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High subsoil chloride concentrations reduce soil water extraction and crop yield on Vertosols in north-eastern Australia

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Abstract. Salinity, sodicity, acidity, and phytotoxic levels of chloride (Cl) in subsoils are major constraints to crop production in many soils of north-eastern Australia because they reduce the ability of crop roots to extract water and nutrients from the soil. The complex interactions and correlations among soil properties result in multi-colinearity between soil properties and crop yield that makes it difficult to determine which constraint is the major limitation. We used ridge-regression analysis to overcome colinearity to evaluate the contribution of soil factors and water supply to the variation in the yields of 5 winter crops on soils with various levels and combinations of subsoil constraints in the region. Subsoil constraints measured were soil Cl, electrical conductivity of the saturation extract (EC_{se}), and exchangeable sodium percentage (ESP). The ridge regression procedure selected several of the variables used in a descriptive model, which included in-crop rainfall, plant-available soil water at sowing in the 0.90–1.10 m soil layer, and soil Cl in the 0.90–1.10 m soil layer, and accounted for 77–85% of the variation in the grain yields of the 5 winter crops. Inclusion of ESP of the top soil (0.0–0.10 m soil layer) marginally increased the descriptive capability of the models for bread wheat, barley and durum wheat. Subsoil Cl concentration was found to be an effective substitute for subsoil water extraction. The estimates of the critical levels of subsoil Cl for a 10% reduction in the grain yield were 492 mg cl/kg for chickpea, 662 mg Cl/kg for durum wheat, 854 mg Cl/kg for bread wheat, 980 mg Cl/kg for canola, and 1012 mg Cl/kg for barley, thus suggesting that chickpea and durum wheat were more sensitive to subsoil Cl than bread wheat, barley, and canola.

Additional keywords: bread wheat, durum wheat, barley, chickpea, canola, ridge regression.

Introduction

Grain cropping areas of north-eastern Australia, including northern New South Wales (NSW), and central and southern Queensland (Qld), occupy 6 million ha of land, of which 75% is typically sown to dryland agriculture. The yield of grain crops grown on the clay soils (mainly Vertosols) of the region is potentially limited by many factors; however, water supply is the dominant factor. Successful dryland crop production depends on utilising soil moisture accumulated in the period preceding sowing. Low and variable in-crop rainfall, heat stress, and high rates of evaporation are features of the region's climate and combine to make stored soil water an important determinant of grain yield (Freebairn *et al*. 1990). Many soils of the region have medium to heavy clay texture and can potentially store 200–250 mm of water in the soil profile (Dalgliesh and Foale 1998). However, the presence of high levels of salinity, sodicity, acidity, and phytotoxic concentrations of chloride (Cl) in the subsoils reduces the effective rooting depth, the amount of water and nutrients that plants can obtain from the soil, and crop yield (Dang *et al*. 2006*b*).

The variable distribution of subsoil constraints, both spatially within a paddock, across the landscape and with depth in the soil profile (Dang *et al*. 2006*a*), and the complex interactions that exist among the various physico-chemical subsoil constraints, make it difficult to determine which constraint is the major limitation to crop yield. Moreover, the correlation between soil properties in adjacent soil layers

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generally results in multi-colinearity between soil properties and crop yield. In the past, useful attempts to assess the contribution of soil variables to crop yield variation have been made using descriptive models such as ordinary least square, stepwise multiple regression (Majchrzak *et al*. 2001), or principal component analysis (Shukla *et al*. 2004). Most of these studies assessed the contribution of topsoil (0–0.20 m depth) properties to crop yield variation. However, variability in both topsoil and subsoil properties contributes to the total variation in crop yield. Evaluating the contribution of individual soil physico-chemical properties in different soil layers within the root zone, using simple statistical descriptive models, may be confounded due to the effect of colinearity (Chatterjee *et al*. 2000). Ridge-regression analysis has allowed the construction of stable models to overcome colinearity between variables by eliminating variables that had unstable regression coefficients and/or coefficients that were stable but small (Afifi and Clark 1984; Chatterjee *et al*. 2000; Nuttall *et al*. 2003).

Improved understanding of the magnitude of reduced water extraction and grain yield due to various subsoil constraints will assist in the development of decision support tools (including systems modelling). Advances in systems modelling to incorporate the effects of subsoil constraints will allow producers and advisors to make more informed decisions about managing production systems where subsoil constraints are a limiting factor. The objective of this study was to quantify the relative effect of a range of abiotic factors on subsoil water extraction and grain yield of bread wheat, durum wheat, barley, chickpea, and canola, winter crops widely grown in the study region.

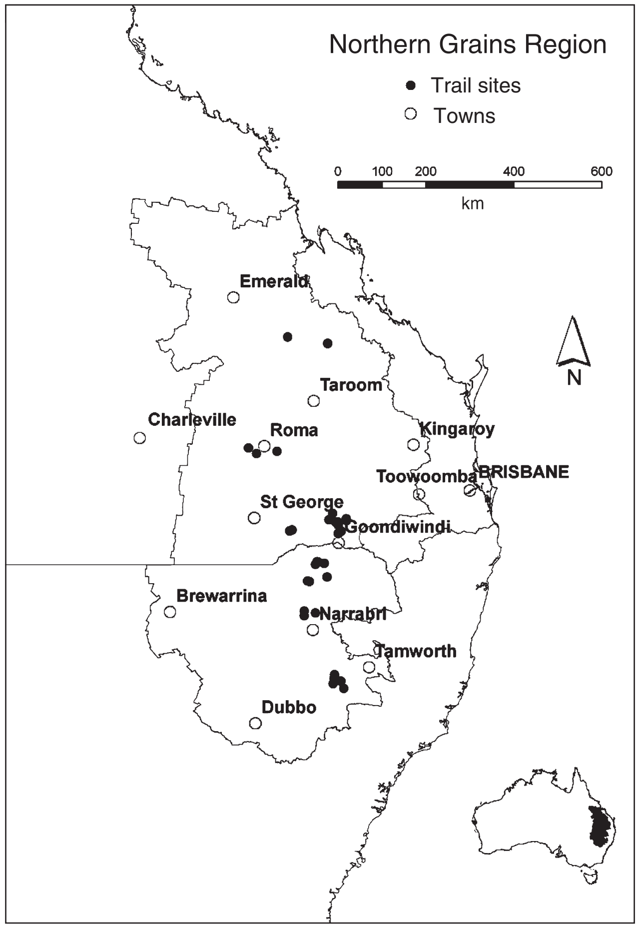

Fig. 1. Location of trial sites in north-eastern Australia.

