5) (Rayment and Higginson 1992). Prior to extraction, soluble salts were first removed by pre-washing with aqueous alcohol (60%) (Tucker 1985). Both soluble and exchangeable cations were measured separately using an inductively coupled plasma-optical emission spectrometer. Exchangeable sodium percentage was calculated as the ratio of exchangeable Na to CEC. Clay concentration was determined by the pipette method (Day 1965). Soluble B was determined using hot 0.01 M $CaCl_2$ extracting solution, and sulfate-S concentration was determined using Ca $(H_2PO_4)_2$ extracting solution (Rayment and Higginson 1992). Available P was extracted with 0.5 M $NaHCO_3$ (pH 8.5) as described by Colwell (1963), and available Zn was extracted with DTPA-TEA-$CaCl_2$ (Lindsay and Norvell 1978).

Plant-available water capacity (PAWC)

The soil at each site was characterised for bulk density, drained upper limit (DUL), CLL, and PAWC (PAWC = DUL–CLL) using the method of Dalgliesh and Foale (1998). Briefly, DUL was determined by wetting up an area of soil until it reached saturation, allowing time for drainage, and then sampling for soil water content in 7 depth intervals (0–0.10, 0.10–0.30, 0.30–0.50, 0.50–0.70, 0.70–0.90, 0.90–1.10, and 1.10–1.30 m). Bulk density was calculated at DUL from gravimetric water content (Gardner *et al*. 1984), using the formula:

$$\text{BD (g/cm}^3) = (1 - \text{e})/(1/\text{ad} + \theta\text{g})$$

where θg is gravimetric water content (g/g) at DUL, ad is absolute density of the solid matter in the soil, and e is air-filled porosity at θg.

For determining CLL, rain exclusion tent for each crop at each site was erected over a portion (3 m by 3 m area) of the vigorously growing crop, at the time of flowering and was left in place until the crop reached maturity. Soil water content was measured at the time of installation of the rain-exclusion tent and at crop maturity, to determine water extraction patterns and CLL.

Soil water lower limits (LL15) at –1.5 MPa (water contents at permanent wilting point) were calculated from the clay content (Shaw 1996), using the formula:

$$\text{LL15} = (0.518 + 0.38\ \text{clay}\ \%)/100$$

Apparently, unused plant-available water was calculated as the difference between CLL and wilting point (LL15) at −1.5 MPa.

Osmotic potential was calculated from EC_{se} (Groenevelt *et al*. 2004), using the formula:

$$\text{Osmotic potential (MPa)} = 0.036\ \text{EC}_{se}\ \text{(dS/m)}$$

Soil water content

Soil water content (mm) was measured for each crop throughout the growing season using a neutron moisture meter (Campbell Pacific Nuclear Corp., California, Model 503) with an aluminium (Al) access tube inserted in the soil to 1.30-m depth. The 1.30-m profile was chosen, which was deeper than the maximum rooting depth of 1.00–1.20 m measured for annual winter crops in south-west Queensland in the presence of the potential root-limiting subsoil factors (Dalal *et al*. 2002; Routley 2002). The soil water measurements were made from at least one Al access tube in each plot in replicated trials, whereas in commercial crops, the measurements were made from 3 Al access tubes inserted at a distance of 2–3 m in each plot. Measurements were made at 0.20-m intervals throughout the 0.10–1.30 m soil profile, using a 16-s counting time. Neutron moisture meter field calibrations were obtained for each site using a linear regression between neutron moisture counts and volumetric moisture contents measured on soil samples obtained at the time of inserting the Al access tube.

Crop water use

Crop water use (CWU) was measured as the sum of the change in soil water content within the root zone (0.10–1.30 m) between sowing and maturity and growing-season rainfall. The topsoil layer (0–0.10 m) was excluded from the analysis to avoid confounding effects of soil evaporation and plant water uptake on minimum soil water content (Sadras *et al*. 2003). In this study, runoff was assumed to be negligible. Seasonal drainage, although unknown, was expected to be small and less than the error of measurement of the overall water balance. Water use efficiency (WUE, kg/ha.mm) was obtained as grain yield per unit of crop water use (Dalal *et al*. 1998). Rooting depth was estimated as maximum depth of water extraction by the crop (Routley 2002).

Plant analysis

At anthesis, about 50 youngest mature leaves (YML) were obtained randomly from each replication and carefully rinsed with distilled deionised water and then dried at 70°C for 48 h. Dry samples were ground into a fine powder to pass a 0.5-mm sieve. For the determination of Na, K, and Ca concentrations, plant material was digested in a diacid mixture of nitric and perchloric acid. Concentrations of ions were measured on inductively coupled plasma-optical emission spectrometer.

For Cl, ground samples of YML were extracted in hot water at 80°C for 4 h (Rayment and Higginson 1992). The Cl concentration was determined on an auto-analyser (Spann and Lyons 1985).

Statistical analyses

Analysis of variance for data on soil water, above-ground crop biomass, and grain yield for each site was done using Genstat 6.1. The effect of subsoil constraint sites was analysed separately for each crop using site × replications blocking, whereas differences in crop species with a range of subsoil constraints were analysed using crop × sites and replications blocking. Significant differences between treatments were assessed using Fisher's l.s.d. ($P = 0.05$). To explain observed CLL, step-wise regressions were performed with a set of independent variables including EC_{se}, soil Cl, ESP, bulk density, NO_3-N, initial soil volumetric moisture, and clay content using the statistical package Genstat 6.1. We used *all subset regression (linear model)* to identify variables resulting in higher values of adjusted coefficient of determination (R^2) and with low P values based on F-statistics. The regression coefficients for statistically significant independent variables were then determined using multiple linear regressions. To determine the equation that best described the relationships between CLL and grain yield, a relatively high value of the coefficient of determination (R^2) and low standard error were used as criteria for the best fit.

Results

Soil characterisation

Range and mean values for various soil properties for the 19 experimental sites are given in Table 1. Most of these soils were considered saline ($EC_{se} > 4.0$ dS/m) at 0.50–0.70 m depth, and sodic (ESP $\geq 6\%$) at 0.10–0.30 m depth. At 0.50–0.70 m depth, levels of soil Cl (>700 mg/kg) were potentially phytotoxic (Northcote and Skene 1972; Shaw 1999; Dang *et al*. 2004). In most of the soil profiles, high $EC_{1:5}$ or EC_{se} in the subsoils was due to Cl salts, whereas in 3 soil profiles it was due to Cl and/or SO_4 (sulfate) salts. Mean boron concentrations were ≤2.2 mg/kg and mean bulk density ranged from 1.0 to 1.6 g/cm^3 in the 0–1.30 m soil profile.

Soil nutrients at sowing

Mean soil NO_3-N in the 0–1.30 m depth at sowing was 190 ± 88 kg N/ha and ranged from 48 to 375 kg N/ha. The amount of NO_3-N in the topsoil (0–0.10 m) ranged from 1.1 to 41.8 kg N/ha, with a mean value of 15.7 ± 15 kg N/ha, and in subsoil (0.10–1.30 m), NO_3-N ranged from 5.8 to 183 kg N/ha, with a mean value of 43.3 ± 37.3 kg N/ha. Mean available P in the 0–1.30 m depth at sowing was 7.1 mg P/kg, and ranged from 4.2 to 19.1 mg P/kg. The amount of P in the topsoil (0–0.10 m) accounted for 40% of the total available P in the 0–1.30 m soil depth. Mean Zn at sowing was 0.5 mg Zn/kg, and ranged from 0.3 to 0.8 mg Zn/ha. The amount of Zn in the topsoil (0–0.10 m) accounted for 25% of the total available Zn in the 0–1.30 m soil profile.

Plant-available water at sowing and growing-season rainfall

Mean total volumetric water content (θ_v) over 19 sites at sowing in the 0.10–1.30 m soil depth was 480 ± 51 mm and ranged from 389 to 555 mm. All the soil profiles were close to their drained upper limit at the time of sowing in both the years.

