

Diagnosis, extent, impacts, and management of subsoil constraints in the northern grains cropping region of Australia

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Abstract. Productivity of grain crops grown under dryland conditions in north-eastern Australia depends on efficient use of rainfall and available soil moisture accumulated in the period preceding sowing. However, adverse subsoil conditions including high salinity, sodicity, nutrient imbalances, acidity, alkalinity, and high concentrations of chloride (Cl) and sodium (Na) in many soils of the region restrict ability of crop roots to access this stored water and nutrients. Planning for sustainable cropping systems requires identification of the most limiting constraint and understanding its interaction with other biophysical factors. We found that the primary effect of complex and variable combinations of subsoil constraints was to increase the crop lower limit (CLL), thereby reducing plant available water. Among chemical subsoil constraints, subsoil Cl concentration was a more effective indicator of reduced water extraction and reduced grain yields than either salinity or sodicity (ESP). Yield penalty due to high subsoil Cl was seasonally variable, with more in-crop rainfall (ICR) resulting in less negative impact. A conceptual model to determine realistic yield potential in the presence of subsoil Cl was developed from a significant positive linear relationship between CLL and subsoil Cl:

$$\text{Realistic potential yield} = [(\text{ICR} + \text{plant available water}) \times \text{water use efficiency}] \pm \text{subsoil Cl}$$

Since grid sampling of soil to identify distribution of subsoil Cl, both spatially across landscape and within soil profile, is time-consuming and expensive, we found that electromagnetic induction, coupled with yield mapping and remote sensing of vegetation offers potential to rapidly identify possible subsoil Cl at paddock or farm scale.

Plant species and cultivars were evaluated for their adaptations to subsoil Cl. Among winter crops, barley and triticale, followed by bread wheat, were more tolerant of high subsoil Cl concentrations than durum wheat. Chickpea and field pea showed a large decrease in yield with increasing subsoil Cl concentrations and were most sensitive of the crops tested. Cultivars of different winter crops showed minor differences in sensitivity to increasing subsoil Cl concentrations. Water extraction potential of oilseed crops was less affected than cereals with increasing levels of subsoil Cl concentrations. Among summer crops, water extraction potential of millet, mungbean, and sesame appears to be more sensitive to subsoil Cl than that of sorghum and maize; however, the differences were significant only to 0.7 m. Among pasture legumes, lucerne was more tolerant to high subsoil Cl concentrations than the others studied.

Surface applied gypsum significantly improved wheat grain yield on soils with ESP >6 in surface soil (0–0.10 m). Subsurface applied gypsum at 0.20–0.30 m depth did not affect grain yield in the first year of application; however, there was a significant increase in grain yield in following years. Better subsoil P and Zn partially alleviated negative impact of

high subsoil Cl. Potential savings from improved N fertilisation decisions for paddocks with high subsoil Cl are estimated at ~\$AU10 million per annum.

Additional keywords: subsoil Cl concentration, dryland cropping, plant available water capacity, plant adaptation, gypsum.

Introduction

The northern grains cropping region of Australia includes central Queensland, southern Queensland, and northern New South Wales between 16° and 32°S, and 148° and 151°E. The region occupies 6 Mha of agricultural land, of which 75% is typically sown to dryland agriculture. The climate of this region is semi-arid with high potential evapotranspiration (1300–2200 mm/year), and low and variable rainfall (550–800 mm average annual, coefficient of variation 30%), 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), which are generally uniform in texture down to at least 1 m depth. The yield of grain crops grown on soils of the region is potentially limited by many factors, but water supply is the dominant factor. Due to summer-dominant rainfall, winter crops largely rely on water stored in the soil profile during previous summer–autumn fallow (Freebairn *et al.* 1990). On average, grey Vertosols of this region have a plant-available soil water capacity (PAWC) of 182 mm (Hochman *et al.* 2001), but presence of subsoil constraints (SSC) limits the effective rooting depth and increases crop lower limit (CLL), thereby reducing the amount of water and nutrients that plants can access from soil (Sadras *et al.* 2003; Dang *et al.* 2006b; Hochman *et al.* 2007). These subsoil constraints include sodicity and salinity in Vertosols of north-west New South Wales and southern Queensland, acidity in Vertosols dominated by N-fixing brigalow (*Acacia harpophylla*) vegetation, and sodicity in Vertosols of central Queensland (Irvine and Doughton 2001; Daniells *et al.* 2002; Dang *et al.* 2006a). Many subsoils also have toxic concentrations of sodium carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), chloride (Cl⁻), and sodium (Na^+), as well as severe compaction (McGarry 1992; Shaw *et al.* 1994; Dang *et al.* 2006a). Several of these constraints may occur together in some soils, making diagnosis of the most limiting soil property difficult. Moreover, several soil characteristics in topsoil (A-horizon, 0–0.10 m) and subsoil (B-horizon, below 0.10 m) layers may interact to determine the edaphic environment upon which plant roots depend at a given time. Therefore, identification of the most limiting constraint and its interaction with other factors is a first step in planning for sustainable site-specific soil management.