Materials and methods

Experimental sites

The study area spanned north-eastern Australia's grain-growing region, located between 16°S and 32°S, and 148°E and 151°E (Fig. 1). The climate of this region is semi-arid with high potential evapotranspiration (1300–2200 mm/annum), low (550–800 mm of average annual rainfall) and variable (coefficient of variation 30%) rainfall, most of which falls during summer (Webb *et al*. 1997). The most common cropping soils are grey, brown, and red cracking clays (Vertosols) (Isbell 1996).

Field experiments

Twenty-eight field experiments were established in farmers' paddocks in the winter cropping seasons of 2003, 2004, and 2005 on soils with various combinations and levels of subsoil constraints. Treatments consisted of selections of the following crop species: durum wheat (*Triticum turgidum*), bread wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), chickpea (*Cicer arietinum*), and canola (*Brassica napus*). At all sites, 2–5 crop species were included in experiments planted in a complete randomised block design with 3 replications. Altogether a total of 28 crops of bread wheat cv. Baxter, 17 chickpea cv. Jimbour, 19 barley cv. Mackay, 14 canola cv. Hyola 43 in Qld and cv. Rivette in NSW, and 10 durum wheat cv. Yallaroi in Qld were monitored over 3 years. At all the experimental sites, rainfall was measured with a manual rain gauge located within 500 m of the experimental plots. All Qld and some NSW crop sowing and management were carried out using the co-operating farmer's equipment with management practices following accepted district practice. The remainder of NSW crops were sown with experimental plot-size planters, then managed and harvested by the NSW Department of Primary Industries. All crops in Qld were supplied with 40–50 kg mono-ammonium phosphate (MAP) blended with Zn fertiliser (9.3% N, 20.3% P, 2.6% S, 2.5% Zn) and crops in NSW received a total of 110 kg N as urea and 98 kg MAP blended with Zn fertiliser/ha (11% N, 16.5% P, 4.5% S, 2% Zn) at sowing. All crops were well managed and no substantial weeds, pests, diseases, or visual nutrient deficiencies were observed. Lack of nutrient deficiency was evident from optimum ranges in nutrient concentration in young mature leaves of 5 crop species (Dang *et al*. 2006*b*). At crop maturity, plant samples from quadrats (2 m by 1 m) were taken randomly from 2 places within each plot to determine grain yield in Qld in all years and during 2004 in NSW, and with a small plot harvester in 2005 in NSW. Samples were oven-dried at 70°C to constant weight. Grain was threshed using a stationary thresher with negligible losses, and weighed. Grain yield was expressed in kg/ha at 12% moisture.

Soil sampling and analysis

In April–May of each year, 3–9 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 0.0–0.10, 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 through 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 saturation extracts (EC_{se}) was calculated from EC (1 : 5 soil : water suspension), Cl, and clay content using the method of Shaw (1999).

Cation exchange capacity (CEC) and concentration of exchangeable cations (K, Na, Mg, and Ca) were determined using a 1 M NH_4Cl (pH 8.5) extracting solution (Rayment and Higginson 1992). Prior to extraction, soluble salts were removed by pre-washing with 60% aqueous alcohol (Tucker 1985). The exchangeable cations were measured using an inductivity coupled plasma-optical emission spectrometer. Exchangeable sodium percentage was calculated as the ratio of exchangeable Na to CEC. Clay content was determined by the pipette method (Day 1965). Sulfate-S concentration was determined using Ca $(H_2PO_4)_2$ extracting solution (Rayment and Higginson 1992).

Soil water content

Soil water content (mm) was measured for each crop either using a neutron moisture meter (Campbell Pacific Nuclear Corp., California Model 503) from aluminium (Al) access tubes inserted in the soil to 1.30 m depth or by obtaining 50-mm-diameter soil cores using a hydraulic sampling rig and measuring gravimetric moisture. Volumetric soil moisture was determined by multiplying gravimetric moisture by bulk density. Measurements were made at 0.20-m intervals throughout the 0.10–1.30 m soil profile. Neutron moisture meters were calibrated for each site using a linear regression between neutron moisture meter counts and volumetric moisture contents measured on soil samples obtained at the time of inserting Al-access tubes and again at harvest when soils were drier.

Plant-available water at sowing (PAW)

Plant-available water (PAW) at each site was obtained by subtracting volumetric crop lower limit (CLL) for each crop from volumetric soil moisture at the time of sowing using the method of Dalgliesh and Foale (1998). For determining CLL (Dang *et al*. 2006*b*), a 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 CLL.

Statistical analyses

To explain observed grain yields, descriptive models were constructed using water supply and physico-chemical properties at sowing as independent variables. Water supply included available water at sowing at 6 soil depth intervals: 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 and in-crop rainfall (ICR). 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). The physico-chemical properties included EC_{se}, soil Cl and ESP, each at 7 soil depth intervals: 0.0–0.10, 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. In total, 28 variables were considered in this study.

The ridge-regression technique was used to detect colinearity and determine ridge-point estimates (Chatterjee *et al*. 2000; Nuttall *et al*. 2003). The procedure allows detection of colinearity and simultaneous estimation of new regression coefficients through reduction of the correlations between the related independent variables by adding a constant (k) to the correlation matrix among predictors (Bowerman and O'Connell 1990). The procedure involves selection of independent variables based on examining ridge traces on plots of ridge regression coefficients against the constant (k) for each variable. The k-values were incremented by 0.1 from 0 to 1.0. When $k = 0$ then the coefficient estimates are the same as in the ordinary least square model. A variance inflation factor (VIF), which provides a simple diagnostic procedure for detecting overall colinearity was obtained. A VIF greater or equal to 10 suggests that a multi-colinearity problem exists (Neter *et al*. 1996). The VIFs were evaluated relative to the fit of the model. The models with a balance between acceptable fit for R^2-values and VIFs provided the best parameter estimates.