The growing season generally extended from mid May to October in both the years. The growing-season rainfall ranged from 126 to 209 mm, with a mean value of 160 mm during

Table 1. Range and mean values of soil properties over 19 experimental sites in south-western Queensland

CEC, cation exchange capacity; ρb, soil bulk density; pH_w, pH of 1 : 5 soil: water suspension; $EC_{1:5}$, electrical conductivity of 1 : 5 soil : water suspension; EC_{se}, estimated electrical conductivity of saturated extract calculated from $EC_{1:5}$, clay and Cl concentrations (Shaw 1999); $Na_{Exch+Soluble}$, soluble plus exchangeable sodium; ESP, exchangeable sodium percentage; θ_v, volumetric moisture content

	Soil layer (m)						
	0–0.10	0.10–0.30	0.30–0.50	0.50–0.70	0.70–0.90	0.90–1.10	1.10–1.30
Clay (%)	26–66 (40.2)	27–65 (46.2)	27–63 (47.4)	31–63 (48.0)	31–64 (49.1)	32–63 (49.9)	30–63 (48.8)
CEC ($cmol_c$/kg)	17–47 (25.4)	18–46 (28.8)	16–46 (28.9)	19–45 (28.6)	16–48 (28.3)	16–48 (27.7)	16–49 (27.4)
ρb (g/cm^3)	1.0–1.5 (1.33)	1.2–1.5 (1.37)	1.2–1.5 (1.36)	1.2–1.5 (1.38)	1.2–1.6 (1.42)	1.2–1.6 (1.41)	1.2–1.6 (1.42)
pH_W	6.6–8.9 (7.82)	7.2–9.2 (8.58)	7.0–9.3 (8.70)	6.4–9.5 (8.33)	4.8–9.5 (7.64)	4.6–9.3 (6.70)	4.5–9.4 (6.17)
$EC_{1:5}$ (dS/m)	0.1–0.7 (0.21)	0.1–2.5 (0.41)	0.2–4.1 (0.86)	0.2–5.6 (1.49)	0.2–5.7 (1.61)	0.4–5.0 (1.54)	0.4–5.0 (1.52)
EC_{se} (dS/m)	0.3–2.3 (0.8)	0.2–7.1 (1.5)	0.6–13.2 (3.4)	1.1–18.0 (6.2)	1.6–18.1 (7.7)	3.0–19.5 (8.4)	3.1–19.4 (8.6)
Cl (mg/kg)	1–164 (34)	1–358 (64)	1–983 (191)	39–1467 (404)	169–1567 (669)	290–1750 (948)	303–1990 (1025)
$Na_{Exch+Soluble}$ ($cmol_c$/kg)	0.35–4.5 (1.77)	1.35–7.5 (3.50)	1.69–11.6 (5.66)	4.02–15.4 (7.89)	5.96–16.5 (9.73)	6.3–17.5 (10.7)	6.01–18.3 (11.0)
ESP (%)	1.6–12.5 (4.8)	3.9–17.2 (9.5)	7.1–22.2 (15.6)	10.8–32.7 (20.9)	13.0–35.5 (24.9)	15.5–34.7 (25.8)	15.8–36.2 (25.6)
B (mg/kg)	0.5–1.5 (1.1)	0.7–2.8 (1.3)	0.8–3.8 (1.8)	1.0–4.8 (2.2)	0.9–6.1 (2.1)	0.6–4.5 (2.0)	0.6–4.7 (2.0)
SO_4-S (mg/kg)	6–310 (30)	4–1600 (129)	6–1500 (239)	8–1700 (348)	14–2700 (512)	41–1900 (481)	7–1900 (453)
NO_3-N (kg/ha)	1.0–41 (15.7)	5.8–183 (56.3)	5.3–131 (40.6)	4.6–138 (40.5)	4.6–98 (37.8)	3.1–77 (30.5)	4.7–71 (28.7)
Available P (mg/kg)	6.0–35 (18.2)	2.2–12 (5.5)	1.6–9 (3.7)	1.6–10 (3.5)	1.3–20 (3.9)	1.4–35 (4.9)	1–36 (5.0)
Available Zn (mg/kg)	0.17–1.9 (0.93)	0.13–1.4 (0.44)	0.01–1.5 (0.35)	0.01–1.3 (0.34)	0.01–1.2 (0.36)	0.01–2.0 (0.46)	0.07–2.8 (0.57)
θ_v (mm)		62–92 (78.1)	61–93 (80.9)	64–92 (80.2)	67–91 (79.1)	66–90 (78.6)	64–90 (78.9)

2003, and from 67 to 180 mm, with a mean value of 117 mm during 2004. This mean rainfall value was less than the long-term (104 years) mean of 184 mm for the same period at Goondiwindi in south-western Queensland (Fig. 2). There was wide variation in the distribution of growing-season rainfall in both the years and long-term mean rainfall. Rainfall was below average in the month of May in both the years. During 2003, rainfall was above average in June, August, and October but was below average in September (zero rainfall). Most of the rainfall was received in the month prior to anthesis. During 2004, rainfall was below average in June, July, August, and October and above average in September. Less than 30% of the average rainfall was received in the month prior to anthesis, followed by above-average rainfall in the post-anthesis period.

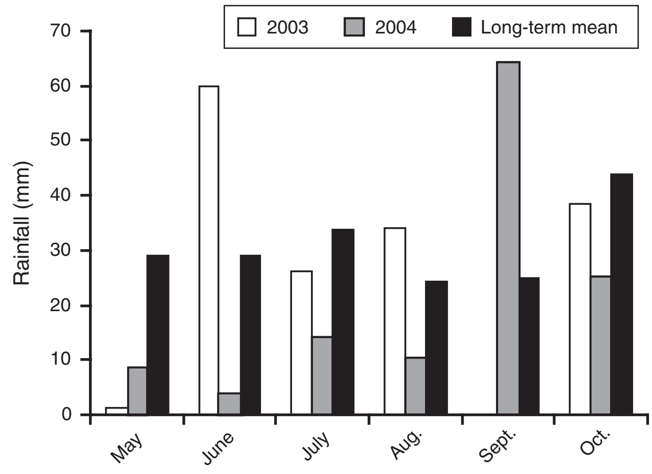

Fig. 2. Distribution of mean growing-season rainfall (May–Oct.) for 19 sites for 2003 and 2004 and average long-term rainfall for Goondiwindi in south-western Queensland.

Effects of subsoil constraints on water extraction and crop yields

To illustrate the effect of subsoil constraints, we present soil water extraction, PAWC, CLL, and crop yield data from 3 sites of similar soil types and initial soil volumetric moisture (511–548 mm in the 0.10–1.30 m soil profile), with all 5 crops grown (Fig. 1), which received similar (85–98 mm) growing-season rainfall (May–Oct.) but different Cl concentrations in the soil profile. The soil Cl concentrations increased distinguishably with depth in these sites. The distribution of Cl in the 0–1.30 m soil profile was 34–759 mg Cl/kg in the low constraint site, 24–1467 mg Cl/kg in the medium constraint site, and 163–1840 mg Cl/kg in the high constraint site (Fig. 3).

The pattern of soil water extraction at the 5 crops grown on low, medium, and high constraint sites is given in Fig. 4. All 5 crops grown on the relatively low constraint site were able to extract water down to 1.20–1.30 m depth. On the medium constraint site, mean maximum depth of water extraction was 0.90–1.00 m for durum wheat and chickpea and 1.10–1.20 m for bread wheat, barley, and canola, whereas on the high constraint site, mean maximum depth of water extraction was reduced to 0.55 m for chickpea, 0.65 m for durum wheat, 0.85 m for both bread wheat and barley, and 1.00 m for canola.