Soil properties vary both horizontally and vertically (Dang *et al.* 2004a). Grid sampling of soil to identify variable distribution of possible subsoil constraints, both spatially across landscape and within soil profile, is time-consuming and expensive. However, sensing technologies have enabled targeted sampling to monitor and locate areas of potential subsoil constraints, providing both practical and economic advantages.

EM38 technology uses electromagnetic induction to provide surrogate measurements of bulk soil electrical conductivity (apparent EC, EC_a), which is a function of total salt concentration and soil water content (O'Leary *et al.* 2003; Dang *et al.* 2008b). The most common salts in the northern grains region include NaCl and CaSO_4 (gypsum) (Dang *et al.* 2006b). Many soils in the region have apparently yield-constraining high conductivity values due to the presence of gypsum, which has only slightly negative or even an ameliorative effect on crop growth (Curtin *et al.* 1993).

We investigated the extent and impacts of subsoil constraints in the northern grains cropping region through the Grains Research and Development Corporation (GRDC) Research & Development initiative over 5 years. The objectives of this initiative were to determine causal factors, extent and location, and impacts of subsoil constraints to farming, and to develop strategies to manage and/or avoid these constraints. We summarise main findings relating to diagnosis, extent, and distribution; potential impacts across regions, seasons, and soil type; and options to manage soils with subsoil constraints in the northern grains region.

Methods and materials

Field experiments

We present the results of 44 trials conducted in 2002–07 in the northern grains region (Fig. 1). The trial sites were sown with various combinations of crop species and their cultivars during winter and summer. Field trials also included several pasture and fodder crops. All sowing, harvesting, and crop management operations were carried out using the collaborating farmers' equipment in Queensland and a research planter in NSW. All crops were well managed with no significant weeds, pests, diseases, or nutrient deficiencies observed. A detailed description of field experimental protocols was provided in Dang *et al.* (2008a).

Soil sampling and analysis

All sites were sampled to determine their PAWC using the methods of Dalgliesh and Foale (1998). Briefly, drained upper limit (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 (0.0–0.10, 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). For determining CLL, a rain exclusion tent for each crop at each site was erected over a portion (3 m by 3 m area) of 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 rain-exclusion

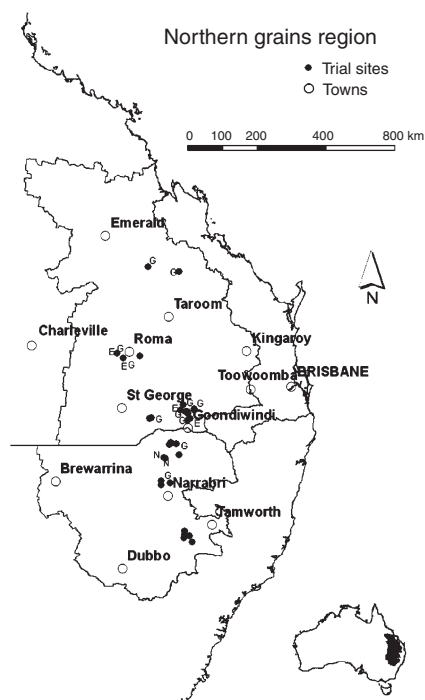


Fig. 1. Northern grains cropping region of north-eastern Australia and location of species (●), gypsum (G), nutrition (N), and EM (E) trial sites.

tent and at crop maturity to determine water extraction patterns and CLL. PAWC was obtained as difference between DUL and CLL. The amount of unused water due to the presence of subsoil constraints was calculated as the difference between CLL and soil water lower limit (LL15) at -1.5 MPa. The LL15 was calculated from the clay content (Shaw 1996) as $LL15 = (0.518 + 0.38 \text{ clay}\%) / 100$.