A subset of variables was retained by (*i*) eliminating variables that had regression coefficients unstable, i.e. tending towards zero; and (*ii*) eliminating variables that had regression coefficients stable but small, by examining the ratio of maximum to minimum values of ridge coefficients over the range of k values ($k = 0$–1.0). The variables with a large ratio (>15) suggest strong colinearity (Chatterjee *et al*. 2000) and hence were eliminated. All statistical analyses were conducted using GENSTAT (2007).

Threshold values of soil Cl concentrations

The effect of subsoil constraints on grain yield of 5 winter crops was estimated from the regression coefficients derived from the relationships between percent relative grain yield and variables selected by the ridge regression. The percent relative grain yield was obtained as grain yield at a given site/maximum grain yield achieved across the trial sites in the present study.

Threshold values of soil Cl concentrations were calculated as per cent reduction in grain yield/regression coefficient for the Cl concentration in the 0.90–1.10 m soil layer in a 3-variable model that included in-crop rainfall, plant-available water, and soil chloride concentration in the 0.90–1.10 m soil layer.

Size of the effect of subsoil constraints was calculated from the location of the constraint within the soil profile. Linear regression relationships between soil Cl concentration (mg/kg) and soil depth (cm) were established for each of the 28 Vertosols. The slope of the curve represented the rate of change of Cl concentration with soil depth for a soil (mg/kg.cm). We used an exponential model to describe the relationships between grain yields and the rate of change of Cl concentration with soil depth, which provided a relatively high value of the coefficient of determination (R^2) and low standard error for the best fit.

Rooting depth was determined as the maximum depth of water extraction (Routley 2002). For a given site, the concentration of subsoil Cl at the maximum rooting depth was used to calculate the probability of water extraction as affected by the presence of subsoil Cl concentration.

Results

Soil characterisation

Mean values and range for various soil properties for the experimental sites are given in Table 1. On average, most of these soils were saline ($EC_{se} > 4.0$ dS/m) below 0.5-m depth, sodic (ESP $\geq$ 6%) below 0.1-m depth, and had potentially phytotoxic levels of Cl (>700 mg/kg) below 0.5-m depth (Northcote and Skene 1972; Shaw 1999; Dang *et al*. 2004).

In-crop rainfall and grain yield

The growing season generally extended from mid May to October in Qld and to November in NSW. The in-crop rainfall ranged from 35 to 292 mm, with a mean value of 143 mm across all sites (Fig. 2).

Across all sites, the grain yield of 5 crops in the present study varied by a factor of 5–10. For example, grain yield of bread wheat ranged from 1038 to 5640 kg/ha. A similar variation in grain yields of barley, durum wheat, chickpea, and canola was observed across all the sites (Fig. 3). The median grain yields across all sites were 2440 kg/ha for bread wheat, 2115 kg/ha for barley, 1700 kg/ha for durum wheat, 1204 kg/ha for chickpea, and 683 kg/ha for canola. The grain yields for all crops were significantly correlated with in-crop rainfall (Fig. 3).

Ridge regression analysis

The ridge procedure was applied to the variables of water supply and soil physico-chemical properties to identify variables with stable and large coefficients. A large degree of instability was observed in the ridge coefficients at low values of $k < 0.2$ but stabilised thereafter. In the present study, $k = 0.2$ was regarded as the point of maximum model improvement. Ridge regression coefficients converged towards zero as the k value increased (Fig. 4).

For water available to the crops, in-crop rainfall (trace 1) and the variable defined by trace 6 (θ_v at 0.90–1.00 m) were stable as their regression coefficient estimates did not vary greatly with increasing values of the parameter (k) and hence these were retained (Fig. 4*a*). The variables defined by traces 3, 4, and 7 had coefficient estimates that varied greatly with increasing k values and hence were omitted. Traces 2 and 5 were negatively related to grain yield and not explicable in agronomic terms and hence omitted. For salinity (EC_{se}) variables, traces 2, 4, 5, 6 and 7 were clearly unstable, while trace 1 had coefficients close to zero and possessed the wrong sign and was hence omitted (Fig. 4*b*). Trace 2 (EC_{se} 0.30–0.50 m) was used to explain variation in bread wheat grain yield because its coefficient did not vary greatly and had stable coefficients and possessed the correct sign. For soil Cl concentrations (Fig. 4*c*), the variables defined by traces 2, 3, 4, 5, and 7, were clearly unstable. Trace 1 and 6 coefficients did not vary greatly, had stable coefficients, and possessed the correct sign; however, trace 6 had slightly higher stability and hence was retained. Sodicity (ESP) variables, traces 3, 4, 5, 6, and 7 were clearly unstable and possessed the wrong sign. Traces 1 and 2 did not vary greatly, possessed the correct sign and could explain variation in grain yield, but trace 1 was used because it had higher values of coefficients and had slightly higher stability than trace 2. Similar subsets of variables were obtained for barley, durum wheat, chickpea, and canola (figures not shown) and were used to explain variation in the grain yields.

The subset of selected variables that included in-crop rainfall, plant-available soil water in the 0.90–1.00 m soil layer at sowing, EC_{se} in the 0.30–0.50 m soil layer, Cl concentration in the 0.90–1.10 m soil layer, and ESP in the 0.0–0.10 m soil layer was used to explain the variation in the bread wheat grain yield. In a 3-variable model, in-crop rainfall accounted for most

Table 1. Mean values and range of soil properties in 28 experimental sites in north-eastern Australia

ρb, Soil bulk density; pH_w, pH of 1 : 5 soil : water suspension; EC_{se}, electrical conductivity of saturated extract calculated from $EC_{1:5}$, clay, and Cl concentration (Shaw 1999); ESP, exchangeable sodium percentage; θ_v, plant-available water at sowing (mm)