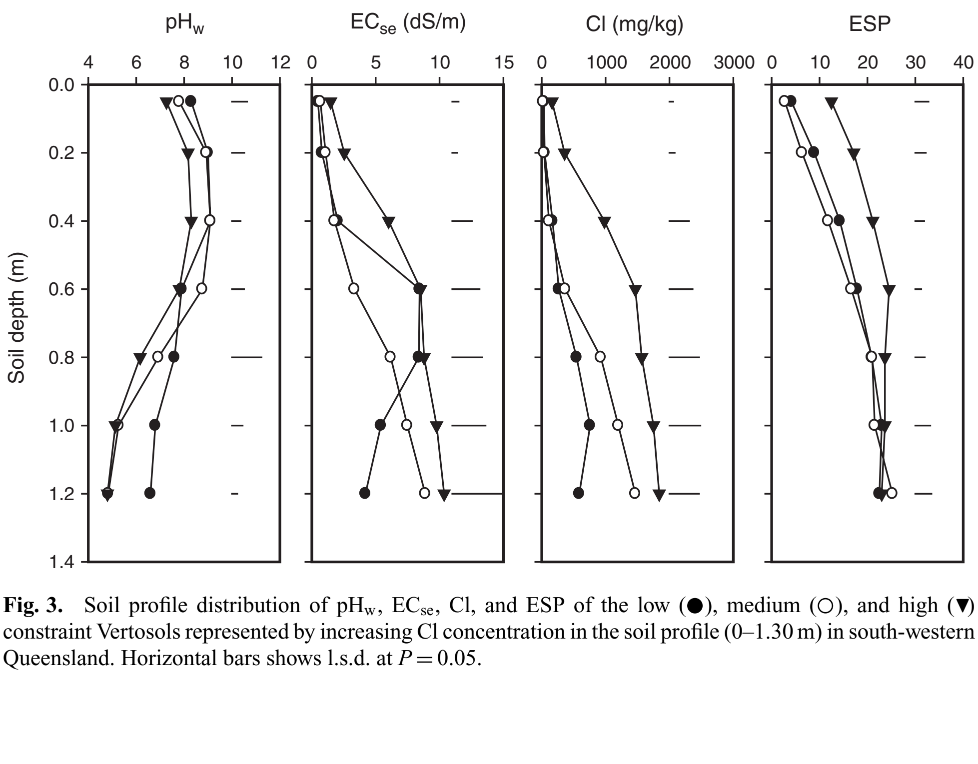

Fig. 3. Soil profile distribution of pH_w, EC_{se}, Cl, and ESP of the low (●), medium (○), and high (▼) constraint Vertosols represented by increasing Cl concentration in the soil profile (0–1.30 m) in south-western Queensland. Horizontal bars shows l.s.d. at $P = 0.05$.

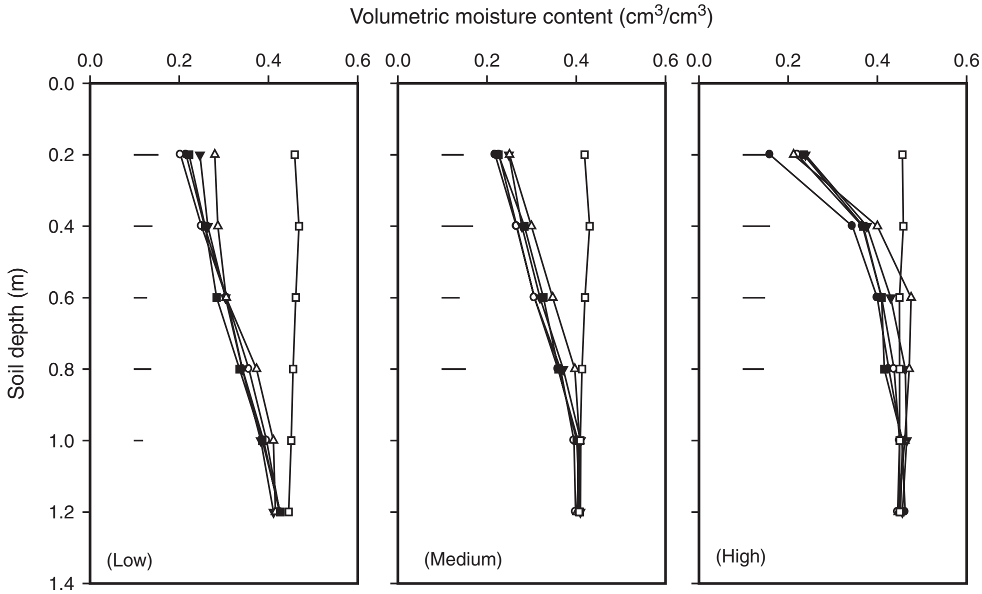

Fig. 4. Patterns of soil water extraction of bread wheat (●), barley (○), durum wheat (▼), chickpea (△), canola (■), and initial soil moisture (□) on low, medium, and high constraint Vertosols represented by increasing Cl concentration in the soil profile (0–1.30 m) in south-western Queensland during 2004. Horizontal bars shows l.s.d. at $P = 0.05$.

Increasing levels of subsoil constraints from low to medium or medium to high significantly decreased grain yield and PAWC for all 5 crops (Table 2). Increasing levels of subsoil constraints from low to high decreased grain yield by about 50% for bread wheat, barley, durum wheat, and canola and by 65% for chickpea. The corresponding decrease in PAWC was 50% for bread wheat, barley, and canola and 65% for chickpea and durum wheat. As subsoil constraints increased from low to medium the decrease in grain yield was severe for chickpea (47%) and durum wheat (35%) as compared with canola (30%), bread wheat (26%), and barley (22%). As subsoil constraints increased from medium to high, further decrease in grain yield was severe for bread wheat (39%), barley (37%), canola (39%), chickpea (33%), and durum wheat (23%). The corresponding decrease in the PAWC was approximately 25% for bread wheat and barley, and 35% for durum wheat, chickpea, and canola as subsoil constraints increased from low to medium, whereas an increase in constraints from medium to high resulted in decreased PAWC by 20% for bread wheat and canola, 35% for barley, and 45% for chickpea and durum wheat.

Variation in crop species response to subsoil constraints

Figure 5 shows the depth distribution in mean values of CLL for 5 crop species, and PAWC of 5 Vertosols with various combinations of subsoil constraints. Of the 5 crops, bread wheat, barley, and canola had lower CLL and higher PAWC throughout the soil profile than durum wheat and chickpea. Compared with other crops, the soil under chickpea had lowest PAWC and highest CLL values below 0.50-m depth. The PAWC of soils used for growing barley and canola was similar to bread wheat but in the 0.90–1.30 m layer both canola and barley had higher PAWC than bread wheat, with significant differences for canola only.

Average PAWC (0.10–1.30 m) for soils with various combinations of subsoil constraints varied for crop species:

Table 2. Grain yield and PAWC of 5 winter crop species grown on one of the low, medium, and high constraint Vertosols represented by increasing Cl concentration in the soil profile (0–1.30 m) in south-western Queensland during 2004

Crop species	Yield (kg/ha)				PAWC (mm)			
	Low	Medium	High	l.s.d. ($P = 0.05$)	Low	Medium	High	l.s.d. ($P = 0.05$)
Bread wheat	2587	2082	1266	224	161	120	93	18
Barley	2395	1987	1244	302	160	120	77	20
Durum wheat	2160	1401	1075	179	158	104	57	32
Chickpea	1822	958	639	256	134	91	49	35
Canola	927	651	461	144	166	110	88	19