In April–May each year, 3–9 soil samples were taken per site, depending on size of the experimental area, using a 50-mm-diameter tube and a hydraulic sampling rig. Samples were separated into intervals of 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, dried at 40°C in a forced-draught oven, and ground to pass through a <2 -mm sieve. Soil pH, EC, Cl, and $\text{NO}_3\text{-N}$ 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 concentrations of exchangeable cations (K, Na, Mg, and Ca) were determined using 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 inductively coupled plasma-optical emission spectrometer. Exchangeable sodium percentage (ESP) 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 $\text{Ca}(\text{H}_2\text{PO}_4)_2$ extracting solution (Rayment and Higginson 1992). Mean values and range for various soil properties for the experimental sites are given in Table 1. Most of these soils were found to be saline ($\text{EC}_{\text{se}} > 4.0$ dS/m) below 0.5 m depth and sodic ($\text{ESP} \geq 6\%$) below 0.1 m depth, and had potentially phytotoxic levels of Cl (> 600 mg/kg) below 0.5 m depth (Northcote and Skene 1972; Shaw 1999; Dang *et al.* 2004b).

Diagnosis of subsoil constraints

Ridge regression analysis was used to overcome collinearity between soil properties and crop yield to identify the most limiting constraints to the grain yield of winter crops in the region. A more detailed description of procedure is provided in Dang *et al.* (2008a). Briefly, to explain observed grain yields, descriptive models were constructed using water supply and physico-chemical properties at sowing as independent variables.

Given that in-crop rainfall (ICR) varied over the trial sites and seasons, grain yields of different crops at different sites were allocated to categories based on their ICR and subsoil Cl concentration. Low, mid, high, and very high Cl categories were based on the threshold levels of < 400 mg Cl/kg with no yield penalties (low), 400–800 mg Cl/kg for 10% yield reduction in chickpea (mid), 800–1600 mg Cl/kg for 10% yield reduction in cereal crops (high), and > 1600 mg Cl/kg (very high) for low grain yields when rainfall is below average; crop production may not be economic (Dang *et al.* 2006a, 2008a).

In a parallel approach the Agricultural Production Systems Simulator (APSIM, Version 5.0; Keating *et al.* 2003) configured with the modules Wheat, SOILN2, SOILWAT2, and RESIDUE2 was used to determine best parameters to use for modelling subsoil constraints in a cropping system. A detailed

Table 1. Mean values and range of soil properties for experimental sites in the northern grains region of Australia

pb, Soil bulk density; pH_w , pH of 1:5 soil:water suspension; EC_{se} , electrical conductivity of saturated extract calculated from $\text{EC}_{1:5}$; 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)
pb (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)
$\text{SO}_4\text{-S}$ (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)
$\text{NO}_3\text{-N}$ (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)

description of this approach is provided in Hochman *et al.* (2007). Briefly, reference CLL values were multiplied by alternative functions based on CI, EC_{se}, or ESP to predict measured CLL values.

Extent of subsoil constraints

Regional mapping

The maps of subsoil constraints were adapted from the ASRIS (Australian Soil Resource Information System, www.asris.csiro.au) 'attribute surfaces'. ASRIS soil attribute surfaces were derived by allocating soil properties to map units (or polygons), using finest scale mapping available and a codified attribution process. The polygons (from land resource survey maps) were overlaid with point data (site information) and values (or attributes) were allocated to polygons according to a hierarchical system of 'attribution' described in Brough *et al.* (2006). The first level of attribution was based on actual site data (laboratory analysis and field observations). The second level used soil profile class within a soil mapping project. The third level incorporated information obtained from reconnaissance mapping. The 'ASRIS methodology' incorporates advanced rule-based iterations for attribute estimation which are 'area weighted' for more accurate results. Overlaying land use coverage (Witte *et al.* 2006) across the regional map allowed us to estimate how much of the land actually used for cropping is affected by subsoil constraints.