	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 (%)	41.2 (26–71)	47.2 (27–72)	48.4 (27–70)	48.0 (31–71)	49.9 (31–70)	50.9 (32–70)	49.2 (30–71)
ρb (g/cm^3)	1.33 (1.0–1.5)	1.37 (1.2–1.5)	1.36 (1.2–1.5)	1.38 (1.2–1.5)	1.42 (1.2–1.6)	1.41 (1.2–1.6)	1.42 (1.2–1.6)
pH_W	7.8 (6.6–8.9)	8.6 (7.2–9.2)	8.7 (7.0–9.3)	8.3 (6.4–9.5)	7.6 (4.8–9.5)	6.7 (4.6–9.3)	6.2 (4.5–9.4)
EC_{se} (dS/m)	0.9 (0.9–3.1)	1.8 (0.2–12.6)	3.9 (0.6–13.2)	6.8 (1.1–21.5)	8.8 (1.6–25.5)	10.2 (3.0–27.2)	10.8 (3.1–24.6)
SO_4-S (mg/kg)	30 (6–310)	129 (4–1600)	239 (6–1500)	348 (8–1700)	512 (14–2700)	481 (41–1900)	453 (7–1900)
Cl (mg/kg)	39 (1–219)	78 (1–389)	230 (1–1230)	468 (32–1760)	762 (124–1940)	1065 (290–2050)	1238 (303–2560)
ESP (%)	5.1 (1.2–13.7)	9.5 (3.3–18.0)	15.2 (6.8–29.5)	20.4 (9.9–43.0)	24.0 (11.8–50.8)	25.2 (14.0–52.4)	25.7 (12.5–53.9)
NO_3-N (kg/ha)	16.9 (1.0–47)	29.6 (2.9–91.6)	23.4 (4.0–73.8)	23.4 (2.0–94.4)	24.4 (1.0–76)	19.9 (1.0–77)	18.2 (1.0–102)
θ_v (mm)		35 (11–60)	25 (4–58)	16 (0–40)	10 (0–38)	4 (0–27)	3 (0–21)

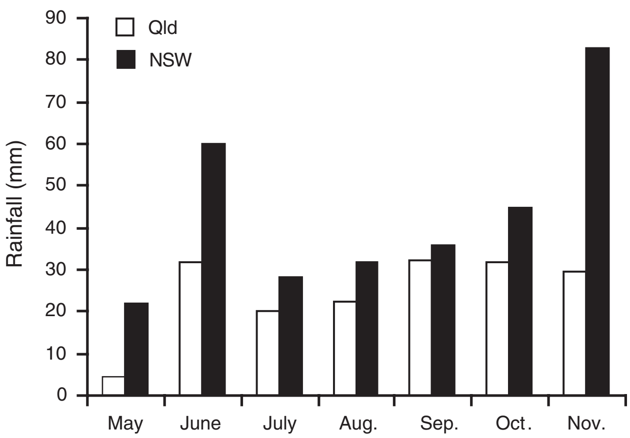

Fig. 2. Distribution of mean in-crop rainfall (May–November) for 28 sites for 2003, 2004, and 2005.

variation in grain yield followed by soil Cl concentration in the subsoil (Table 2). The inclusion of ESP in surface soil marginally improved the descriptive capability in a 4-variable model compared with the 3-variable model. The inclusion of EC_{se} in a 5-variable model did not improve the descriptive capability because it resulted in a decrease in the values of the coefficient of determination compared with the 4-variable model, hence was omitted (Table 2). The soil Cl concentration in the 0.90–1.10 m soil layer alone adequately represented the effect of subsoil constraints in the 3-variable model (Table 2).

Similar descriptive models were obtained for barley, durum wheat, chickpea, and canola (Table 2), using ridge regression (traces not shown). Overall, in-crop rainfall and plant-available soil water at sowing in the 0.90–1.00 m soil layer were important variables in explaining the influence of water supply. Among the factors of subsoil constraints, soil Cl concentration in the 0.90–1.10 m soil layer accounted for the maximum variation in grain yields of all crops in the present study. The inclusion of topsoil ESP had a significant but small effect on grain yields of bread wheat, barley, and durum wheat only. Individually, EC_{se} in the 0.30–0.50 m soil layer significantly affected the grain yields of all crops; however, inclusion of soil EC_{se} in a 5-variable model resulted in decreased values of the coefficient of determination compared with the 4-variable model, thus was not used in descriptive models (Table 2).

Estimating the effect of soil constraints on grain yield

Given the significance of subsoil Cl concentration on grain yield production (Table 2), a 3-variable model was used to obtain the relationships between percent relative grain yield and edaphic constraints including plant-available water in the 0.90–1.10 m soil layer at sowing, in-crop rainfall, and soil Cl concentration in the 0.90–1.10 m soil layer (Table 3). The calculated concentration of subsoil Cl, obtained from regression coefficients, which would cause a 10% reduction in grain yield, varied with crop species, ranging between 492 mg Cl/kg for chickpea and 1012 mg Cl/kg for barley, suggesting that chickpea is most sensitive to subsoil Cl. Out of the 3 cereals used in this study, barley was more tolerant to subsoil Cl than bread wheat or durum wheat. The subsoil Cl concentration that would cause 10% reduction in grain yield of durum wheat was 662 mg Cl/kg, for bread wheat 854 mg Cl/kg, and for canola 980 mg Cl/kg (Table 3).

Predicting water extraction by roots from subsoil in the presence of subsoil Cl

The likelihood of water extraction by crop roots decreased with increasing concentrations of subsoil Cl for all crops, but more so for chickpea and durum wheat than for bread wheat, barley, or canola (Fig. 5). For example, the soil Cl concentration at 0.90–1.10 m depth above which the probability of soil water extraction was reduced to 50% or less was 800 mg/kg for chickpea, 1000 mg/kg for durum wheat, 1200 mg/kg for bread wheat, 1250 mg/kg for barley, and 1300 mg/kg for canola.

Estimating the effect of subsoil chloride

The rate of change of soil Cl concentration with soil depth (*d*Cl) increases with increase in Cl concentration and also with the location of high Cl concentrations within the soil profile. For all the crops, the grain yields decreased ($P < 0.001$) exponentially with increasing values of the rate of change of soil Cl with depth (*d*Cl) except for an outlier with the highest value of *d*Cl and substantially higher observed grain yield than of all the crops (Fig. 6). This was because of the high in-crop rainfall received at this site, which placed lower demand on subsoil water by the crop, and hence, less influence of subsoil Cl on the crop's grain yield at this site.