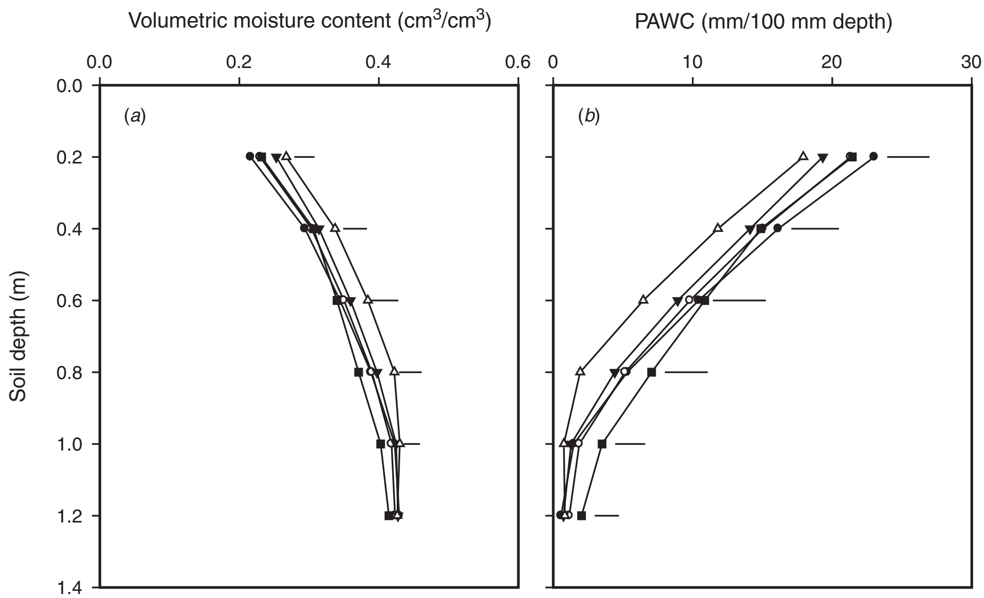

Fig. 5. Mean values of (*a*) volumetric moisture content at crop maturity, crop lower limit (CLL), and (*b*) plant-available water capacity of the soil (PAWC) under bread wheat (●), barley (○), durum wheat (▼), chickpea (△), and canola (■) grown during 2004 on 5 Vertosols in south-western Queensland. Horizontal bars shows l.s.d. at $P = 0.05$.

bread wheat 124 mm; canola 122 mm; barley 116 mm; durum wheat 98 mm; and chickpea 82 mm (Table 3). The PAWC of soil under bread wheat and canola was significantly higher than that under durum wheat and chickpea. All crops grown on these soils except durum wheat had significantly higher PAWC than chickpea. Bread wheat, canola, and barley used significantly more water (about 200 mm) than durum wheat (176 mm) and chickpea (160 mm) (mean rainfall at the 5 sites during the cropping season was 82 mm, with 62 mm from sowing to anthesis). The differences in the CWU were also significant between durum wheat and chickpea. On an average of 5 sites, maximum depth of water extraction for bread wheat, barley, and canola was significantly greater than for durum wheat, and that of the latter was greater than chickpea (Table 3).

Absence of any significant disease, pest, and waterlogging resulted in all crops having high biomass and high harvest index for cereals and legumes (0.42–0.46). The mean grain yield for bread wheat and barley was significantly greater than for durum wheat (Table 3). Also, the grain yields of cereals were significantly greater than chickpea. Comparison of yields between cereals and legumes and/or oilseeds is difficult because of different energy values of the constituents of the harvested products. Mean total dry matter yields (data not shown) of 5 crop species followed a similar trend to grain yield. Mean water-use efficiency of cereal crops (bread wheat, barley, and durum wheat) was significantly higher than the legume (chickpea) and oilseed (canola) crop.

Relationships between subsoil constraints and CLL

The relationships between CLL values measured at 6 equal depth intervals (0.20 m) for wheat grown on 19 sites were not significantly correlated with the corresponding $EC_{1:5}$

Table 3. Grain yield (kg/ha), harvest index, rooting depth (maximum depth of water extraction, cm), plant-available water capacity (PAWC, mm), water-use efficiency (WUE, kg/ha.mm) and crop water use (CWU, mm) for 5 winter crop species grown on 5 Vertosols with various combinations of subsoil constraints in south-western Queensland during 2004

Values within a column followed by the same letter are not significantly different at $P = 0.05$

Crop species	Grain yield	Harvest index	Rooting depth	PAWC	WUE	CWU
Bread wheat	1976a	0.46a	104a	124a	10.2a	202a
Barley	1854a	0.46a	104a	116ab	10.3a	193a
Durum wheat	1554b	0.42a	92b	98b	9.3a	176b
Chickpea	1045c	0.45a	85c	82c	6.8b	160c
Canola	665d	0.29b	108a	122a	3.6c	199a

(Fig. 6). However, the relationship between EC_{se} (Fig. 6*b*) and CLL was significant, accounting for 24% of the variation in CLL. The Cl concentrations in the soil profile were better correlated with CLL than with EC_{se} values. Almost 54% of the variability in the measured CLL could be accounted for by the soil Cl concentration in the 0.10–1.30 m depths (Fig. 6*c*).

The poor relationships between measured $EC_{1:5}$ and/or calculated EC_{se} with measured CLL were greatly improved by excluding 3 Vertosols containing >1000 mg SO_4-S/kg (presumably gypsum as evident from visual observations) in the subsoil from the regressions. Almost 57% of the variation in measured CLL could be accounted for by measured $EC_{1:5}$ and/or calculated EC_{se} in the soil profile in the 0.10–1.30 m depth. The relationship between Cl concentrations in the soil profile and CLL remained unchanged with or without excluding gypsum-dominated soils from the regression analysis.

For wheat grown on 19 sites, ESP at 6 equal depths in the soil profile was significantly correlated with CLL in the 0.10–1.30 m layer and accounted for 44% of the variation in CLL (figure not shown). Among physical subsoil constraints, bulk density at 6 equal depths in the 0.10–1.30 m layers was not significantly correlated with CLL. Similarly, the regression coefficients between CLL measured at 6 depth intervals to 0.10–1.30 m soil profile and the corresponding initial NO_3-N concentration and initial volumetric soil moisture were not significant (figures not shown).

Similar relationships between measured CLL at 6 equal depth intervals in the 0.10–1.30 m soil profile for barley, durum wheat, chickpea and canola and corresponding soil properties ($EC_{1:5}$, EC_{se}, Cl, ESP, NO_3-N, bulk density, and initial volumetric soil moisture) with and without gypsum-dominated soils were obtained (figures not shown).

Apparently, unused plant-available water for bread wheat grown on 19 sites, calculated as the difference between the bread wheat lower limit and LL15 at −1.5 MPa, showed positive relationships with EC_{se}, ESP, and soil Cl concentrations (Fig. 7). Similar positive relationships between apparent unused plant-available water for durum wheat, barley, chickpea, and canola with EC_{se}, ESP, and soil Cl concentrations were obtained (figures not shown). Individually, EC_{se} accounts for 31% of variation in apparent unused plant-available water for bread wheat, ESP accounting