Farm- or paddock-scale mapping

We used a Geonics EM38 (electromagnetic induction instrument measuring bulk soil electrical conductivity; EC_a) in a vertical dipole mode linked to a mobile differentially corrected Trimble GPS to map suspect subsoil constraints by defining relationships between apparent electrical conductivity (EC_a) and measured soil's chemical and physical properties in Vertosols on 4 farms in southern Queensland. Transects were made at 25-m spacing and data collected at 1-s intervals. All positions were corrected for GPS antenna offset. The Geocentric Datum of Australia (GDA94) grid was used for all comparative map and statistical analysis. Position corrected EC_a data were kriged to a 25 by 25 m grid with the software Vesper (Minasny *et al.* 1999). Volumetric soil water content, clay content, EC_{1:5}, EC_{se}, and CI were determined for each 0.30-m increment to depth of 1.5 m for 10–15 soil samples taken the same day at selected positions, to cover full range of EC_a values. Coefficients of determination were obtained between soil EC_a and weighted mean value for each soil analysis for each soil core to 1.5 m soil depth using the formula (Hedley *et al.* 2004):

$$x_m = ((x_n * d_n) + (x_{n+1} * d_{n+1}) + (x_{n+2} * d_{n+2}) \dots) / D$$

where x_m is the weighted mean value, x_n is the analysis value for subsample n of the soil core, d_n is the thickness (m) of subsample n of the soil core, and D is the total depth (m) of soil core.

Site-specific yield data for successive wheat crops were collected at harvest using yield-monitors fitted in grain harvester. Point data were collected at 1-s intervals along the path of the harvester. Wheat grain yield data were kriged to the same 25 by 25 m grid as the EM38 data using Vesper. Landsat

TM 7 satellite images were acquired at flowering to estimate biomass. Satellite images were selected close to the time of anthesis. The Normalised Difference Vegetation Index (NDVI) was calculated as the ratio of differences and sums between reflectance in near infrared and red spectral band, to assess its value as a surrogate for grain yield when yield data was not available (Richardson and Weigand 1977) from:

$$NDVI = (NIR - RED) / (NIR + RED)$$

where NIR is reflectance in near infrared spectral band, 760–900 nm, and RED is reflectance in red spectral band, 630–690 nm. NDVI was also kriged to the same 25 by 25 m grid as the EM38 data and wheat grain yield data using Vesper (Minasny *et al.* 1999).

Economic impact of subsoil constraints

Average gross margins were calculated using grain yield, protein, and grain screenings data for a range of crop species grown on sites of relatively low subsoil CI (<600 mg Cl/kg in 0.1–1.3 m soil depth) and high subsoil CI (>600 mg Cl/kg in 0.1–1.3 m soil depth) across all trials conducted in the northern grains region during 2003–2007. Crop species or cultivars damaged by emus or shattered before harvest were excluded from analysis. Gross margins were calculated by subtracting standard variable costs (sowing, seed, fertiliser, herbicides, pesticides, and harvesting) (Scott 2006) from total income (on-farm price in \$AU/t, and grain yield in tonnes).

Management options

Crop species and cultivars

Plant adaptation to subsoil constraints was evaluated in 44 replicated field trials conducted during winter and summer cropping seasons of 2002–07 (Fig. 1). A minimum of 2 winter crop species that included bread wheat (*Triticum aestivum*), durum wheat (*Triticum turgidum*), barley (*Hordeum vulgare*), triticale (*X Triticosecale*), oats (*Avena sativa*), chickpea (*Cicer arietinum*), faba bean (*Vicia faba*), field pea (*Allium cepa*), lentil (*Lens culinaris*), lupins (*Lupinus angustifolius*), canola (*Brassica napus*), mustard (*Brassica juncea*), and safflower (*Carthamus tinctorius*) were used, and summer crop species including maize (*Zea mays*), sorghum (*Sorghum bicolor*), sesame (*Sesamum indicum*), millet (*Pennisetum glaucum*), and mungbean (*Phaseolus mungo*) were tested in 4 trials. Two trials were conducted to evaluate pasture options, which included lucerne (*Medicago sativa*), burgundy bean (*Macroptilium bracteatum*), butterfly pea (*Clitoria ternatea*), vigna (*Vigna unguiculata*), and lablab (*Lablab purpureus*). Twelve replicated field trials were conducted to evaluate the relative performance of various commercial cultivars of different winter crop species. These cultivars were Baxter, Lang, Sunvale, Strzelecki, Sunco, Sunstate, Drysdale, Sunlin, Kennedy, and Rees for bread wheat; Bellaroi and Wollaroi for durum wheat; Binalong, Fitzroy, Gairdner, Grout, and Mackay for barley; Everest and Kosciuszko for triticale; Jimbour, Flipper, and Genesis 836 for chickpea; Fiord and Cairo for faba bean; Yarrum and Boreen for field pea; Digger and CIPAL414 for lentil; Ripper, Rivette, Kaye, and Micky for canola; and Gila and 555 for mustard.