Discussion

Higher grain yields of bread wheat, durum wheat, barley, chickpea, and canola were associated with higher in-crop rainfall. This suggests that the negative effects of subsoil constraints are likely to be relatively more pronounced in seasons when rainfall is limited, particularly in the post-anthesis phase when crop demand for water stored in the subsoil is high (Sadras *et al.* 2003; Hochman *et al.* 2004; Rodriguez *et al.* 2006). However, in years with adequate in-crop rainfall, crops less reliant on water stored in the subsoil and the effects of subsoil constraints on yields are likely to be diminished. As a consequence, subsoil constraints highlight the importance of climate variability to the productivity of Vertosols in north-eastern Australia (Dang *et al.* 2006*b*; Schwenke *et al.* 2006).

Evaluating subsoil constraints of Vertosols

The variation in grain yields of the crops was strongly linked to subsoil properties. Of the various subsoil constraint factors, soil Cl concentration in the 0.90–1.10 m soil layer accounted for more variation in grain yield and more adequately represented the effect of subsoil constraints than did either subsoil salinity (EC_{se}) or subsoil sodicity (ESP). Dang *et al.* (2006*b*) showed that the presence of high Cl in many Vertosols inhibited subsoil water extraction by these crops through the build up of toxic Cl ions in plant tissue. The lack of significant effects of EC_{se} compared with Cl concentration on grain yields was due to the confounding high EC_{se} values caused by naturally occurring

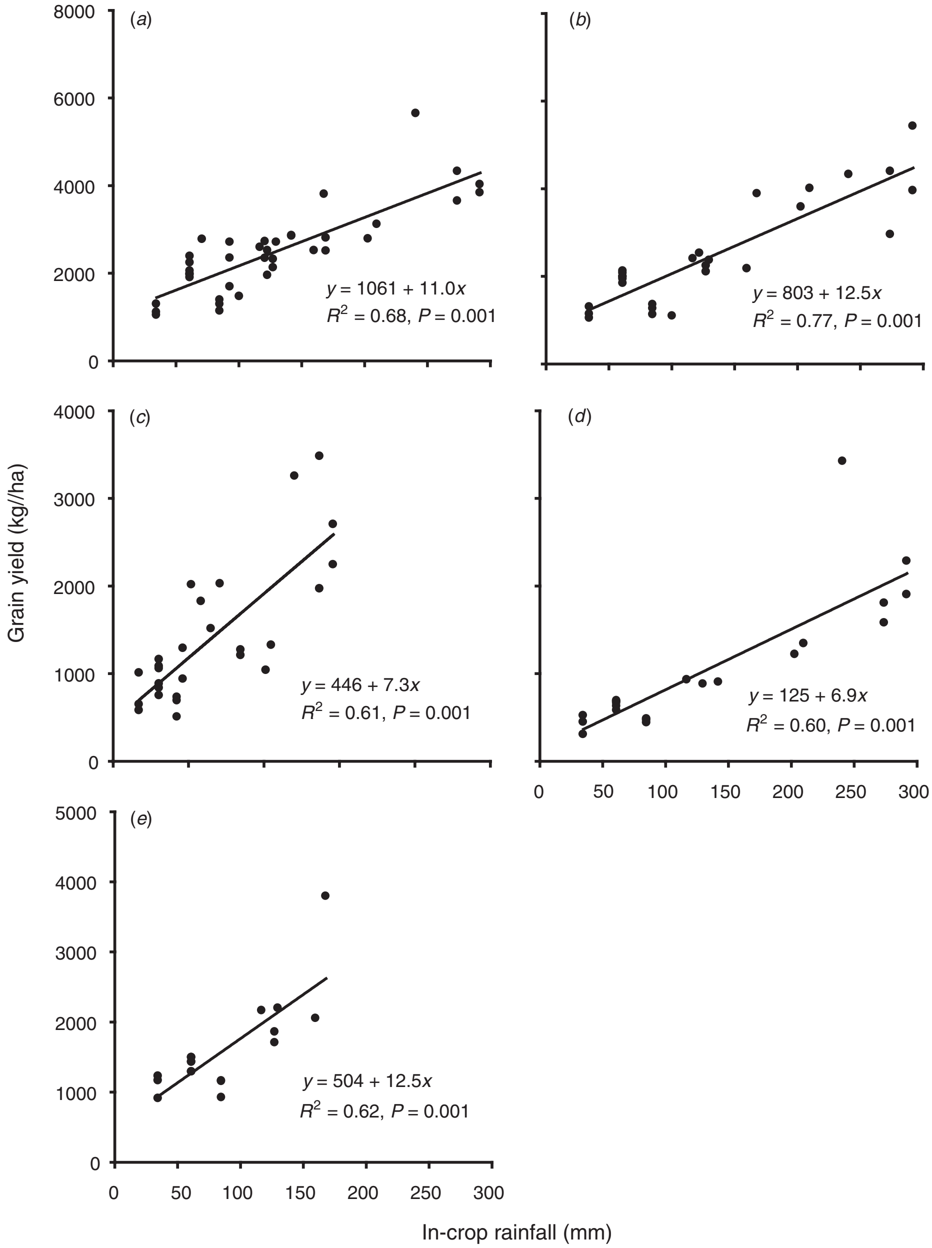

Fig. 3. The relationship between grain yield (kg/ha) and in-crop rainfall (mm) of (*a*) bread wheat, (*b*) barley, (*c*) chickpea, (*d*) canola, and (*e*) durum wheat grown on Vertosols of north-eastern Australia.

sulfate salts (particularly gypsum) in some of the Vertosols in the present study (Table 1; Dang *et al*. 2006*a*).

Measured soil Cl concentrations in the laboratory presumably correlate to Cl concentrations within the rhizosphere under field conditions. The current study and that of Dang *et al*. (2006*b*) showed that in soils with high concentrations of sparingly soluble salts, soil Cl concentration is a more reliable indicator of the ability of roots to extract water than EC_{se}. The presence of gypsum does not affect crop productivity unless other salts are also present since it has been shown to have either a slightly negative or an ameliorative effect on the adverse impact of Cl (Curtin *et al*. 1993; Kelly and Rengasamy 2006).