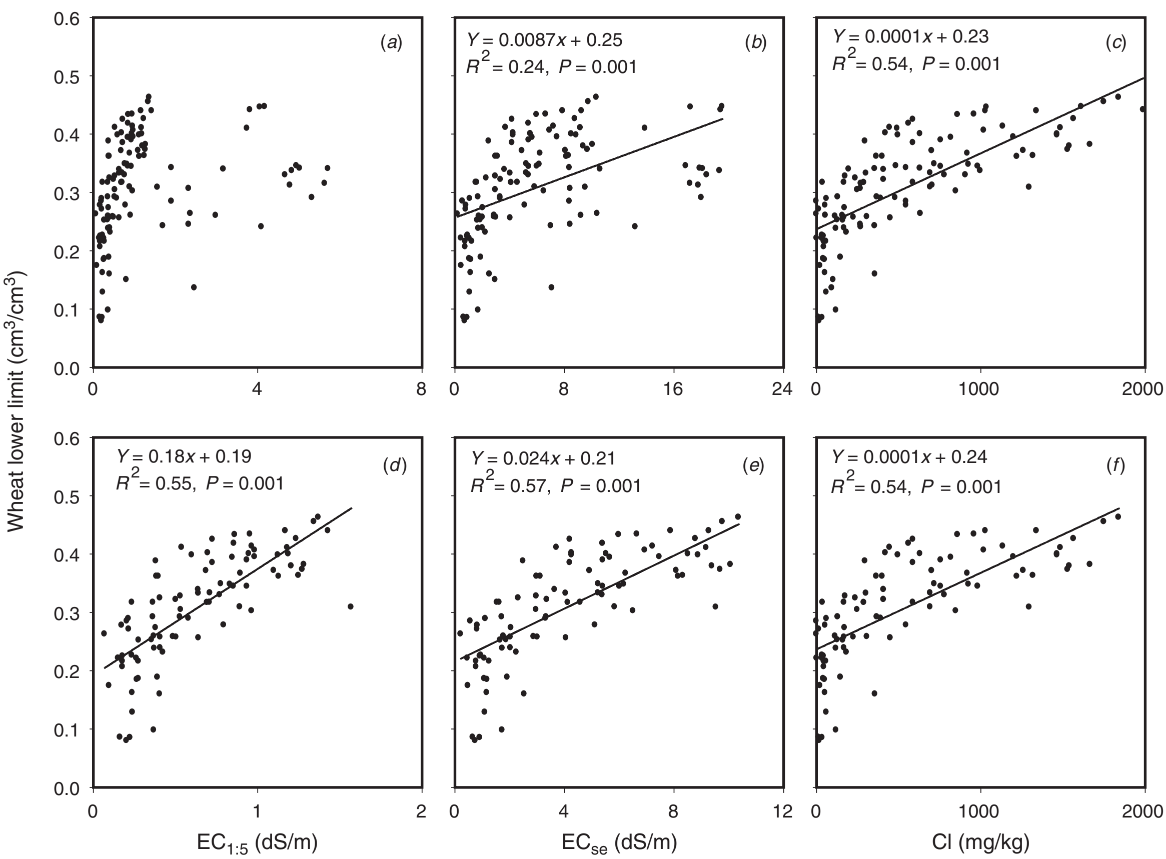

Fig. 6. Relationships between crop lower limit values measured at 6 equal depth intervals for bread wheat grown on 19 sites and (*a*) $EC_{1:5}$, (*b*) EC_{se}, and (*c*) soil Cl; or bread wheat grown on 16 sites containing negligible (<100 mg/kg SO_4-S) in the soil profile (0.10–1.30 m) and (*d*) $EC_{1:5}$, (*e*) EC_{se}, and (*f*) soil Cl in south-western Queensland.

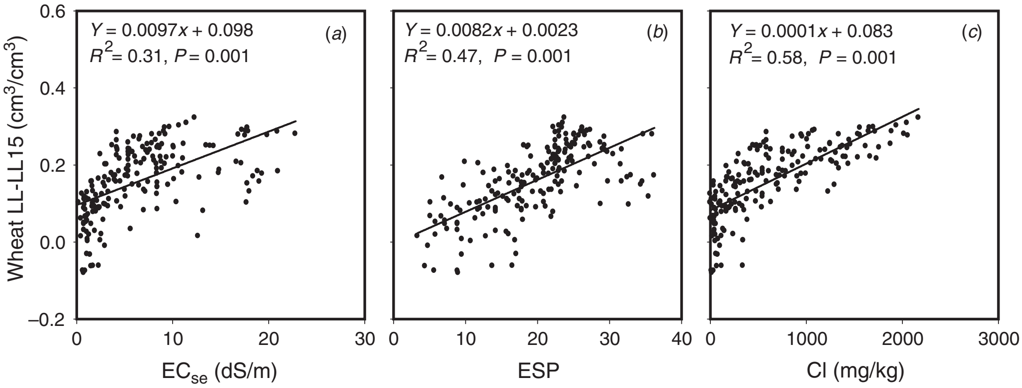

Fig. 7. Relationships between apparently unused plant-available water for bread wheat (bread wheat lower limit, CLL – lower limit measured from texture, LL15) and (*a*) EC_{se}, (*b*) ESP, and (*c*) Cl in the soil profile (0.10–1.30 m) from 19 sites in south-western Queensland.

for 47% and Cl accounting for 58% of the variation. However, in step-wise regression, soil Cl was the principal determinant of the apparent unused plant-available water. It accounted for 58% of the variation, and with ESP as secondary determinant together accounted for 67% of the variation in apparent unused plant-available water. The inclusion of EC_{se} with soil Cl and ESP, although significant, improved the prediction to only 69%. The relationship between apparent unused plant-available water and soil Cl, ESP, and EC_{se} can be summarised by the following equation:

$$\text{Apparent unused plant-available water} = 0.036 + 0.000055\ \text{Cl (mg/kg)} + 0.0045\ \text{ESP (\%)} + 0.0028\ EC_{se}\ \text{(dS/m)};\ R^2 = 0.69,\ P = 0.001,\ \text{s.e.} = 0.04$$

Predicting crop lower limit from subsoil constraints

For all soil combinations at 6 equal intervals, step-wise multiple regression equations involving CLL values and corresponding soil Cl, ESP, and EC_{se} (Table 4) showed that soil Cl was the principal determinant of CLL values in bread wheat, barley, and canola. For predicting CLL values for chickpea and durum wheat, ESP was the principal determinant with soil Cl as the secondary determinant. Between 70 and 80% of the variation in the CLL for 5 crops could be accounted for by soil Cl, ESP, and EC_{se} in these soils.

Predicted values of CLL for 5 crops were obtained using the parameters of regression equations given in Table 4 and compared with measured CLL (Fig. 8). The adjusted R^2 ranged from 0.70 for bread wheat and canola to 0.75 for durum wheat and barley. The intercept was not significantly different from zero and slope was not significantly different from 1 for all 5 crops, suggesting no significant bias in the predictions across the range of CLL values for 5 crop species.

Relationships between grain yields and measured crop lower limit

For all crops, the increased values of measured CLL to 1.30 m (0.10–1.30 m) significantly ($P = 0.001$) decreased the grain yield (figures not shown), suggesting that increased lower limit or decreased water availability or reduced water extraction by crops accounted for most of the effect of subsoil constraints on crop yields.

Visual symptoms

At one site with high average subsoil Cl (1581 mg Cl/kg) at 0.10–1.30 m depth, wheat crops were water stressed initially, with chlorosis on the tips and margins of the older leaves. The chlorosis developed to necrosis and affected younger leaves as well. At maturity, plants were stunted and heads

Table 4. Step-wise multiple regressions relating soil properties and crop lower limit (cm^3/cm^3) values of 5 winter crop species grown in south-western Queensland

R^2 significant at $P = 0.001$; Cl (mg/kg); EC_{se} (dS/m); ESP (%); ***, ** significant at the 1% and 0.1% level, respectively

Crop lower limit (LL)	Step-wise regression equation	R^2	s.e.
Bread wheat LL	0.144 + 0.000067*** Cl + 0.0050*** ESP + 0.00463*** EC_{se}	0.69	0.05
Barley LL	0.172 + 0.000059*** Cl + 0.0061*** ESP	0.74	0.04
Durum wheat LL	0.179 + 0.000064*** Cl + 0.0061*** ESP	0.74	0.04
Chickpea LL	0.247 + 0.000049*** Cl + 0.0046*** ESP	0.70	0.04
Canola LL	0.229 + 0.000073*** Cl + 0.0068** EC_{se}	0.69	0.05