Soil amendments

Nine field trials were conducted on Vertosols in the northern grains region (Fig. 1) to determine the effect of soil amendments on ameliorating soil constraints. Gypsum was applied at 2.5–5.0 t/ha, either on the surface soil by spreading and incorporating in the top 0–0.05 m soil depth or to the subsurface using a para-plow with non-inverting tynes at 0.20–0.30 m soil depth. In one of the trials, gypsum or lime at 5 t/ha application was also compared with gypsum (2.5 t/ha) + lime (2.5 t/ha).

Nutrition

Two trials were conducted on grey Vertosols at Coonamble, NSW (Fig. 1), on soils with either low (430 mg Cl/kg in 0.90–1.10 m soil layer) or high (1100 mg Cl/kg in 0.90–1.10 m soil layer) subsoil Cl to determine effect of application of phosphorus (P) at 10 kg/ha and zinc (Zn) at 2.5 kg/ha in alleviating negative impact of subsoil Cl.

Matching N-nutrition

To investigate whether knowledge of soil's subsoil constraint status would change the optimal nitrogen (N) rate and improve profits, APSIM simulations were obtained for 4 levels of subsoil Cl. The simulations were run over 45 years, from 1957 to 2002, with a continuous wheat cropping system. A marginal economic analysis was conducted on average responses to determine optimum level of N at increasing levels of subsoil Cl. A marginal economic analysis was conducted on wheat yield and protein responses predicted for each subsoil Cl case and best N fertiliser decision was estimated using a 75% return on investment criterion. The potential saving from having better knowledge was estimated by matching N fertiliser decisions, for a very high subsoil Cl soil, as the difference in gross income using very high subsoil Cl-N decision compared with using mid subsoil Cl-N decision for that soil. A detailed description of the modelling approach is given in Farquharson *et al.* (2006).

Results and discussion

Diagnosing presence and severity of subsoil constraints

In-crop rainfall, available soil water at sowing, and subsoil Cl concentration accounted for 80–92% of the recorded variation in grain yields of the 5 winter crop types: bread wheat, durum wheat, barley, chickpea, and canola. Inclusion of ESP of surface soil marginally increased descriptive capability of the ridge regression model. Subsoil Cl concentration was found to be the principal determinant of subsoil water extraction. The presence of high Cl in many Vertosols most likely inhibited subsoil water extraction by these crops through a combination of osmotic effects and build-up of toxic Cl ions in plant tissues (Fig. 2a) and resulting in strong negative impact on grain yield of bread wheat (Fig. 2b). Similar results were obtained for other crop species studied (data not shown).

In surface soil, the presence of high levels of ESP (>6%) is a major soil constraint to crop production (Sumner 1993); however, in subsoil moderate to high ESP (6–25%), which is prevalent in the northern grains region, has been found to be less effective in explaining grain yield. The lack of significant relationship between subsoil ESP and grain yields through its physical effects was likely due to the concurrent presence of soluble salts in many subsoils of the region, thus preventing soil dispersion and water-logged layers. As well, the swelling, shrinking, and cracking nature of Vertosols provides good resilience to structural degradation (Sumner 1993). Potentially, high subsoil ESP could cause a gradual build-up of Na in plant tissues (Sheldon *et al.* 2004), which interferes with uptake of essential macro- and micro-nutrients and disturbs normal plant growth (Naidu and Rengasamy 1993). However, it seems likely that in many of the soils tested, high subsoil Cl concentration affects crop growth before any effects due to high ESP.