Subsoil constraints, in particular high Cl concentration, can be used to predict the likelihood of water extraction from the subsoil, which decreased with increasing levels of soil Cl for all crops tested. Hochman *et al*. (2004), using APSIM modelling, considered the impact of subsoil constraints as effectively increasing crop lower limit, implying less available water for plants grown on a grey Vertosol. Our results also indicate that estimated soil Cl concentration above which the probability of soil water extraction was reduced to 50%, varied with crop species from 800 mg/kg for chickpea, 1200 mg/kg for bread wheat, to 1300 mg/kg for canola.

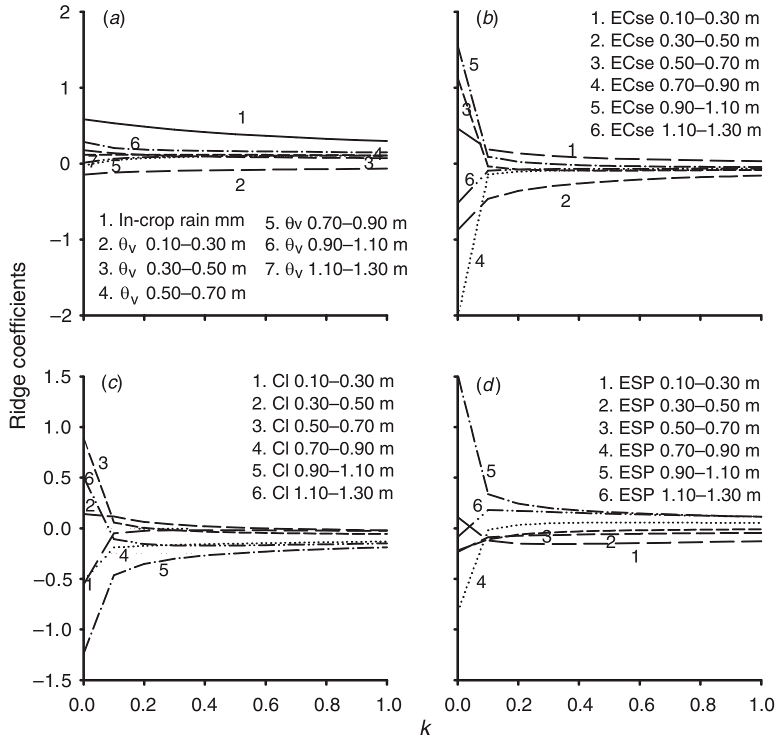

Fig. 4. Ridge traces for (*a*) water supply, (*b*) ECse, (*c*) chloride concentrations, and (*d*) ESP defining grain yield of bread wheat grown on Vertosols of north-eastern Australia.

Table 2. Variables selected by the ridge-regression model describing grain yield

Coefficients are given on original scale at $k=0$. VIF, Mean variance inflation factor; s.e., mean standard error; ICR, in-crop rainfall (mm); θ_v, plant-available water at sowing (mm); Cl, soil chloride concentration (mg/kg); ESP, exchangeable sodium percentage; EC_{se}, electrical conductivity of saturated extract. Significance for regression coefficients: *$P<0.05$, **$P<0.01$ and ***$P<0.001$, respectively

Crop species	Ridge regression coefficients	R^2	s.e.	VIF
Bread wheat				
3 variables	2075 + 7.08 ICR + 29.4 $\theta_{v\ 0.90–1.10\,m}$ – 0.66 Cl $_{0.90–1.10\,m}$	0.858	0.38	1.56
4 variables	2136 + 7.30 ICR + 28.3 $\theta_{v\ 0.90–1.10\,m}$ – 0.45 Cl $_{0.90–1.10\,m}$ – 58 ESP $_{0.0–0.10\,m}$	0.875	0.35	1.66
5 variables	2191 + 7.14 ICR + 27 $\theta_{v\ 0.90–1.10\,m}$ – 0.44 Cl $_{0.90–1.10\,m}$ – 56 ESP $_{0.0–0.10\,m}$ – 15 $EC_{se\ 0.30–0.50\,m}$	0.873	0.35	1.62
Barley				
3 variables	1692 + 9.23 ICR + 21.7 $\theta_{v\ 0.90–1.10\,m}$ – 0.53 Cl $_{0.90–1.10\,m}$	0.835	0.40	1.96
4 variables	1853 + 9.78 ICR + 13.9 $\theta_{v\ 0.90–1.10\,m}$ – 0.21 Cl $_{0.90–1.10\,m}$ – 97 ESP $_{0.0–0.10\,m}$	0.886	0.34	1.97
5 variables	1885 + 9.92 ICR + 12 $\theta_{v\ 0.90–1.10\,m}$ – 0.30 Cl $_{0.90–1.10\,m}$ – 110 ESP $_{0.0–0.10\,m}$ – 35 $EC_{se\ 0.30–0.50\,m}$	0.885	0.34	2.22
Durum wheat				
3 variables	1631 + 6.18 ICR + 48.5 $\theta_{v\ 0.90–1.10\,m}$ – 0.57 Cl $_{0.90–1.10\,m}$	0.793	0.45	1.78
4 variables	1508 + 6.99 ICR + 44.4 $\theta_{v\ 0.90–1.10\,m}$ – 0.36 Cl $_{0.90–1.10\,m}$ – 33 ESP $_{0.0–0.10\,m}$	0.802	0.44	2.11
5 variables	1396 + 9.45 ICR + 29.9 $\theta_{v\ 0.90–1.10\,m}$ – 0.49 Cl $_{0.90–1.10\,m}$ – 62 ESP $_{0.0–0.10\,m}$ – 65 $EC_{se\ 0.30–0.50\,m}$	0.796	0.40	2.64
Chickpea				
3 variables	1519 + 4.53 ICR + 31 $\theta_{v\ 0.70–0.90\,m}$ – 0.62 Cl $_{0.90–1.10\,m}$	0.778	0.47	1.42
4 variables	1511 + 4.61 ICR + 20.0 $\theta_{v\ 0.90–1.10\,m}$ – 0.64 Cl $_{0.90–1.10\,m}$ – 14 ESP $_{0.0–0.10\,m}$	0.771	0.48	1.69
5 variables	1556 + 4.47 ICR + 18.4 $\theta_{v\ 0.90–1.10\,m}$ – 0.64 Cl $_{0.90–1.10\,m}$ – 10 ESP $_{0.0–0.10\,m}$ – 10 $EC_{se\ 0.30–0.50\,m}$	0.762	0.49	1.74
Canola				
3 variables	532 + 5.02 ICR + 32 $\theta_{v\ 0.90–1.10\,m}$ – 0.35 Cl $_{0.90–1.10\,m}$	0.802	0.44	1.77
4 variables	539 + 5.03 ICR + 32.2 $\theta_{v\ 0.90–1.10\,m}$ – 0.34 Cl $_{0.90–1.10\,m}$ – 2.6 ESP $_{0.0–0.10\,m}$	0.782	0.46	1.92
5 variables	521 + 5.25 ICR + 33.0 $\theta_{v\ 0.90–1.10\,m}$ – 0.44 Cl $_{0.90–1.10\,m}$ – 32 ESP $_{0.0–0.10\,m}$ – 70 $EC_{se\ 0.30–0.50\,m}$	0.786	0.46	2.25