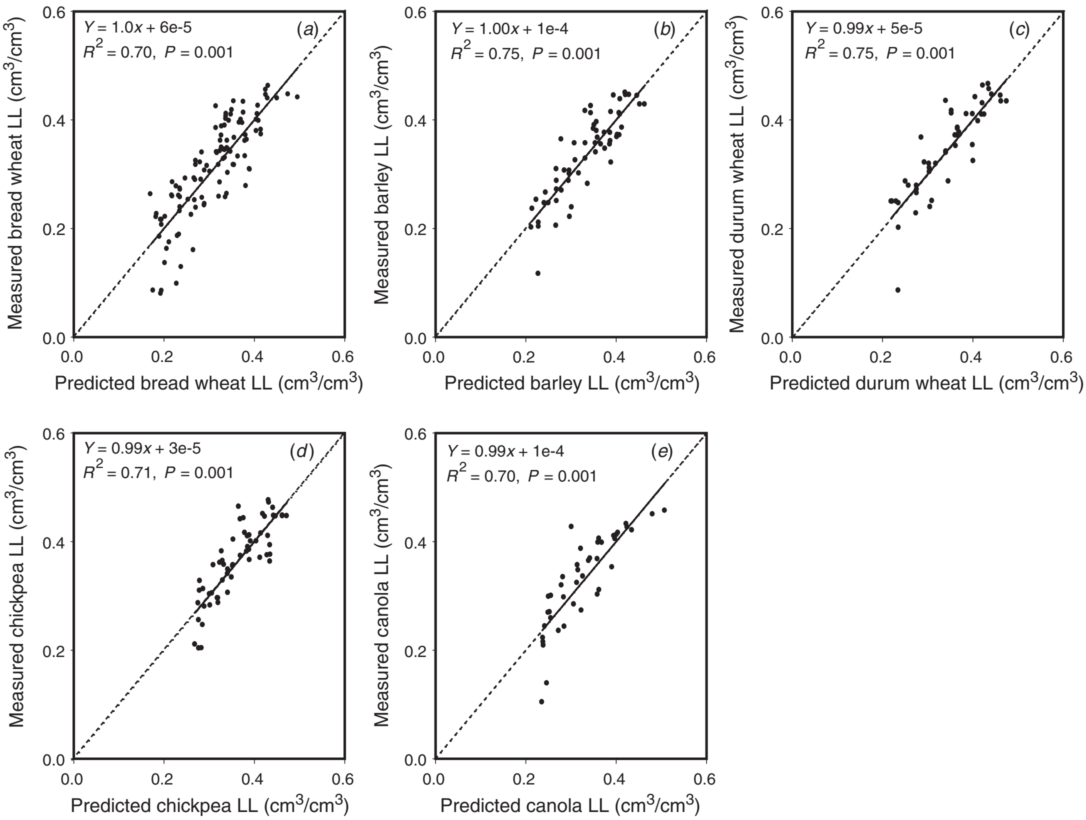

Fig. 8. Relationships between measured and predicted lower limit values (0.10–1.30 m) for (*a*) bread wheat, (*b*) barley, (*c*) durum wheat, (*d*) chickpea, and (*e*) canola grown in all soil combinations in south-western Queensland. The dashed line is 1 : 1.

had few grains. At 3 sites with average soil Cl concentrations >1000 mg Cl/kg in the 0.10–1.30 m soil profile, chickpea showed yellowing and browning of older leaf margins, followed by necrotic lesions. This resulted in senescences of the leaves and ultimately plant death.

Effects of subsoil constraints on nutrient concentrations in YML

Increasing levels of subsoil constraints from low to medium or medium to high significantly increased Cl and decreased Ca concentrations in the YML of bread wheat, durum wheat, and chickpea, with no differences in barley and canola (Fig. 9). Increasing levels of subsoil constraints from low to medium or medium to high significantly increased Na concentrations in the YML of durum wheat, whereas for bread wheat and chickpea, significant increases in Na concentrations were observed only at the high subsoil constraint site, with no significant differences between low and medium constraints. In canola, the increase in subsoil constraints from low to medium or high increased Na concentration in YML with no significant differences between medium and high constraints. In all crop species, the Cl concentration in YML was higher than the corresponding Na concentration. High levels of subsoil constraints significantly decreased K concentration in the YML of bread wheat, durum wheat, and chickpea compared with low or medium constraints (Fig. 9).

Of the 5 crops on average across 3 sites (Fig. 9), canola had significantly higher concentrations of Cl in the YML than bread wheat, barley, durum wheat, and chickpea, with no significant differences among the latter crops. The concentration of Ca in the YML of canola was significantly higher than in chickpea, and that in the latter was significantly greater than in bread wheat, barley and durum wheat. The Na concentration was significantly higher in canola and durum wheat than in barley, and that in the latter was significantly greater than in bread wheat and chickpea.

Relationships between grain yield and Cl, Na, Ca, and K concentration in the YML

The coefficient of linear relationships between grain yield and concentration of ions (Cl, Na, Ca, and K) in the YML of 5 winter crop species is given in Table 5. Relationships between relative bread wheat grain yield and ion concentration were significant for Cl, Ca, and K, being positive for Ca and K and negative for Cl. For barley, the relationships between relative grain yield and ion concentrations in the YML were significantly positive

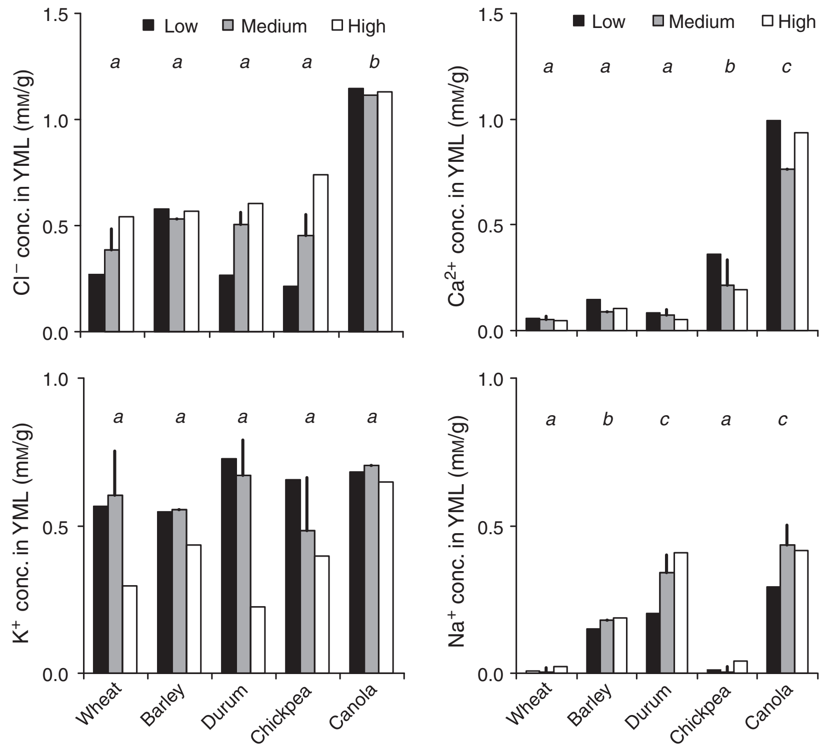

Fig. 9. Concentrations of Cl, Ca, Na, and K in the YML of 5 winter crop species grown on the low, medium, and high constraint Vertosols represented by increasing Cl concentration in the soil profile (0–1.3 m) in south-western Queensland during 2004. Vertical bars represent l.s.d. at $P = 0.05$. Values within a plot followed by same letter are not significantly different at $P = 0.05$ in mean nutrient concentration among crop species in low, medium, and high constraint Vertosols.

Table 5. Simple correlation between relative grain yield and ion (Cl, Ca, Na, and K) concentration in the YML of 5 winter crops grown on soils with various combinations of subsoil constraints
***, **, Significant at the 1% and 0.1% level, respectively; n.s., not significant

Crop	Coefficient of correlation (*r*)			
	Cl	Ca	Na	K
Bread wheat	−0.79***	0.67***	n.s.	0.54***
Barley	n.s.	0.53**	0.56**	n.s.
Durum wheat	−0.84***	0.47**	−0.47**	0.51**
Chickpea	−0.74***	0.47**	n.s.	0.48**
Canola	n.s.	n.s.	n.s.	0.41**

for Na and Ca. The relationships between relative grain yield of durum wheat and concentrations of Na and Cl in the YML of durum wheat were significantly negative but positive for Ca and K. Similar to durum wheat, the relationship between relative grain yield of chickpea and Ca and K concentrations was positive, whereas it was negatively correlated with Cl and Na concentrations in the YML. The relative grain yield of canola increased with K concentration in the YML but was not significantly correlated with Cl, Na, and Ca (Table 5).

Discussion

Subsoil constraints in Vertosols in south-western Queensland

Cracking clay soils (Vertosols), mostly grey, brown, and red clays in north-eastern Australia, exhibit various combinations of high levels of subsoil salinity, subsoil sodicity, potentially phytotoxic concentrations of soil Cl, and subsoil acidity in the case of brigalow-dominated vegetation (*Acacia harpophylla*) soils (Dalal *et al*. 2002; Dang *et al*. 2006), and this was also evident in the current study from the Vertosols sampled in the south-west of Queensland. Subsoil salinity in these soils appeared to be due primarily to Cl salts. However, in some grassland soils (dominated in the native state by Mitchell grass, *Astrebla lappacea*), high values of $EC_{1:5}$ (>3.0 dS/m) and/or calculated EC_{se} (10–25 dS/m) were due to the presence of subsoil gypsum, which was visually evident and further supported by high SO_4-S concentrations in these soils (Table 1).