High and low values of pH are an important constraint in surface layers as well as subsoils of northern grains region. A pH value <5.5 would indicate acidity and potential deleterious effects through aluminium toxicity, and a pH value >8.5

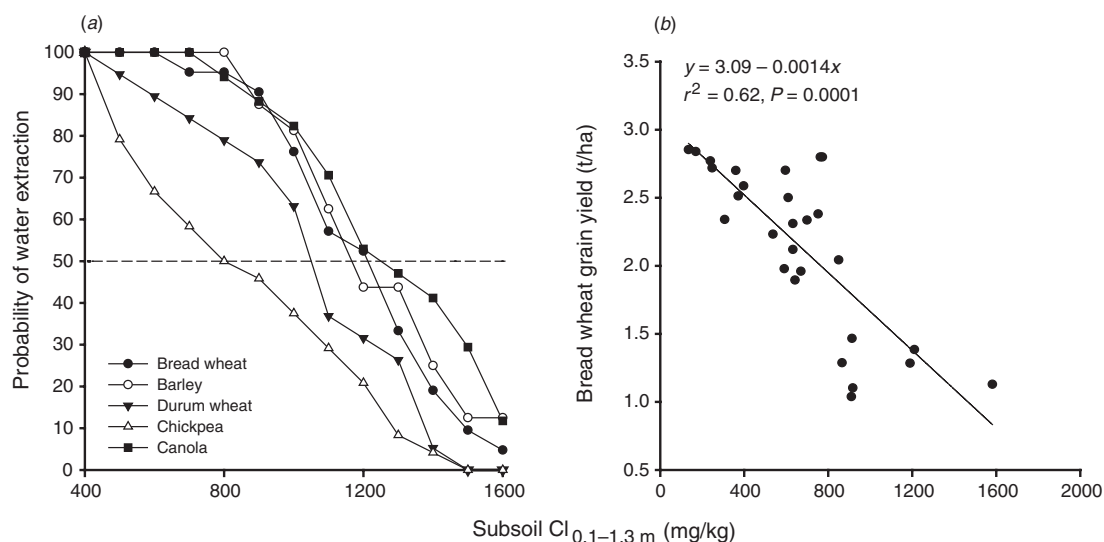


Fig. 2. Effects of subsoil Cl concentration on (a) probability of water extraction by 5 winter crops and (b) bread wheat grain yield.

would indicate alkalinity as the potential constraints through reduced nutrient availability and potential for toxicities, including HCO_3^- and CO_3^{2-} at very high pH (Bruce 1997).

Interaction between subsoil constraints and rainfall

In-crop rainfall influenced impact of subsoil CI on grain yield of crops. Summarising results of 44 field trials conducted in the region, for example in the case of bread wheat, more ICR resulted in less negative impact from high subsoil CI (Fig. 3). Similar results were obtained for other crop species studied (data not shown). Detailed results for other crop species studied are given in Schwenke (2007). These results support APSIM-simulated impact of ICR studied by Sadras *et al.* (2003) in southern Australia. They hypothesised that plant-available water is the key link between crop functionality and complex combinations of subsoil constraints, and that negative

responses of subsoil constraints were more frequent in sites where conditions contributed to severe water deficits, i.e. low ICR, less available water at sowing, and greater evaporative demands. Hochman *et al.* (2004), using APSIM simulation of wheat grown over 100 years in southern Queensland on relatively low and high subsoil constraint grey Vertosols, showed that yield differences vary from <200 kg/ha in some years to nearly 3 t/ha in others. The yield penalty due to subsoil constraints was seasonally variable; ICR in the early part of the season (1 May to 15 August) was positively correlated with differences in grain yield ($P < 0.001$).

Realistic yield potential

Apparent unused plant-available water showed positive relationships with subsoil CI, suggesting osmotic impact of subsoil CI on water availability (Fig. 4a). Given the significance of available water on subsoil and subsoil CI, yield losses due to the unused water were obtained to determine realistic yield potential.