Our results further suggest that the depth at which the high Cl concentrations occur within the soil profile determines the size of the effect on crop grain yield. The exponential decrease in the grain yield with increased values of *d*Cl suggests that occurrence of high Cl at the shallower depth would result in greater negative effect on the crop than in deeper subsoil. Thus,

Table 3. Threshold values of chloride (mg/kg) for 10% reduction in grain yield of 5 winter crops

Regression coefficients were derived from the relationships between per cent relative grain yield and variables selected by the ridge regression in a 3-variable model. Significance for regression coefficients: *$P<0.05$, **$P<0.01$ and ***$P<0.001$, respectively. ICR, In-crop rainfall (mm); θ_v, plant-available water at sowing (mm); Cl, soil chloride concentration (mg/kg)

Crop species	Regression coefficients	R^2	Threshold value of Cl
Bread wheat	$36.8 + 0.125^{***}$ ICR $+ 0.52^{**}\ \theta_{v\ 0.90–1.10\,m} - 0.0117^{***}$ Cl $_{0.90–1.10\,m}$	0.846	854
Barley	$31.2 + 0.17^{***}$ ICR $+ 0.40^{*}\ \theta_{v\ 0.90–1.10\,m} - 0.0098^{***}$ Cl $_{0.90–1.10\,m}$	0.827	1012
Durum wheat	$43.0 + 0.163^{***}$ ICR $+ 1.28^{**}\ \theta_{v\ 0.90–1.10\,m} - 0.0151^{***}$ Cl $_{0.90–1.10\,m}$	0.779	662
Chickpea	$43.6 + 0.130^{***}$ ICR $+ 0.56^{**}\ \theta_{v\ 0.90–1.10\,m} - 0.0203^{***}$ Cl $_{0.90–1.10\,m}$	0.802	492
Canola	$15.6 + 0.146^{***}$ ICR $+ 0.95^{**}\ \theta_{v\ 0.90–1.10\,m} - 0.0102^{***}$ Cl $_{0.90–1.10\,m}$	0.782	980

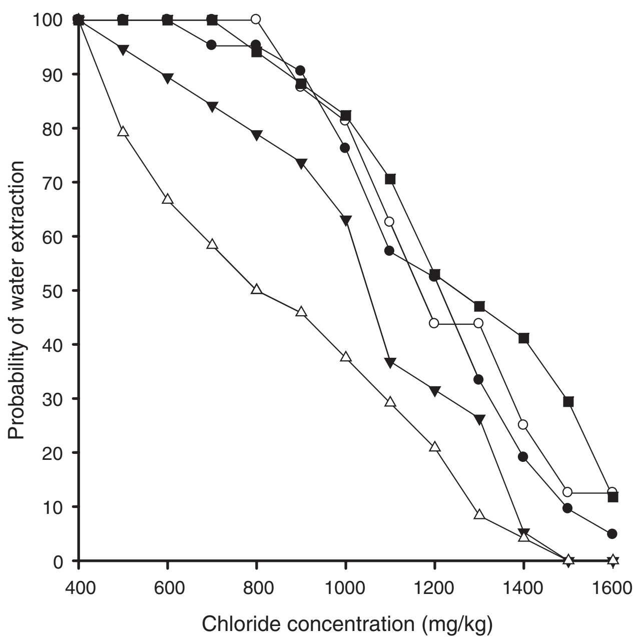

Fig. 5. Probability of water extraction by bread wheat (●), barley (○), durum wheat (▼), chickpea (△), and canola (■) as affected by chloride concentration in Vertosols of north-eastern Australia.

for decision-support purposes, physico-chemical measurements of subsoil constraints at key shallow depths could be used to infer the likelihood of water extraction by crops.

The lack of significant effect of subsoil ESP on grain yields through physical effects was likely due to the concurrent presence of soluble salts in many subsoils of the region (Table 1), thus preventing soil dispersion (Sumner 1993). Potentially, high subsoil ESP could cause a gradual build up of sodium in plant tissues (Sheldon *et al*. 2004), which interferes with the uptake of essential macro- and micro-nutrients and disturbs normal plant growth (Naidu and Rengasamy 1993). In contrast to the present study, Nuttall *et al*. (2003) in Victoria found that EC_{se} and ESP in the 0.60–1.0 m soil layer affected wheat grain yield on Calcarosols of southern Australia, although they did not consider soil Cl in their studies. Also unreported, these soils presumably did not have high concentrations of sparingly soluble salts and hence the strong relationship between EC_{se} and grain yield reported by these authors. To support the results of the present study, Dang *et al*. (2006*b*) showed that subsoil Cl levels had a greater restricting effect on water availability than did either EC_{se} or ESP and found soil Cl to be a more reliable indicator of the ability of roots to extract water in Vertosols than EC_{se} or ESP.

The presence of large number (>2000/kg) of root-lesion nematodes (*Pratylenchus thornei* and *P. neglectus*) can also affect the root system and result in poor water extraction by roots (John Thompson, pers. comm.). However, in the present study, the pre-plant population of root-lesion nematodes at most of the experimental sites was less than <2000/kg soil, which was not enough to cause a significant effect.