Effects of subsoil constraints on water extraction and crop yield

Comparing the water extraction and depth-wise distribution of subsoil constraints for low and medium constraint sites, increasing concentrations of soil Cl were associated with the restricted extraction of subsoil water by the crops (Fig. 4), resulting in lower yields (Table 2), as both sites had no significant differences in depth-wise distribution of ESP and soil pH_w in the soil profile to 1.30 m and EC_{se} in the 0.50–0.90 m layers. High EC_{se} at 0.50–0.70 m in the low subsoil constraint site was due to the presence of gypsum (520–660 mg SO_4-S/kg) compared with the medium constraint site (23–99 mg SO_4-S/kg), suggesting that the calculated high EC_{se} due to gypsum in the subsoil of the low constraint site had little effect on water uptake and yields of all 5 crops. Generally, evidence in the literature points to gypsum either having a slight negative or an ameliorative effect on the adverse impact of Cl (e.g. Curtin *et al*. 1993; Marschner 1995).

Further, at the high subsoil constraint site, the maximum depth of water extraction was severely restricted, resulting in further reduction in PAWC and grain yield. Since all the 3 sites had no significant differences in levels of subsoil ESP below 0.70 m depth, high concentrations of subsoil Cl to 1.30 m depth may have restricted access to subsoil water. Comparing differences in water extraction with levels of subsoil constraints at the 3 sites (low, medium, high), greater contrasts in water extraction were observed among high/medium/low Cl than high/medium/low EC_{se} and/or ESP.

At the low subsoil constraint site in the present study, soil under chickpea had significantly lower PAWC than under bread wheat, barley, durum wheat, and canola. The latter had non-significant differences among them, suggesting that chickpea has lower ability to extract water from the subsoil (Table 2). However, Hochman *et al*. (2001) found no significant differences between mean PAWC of grey and black Vertosols under bread wheat, chickpea, and barley, possibly due to low or no subsoil constraints in these soils. Sheldon *et al*. (2004) also suggested that in salt-free conditions, water extraction by both bread wheat and chickpea was almost similar, suggesting that the relatively low constraint site used in the present study had enough salts in the soil profile to result in lower PAWC for chickpea than for all other crops.

Canola has been suggested as tolerant to salinity (Francois 1994), although it is moderately sensitive to salinity during emergence (Steppuhn *et al*. 2001). Barley is generally regarded as more salt-tolerant than bread wheat (Mass and Hoffman 1977). However, in the present study, both barley and bread wheat had similar tolerance to salts, possibly due to limited range in PAWC of soils in the field trials.

Presence of subsoil constraints generally results in poor harvest index, resulting from either smaller grain size or reduced grain yield due to restricted ability of the roots to extract stored water in the subsoil during grain fill (Nuttall *et al*. 2003). However, in the present study, the relatively high harvest index reported for 5 crop species (Table 3) could be due to soft finish during 2004 (Fig. 2).

Relationships between CLL and subsoil constraints

The results of the present study have shown increased CLL with increased subsoil constraints (Fig. 6). This supports the hypothesis proposed by Sadras *et al*. (2003) that the primary effect of complex and variable combinations of subsoil constraints is to reduce plant-available water, evident from increased CLL. However, the measured values of $EC_{1:5}$ or calculated EC_{se} using the equation of Shaw (1999) for all 19 sites showed discrepancies in the direct relationship with CLL of bread wheat. The relationships between bread wheat CLL and measured $EC_{1:5}$ and/or calculated EC_{se} were greatly improved when soils high in gypsum were excluded, suggesting that measured $EC_{1:5}$ or calculated EC_{se} would not be a good predictor of CLL in the presence of significant quantities of gypsum in the soil. Since gypsum is sparingly soluble (30 mmol/L H_2O), it would make only small contribution to soil solution EC (Shaw 1999). Also, depending upon the presence of other associated cations and anions, the solubility of gypsum is further reduced by the presence of common ions and enhanced by the presence of dissimilar ions (Arslan and Dutt 1993).

The strong relationship between Cl concentrations and CLL remained unchanged with or without excluding gypsum-dominated soils. Therefore, the reduced crop uptake of water may have resulted from the increased osmotic effect of soluble soil Cl and/or build-up of toxic Cl or Na ions in the plants (Greenway and Munns 1980; Marschner 1995; Orcutt and Nilsen 2000). High correlation between CLL and ESP (figure not shown) makes it difficult to conclude whether sodicity or the soil Cl *per se* resulted in the reduced uptake of water. However, given the presence of high salt concentrations in the subsoils, there is sufficient salt concentration to maintain flocculation (Sumner 1993). The effect of sodicity could be due to high plant-available Na concentrations in the soil. Reduced uptake of water resulting in growth inhibition may largely be related to gradual build-up of Na (Sheldon *et al*. 2004). The uptake of excessive amounts of Na is known to interfere with the uptake of essential macro- and micro-nutrients, and this may also disturb normal growth (Naidu and Rengasamy 1993).

Poor correlation between CLL and bulk density, NO_3-N, or initial volumetric soil water (figures not shown) showed that physical impedance due to high bulk density, or reduced growth due to N deficiency was not implicated in reduced maximum depth of water extraction. The ranges in the bulk density of the selected sites were fairly narrow with a minimum of 1.2 g/cm^3 and a maximum of 1.6 g/cm^3 in the 0.10–1.30 m soil profile. All crops were supplied with sufficient N, P, and Zn to minimise the differences in CLL of water extraction due to nutrition limitations. All sites in the present study were at their DUL before the start of the trials; therefore, the difference in stored water as a factor underlying the crop response to subsoil constraints was minimised.

Predicting crop lower limit of available water

To account for the effect of subsoil constraints, the CLL can either be measured in each individual paddock or derived from empirical relationships relating soil properties and lower limit of plant-available water. Previous studies have related the estimated CLL to various soil properties including soil particle size, organic carbon, bulk density, drained upper limit, and subsoil constraints (Gupta and Larson 1979; Hochman *et al*. 2001; Sadras *et al*. 2003). In the present study, soil Cl concentration, EC_{se}, and ESP in various combinations in the subsoil accounted for 69–74% of variability in CLL of 5 crop species on Vertosols (Table 4).

Inclusion of clay content either did not improve the prediction of CLL or had little effect in all crop species except canola, where the prediction was improved by 5% (results not shown). Clay content alone accounted for $<$10% of variation in the CLL for all crops except canola where it was 27%. In contrast, Sadras *et al*. (2003) reported strong relationships between CLL and clay concentrations, ranging between 5% and 30% for wheat. The higher clay concentration of the soils in the present study may explain the different relationship with CLL in this study. The CLL for all 5 crop species was higher than the lower limit at –1.5 MPa (LL15) calculated from texture alone (Shaw 1996) (Fig. 7). The stronger relationship between apparent unused plant-available water (CLL – LL15) and Cl concentrations than ESP or EC_{se} further suggested that the high concentration of Cl in these soils most likely inhibited subsoil water extraction by the crops.

The predictive values of CLL for 5 crops were highly significant ($R^2 = 0.70$–0.75), with slope not significantly different from 1 and intercept not significantly different from zero (Fig. 8), which shows the robustness of the model in determining CLL on Vertosols with these subsoil constraints. There may be significant differences in other soils due to texture, structure, and clay mineralogy (Williams *et al*. 1983), nutrient deficiency (Ritchie 1981), and the positive and negative influence of various soil biota.

Effect of subsoil constraints on nutrient concentration

All crop species had higher concentrations of Cl than Na in the YML. However, the differences in Na concentrations in the YML among the species were greater than Cl (Fig. 9). The Na concentration of the YML was lowest in the least salt-tolerant crops such as chickpea and also in the tolerant crops such as bread wheat. Therefore, a direct toxic effect of Na in the leaves seems unlikely to be a causative factor for the growth depression in chickpea and bread wheat, although it cannot be excluded since even a low Na concentration in the plant can induce considerable changes in carbohydrate metabolism through its effect on activities of enzymes of carbohydrate metabolism, particularly starch synthetase (Marschner 1995). Both chickpea and bread wheat were able to exclude Na from the YML, with the latter able to exclude Na better than the former, but both crops had high concentrations of Cl, resulting in reduced growth and further development of chlorosis, necrosis, and death of plants with increasing levels of constraints in terms of soil Cl concentrations. In the present study, the foliar symptoms observed for both bread wheat and chickpea were consistent with those described previously for salt stress or Na or Cl toxicity (Marschner 1995; Xu *et al*. 2000).

The concentration of Cl in the YML beyond 0.63 mM Cl/g in bread wheat and 0.50 mM Cl/g in chickpea was primarily responsible for leaf burning, chlorosis, and dieback in bread wheat and chickpea. This concentration of Cl reported for toxicity in the present study was similar to the $>$0.56 mM Cl/g for wheat (Chauhan and Chauhan 1985) and 0.45 mM Cl/g for chickpea reported previously (Reuter *et al*. 1997), but was much lower than the 1.4 mM Cl/g reported for phytotoxicity in chickpea with almost no seed yield (Manchanda and Sharma 1989).

In the present study, canola had significantly higher Na and Cl concentrations in the YML compared with all other crop species (Fig. 9), without showing any evidence of toxicity symptoms, suggesting that canola is able to sequester the high concentrations of Na or Cl into vacuoles (Francois 1994). Among cereals, durum wheat had a significantly higher concentration of Na in the YML than barley and bread wheat, but that of bread wheat was significant lower than barley. Barley has been shown to tolerate high Na concentrations within the leaves, probably by maintaining low levels of Na in the cytoplasm and sequestering the Na in vacuoles, whereas bread wheat has a greater ability to restrict Na, but not Cl transport to the leaves (Gorham and Wyn Jones 1993). Durum wheat was found to be more salt sensitive than the other 2 cereals. The sensitivity of durum wheat to salts is due to it lacking the genes for restricting Na uptake in the shoot as in bread wheat, and sequestering Na in vacuoles as in barley (Munns *et al*. 2000).

Salinity not only causes high concentration of Na and Cl in plants, it also influences the uptake of essential nutrients such as K and in particular Ca through the effect of ion selectivity (Marschner 1995). Therefore, maintenance of higher K and Ca concentrations in the salt-tolerant genotypes has been shown to be one of the mechanisms underlying their superior salt tolerance (El-Hendawy *et al*. 2005). However, in the present study, cereals had a significantly lower concentration of Ca in the YML than chickpea. This may suggest that chickpea, having better control over Ca nutrition than cereals, would have superior salt tolerance, when it is clearly inferior to all the cereals in terms of its ability to exclude Na and Cl. In the present study, canola accumulated significantly higher concentrations of Ca in the YML than all the other crops.

There was no significant difference in the concentration of K in the YML of the 5 crop species.

Relationships between yield and nutrient concentrations in YML

The grain yield reduction corresponded well with the increased Cl concentration in the YML of bread wheat, durum wheat, and chickpea and with increased Na concentration in durum wheat and chickpea (Table 5). In the present study, Na ions *per se* are not phytotoxic to bread wheat. It appears that Cl is more damaging. This contradicts findings of Kingsbury and Epstein (1986) who concluded that toxicity of NaCl solutions to the sensitive wheat was a function of the Na, rather than Cl ion. However, their findings may be affected by the use of a very high concentration of nitrate as the counter ion with Na, which itself could be toxic. Martin and Koebner (1995) showed that although Cl is more damaging to wheat, the full toxic effect is only expressed when both Na and Cl are simultaneously present in excess.

For durum wheat and chickpea, increased uptake of Na also resulted in reduced yield of both the crops and more so for the former than the latter. For chickpea it appears that a concentration of 0.08 mM Na/g or lower in the YML had no influence on the grain yield (figure not shown). Reuter *et al*. (1997) also suggested a concentration of 0.004–0.08 mM Na/g as adequate for the normal growth of chickpea.

For barley, grain yield was positively related to Na concentration, with no significant relationship with Cl concentration in the YML, suggesting that the yield reduction in barley may not be related to Na and/or Cl concentration in the YML (Table 5). Munns *et al*. (1988) suggested that although barley accumulates high concentrations of Na and Cl in fully expanded leaves, these high concentrations do not determine the growth of barley. The positive relationship between barley yield and Na concentration in the YML could be due to Na substituting for K, which can be beneficial (Marschner 1995).

The grain yield reduction in bread wheat, durum wheat, chickpea, and barley corresponded well with decreased Ca concentration. Calcium concentration in the YML showed a greater variation with increasing subsoil constraints than Na and K concentrations. Calcium is a critical factor in maintaining membrane integrity and influencing selectivity in ion uptake and transport, and high salts inhibit uptake and transport of Ca and may induce Ca deficiency with a high Na/Ca ratio (Dang *et al*. 1999).

Relationships between grain yield and subsoil constraints

Marschner (1995) and Orcutt and Nilsen (2000) reviewed the multiple effects of salinity and sodicity on plants and ascribed these effects to (*i*) reduced crop-available water, associated with high osmotic potential, resulting in reduced ability of roots to obtain soil water; (*ii*) impaired root growth and functions due to toxicity of Na and/or Cl; and (*iii*) nutrient imbalance by depression in uptake of other mineral nutrients. In the present study, calculated values of osmotic potential using the equation of Groenevelt *et al*. (2004) in bulk soil solution were less than –0.3 MPa for all soils, except for those dominated by gypsum in which it was about –0.6 MPa (data not shown). However, osmotic potential and salt ion concentrations in the rhizosphere, to which the plants were exposed and responding, were likely to be much higher than those in bulk soil solution (Schleiff 1986). In the present study, the effect of subsoil constraints in these soils appears to be build-up of toxic Cl and/or Na ions in the plants, although osmotic effects cannot be ruled out since these ions also contribute to salinity. The relative importance of Na and Cl as the major ion causing toxicity may vary among species.

Conclusions

Soils used for grain cropping in south-western Queensland are predominantly Vertosols and have subsoils that exhibit high salinity, sodicity, and high levels of Cl concentration. Increasing severity of subsoil constraints resulted in decreased depth of water extraction, relative inability to extract water, lower PAWC, and reduced grain yield for all 5 crops, especially more severe for chickpea and durum wheat. Bread wheat, canola, and barley were found to be more tolerant to these subsoil constraints than chickpea and durum wheat. We found that Cl concentrations had a greater effect in restricting the ability of roots to extract water in the subsoil than did salinity (EC_{se}) and sodicity (ESP).

The effect of subsoil constraints was evident from the increased CLL. However, $EC_{1:5}$ or EC_{se} would not be a good predictor of CLL in the presence of significant quantities of gypsum in the subsoil. Therefore, care needs to be taken in relating $EC_{1:5}$ or calculated EC_{se} to the abilities of roots to extract soil water in these soils. This study developed empirical relationships between subsoil constraints and CLL, which can effectively estimate water extraction of 5 winter crop species with subsoil constraints.

Increased concentrations of Na and in particular Cl in the YML were associated with reduced grain yields of bread wheat, durum wheat, and chickpea. Further, Cl concentration in the YML of at least bread wheat, durum wheat and chickpea showed greater variability with increasing levels of subsoil constraints than Na concentration, which suggests a high potential for using Cl concentration in the YML for screening of salt tolerance in these species grown on soils with subsoil constraints.

Acknowledgments

The Grains Research&Development Corporation funded this research. The generous support of our collaborative growers and their families in providing sites and managing the trials is greatly appreciated. Thanks are also due to Dr David Mayer, Biometrician, for suggestions, Vanessa Alsemgeest and David Cooper for helping with data collection, Dave Lyons for plant analysis, Dr Brian Bridge, Dr Zvi Hochman, Dr Neal Menzies, Mr George Rayment, Dr Daniel Rodriguez, and Dr Roger Armstrong, and two anonymous reviewers for comments and valuable suggestions.

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Manuscript received 21 July 2005, accepted 5 May 2006