Variation in crop species response to subsoil Cl concentration

The calculated concentration of subsoil Cl that would cause a 10% reduction in grain yield varied with crop species, suggesting variation in crop tolerance to subsoil Cl levels. These results suggest that barley followed by canola and bread wheat was more tolerant of the subsoil constraints than durum wheat and chickpea. Chickpea was the most sensitive to high subsoil Cl levels. Generally, canola has been suggested as tolerant to salinity (Steppuhn *et al*. 2001). Barley is generally regarded as more salt-tolerant than bread wheat and durum wheat (Mass and Hoffman 1977; Steppuhn *et al*. 1996). Chickpea has been found to be more sensitive to the subsoil constraints in north-eastern Australia than wheat (Whish *et al*. 2007). Dang *et al*. (2006*b*) also reported significantly higher plant-available water capacity of soil under bread wheat, canola, and barley than under durum wheat and chickpea, entirely due to the differences in the lower limit of soil water extraction among the different crops. Also, the likelihood of water extraction by chickpea roots declined sharply with increasing subsoil Cl concentrations, which was followed by durum wheat, then bread wheat, barley, and canola. Differences in the tolerance of crop species to high subsoil Cl suggest that excluding sensitive crops species, such as durum wheat and chickpeas, from crop rotations on these soils may be an effective way of mitigating the negative effect of subsoil constraints on profitability. Canola has been suggested to be more sensitive to salinity during emergence than in later growth stages (Steppuhn *et al*. 2001), which should suit its use in areas where salts are low near the surface but more concentrated at depth, as shown by Dang *et al*. (2006*b*).

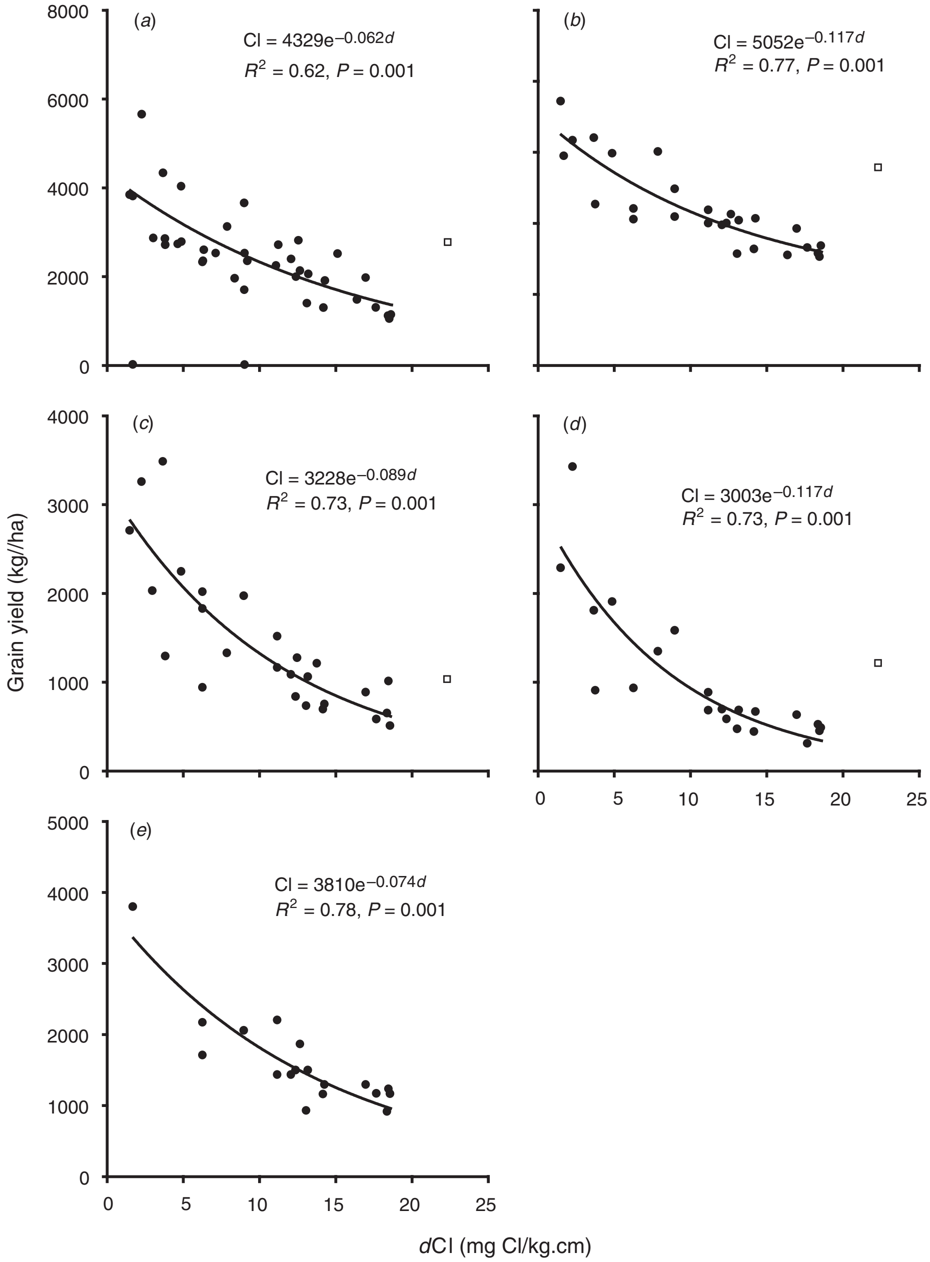

Fig. 6. Relationship between rate of change of chloride concentration (*d*Cl) with soil depth (0–1.30 m) and grain yield of (*a*) bread wheat, (*b*) barley, (*c*) chickpea, (*d*) canola, and (*e*) durum wheat in Vertosols of north-eastern Australia except for an outlier (□). The equation is: grain yield = $ae^{-r(dCl)}$.

Conclusions

Vertosols in northern Australia are generally suitable for cereal production; however, adverse subsoil conditions including high salinity, sodicity, and chloride may occur in many of these soils. Among subsoil constraints, subsoil Cl concentrations had a greater effect in reducing soil water extraction in the subsoil and hence grain yield than did either salinity (EC_{se}) or sodicity (ESP). Subsoil Cl concentration was an effective substitute for estimating the probability of water extraction from the deeper subsoil layers by 5 winter crops. We found that chickpea and durum wheat were more severely affected by high subsoil Cl than bread wheat, barley, or canola and should be avoided on soils with high Cl concentrations and where changes in Cl concentration with depth in the subsoil occur.

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