Yield is a function of PAWC at sowing and ICR, whereas PAWC could be defined as $\text{DUL} - \text{CLL}$. Traditionally maximum yield potential was obtained:

$$\begin{aligned} \text{Maximum yield potential} &= [\text{ICR} + (\text{DUL} - \text{CLL})] \\ &\times \text{water use efficiency} \end{aligned}$$

Given that subsoil CI resulted in increased CLL (Fig. 4b) and thus resulted in reduced PAWC, a conceptual model was developed to determine realistic yield potential.

$$\begin{aligned} \text{Realistic potential yield} &= [(\text{ICR} + \text{PAW}) \\ &\times \text{water use efficiency}] \pm \text{subsoil constraints} \end{aligned}$$

Impact of subsoil constraints

Results were compared for 3 field trials conducted in Goondiwindi with similar soil types, initial starting moisture, and ICR, but with increasing levels of soil CI concentrations in the soil profile to 1.30 m soil depth (Fig. 5a). The pattern of soil

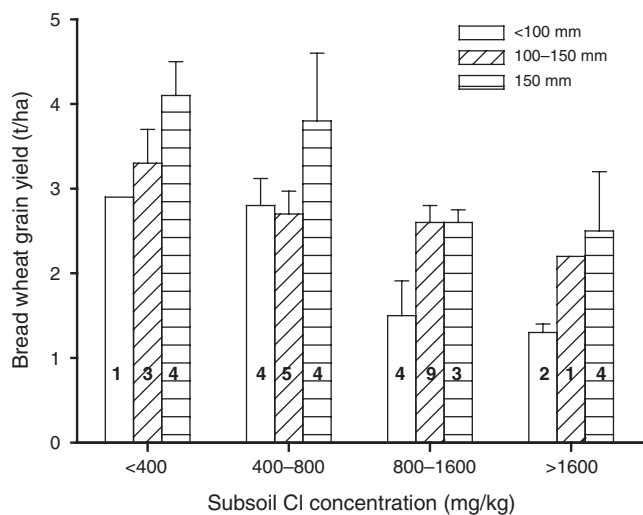


Fig. 3. Effects of subsoil CI concentration on average bread wheat grain yield as influenced by in-crop rainfall. Numbers within bars indicate the number of trials conducted.

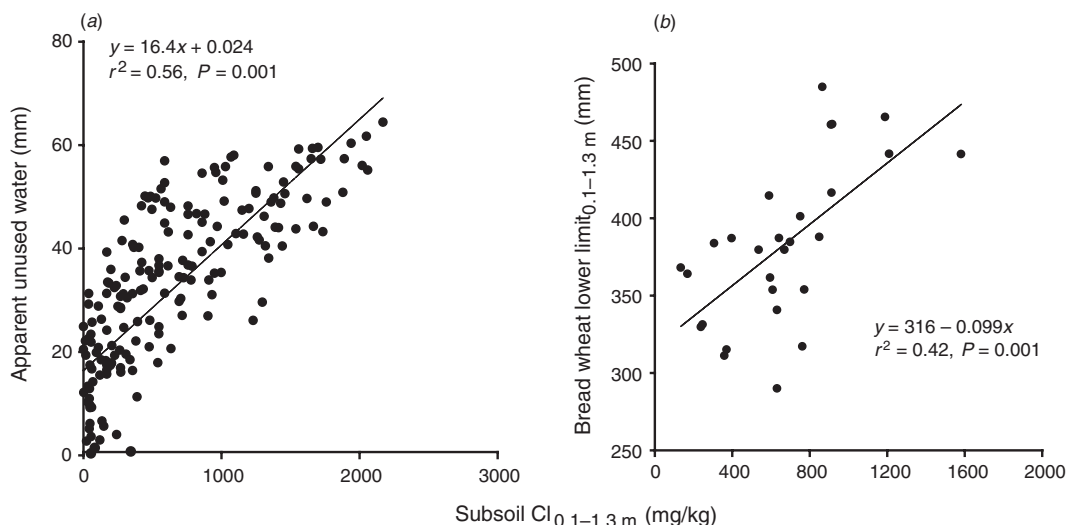


Fig. 4. Effects of subsoil CI concentration on bread wheat (a) apparent unused water and (b) lower limit of water extraction.

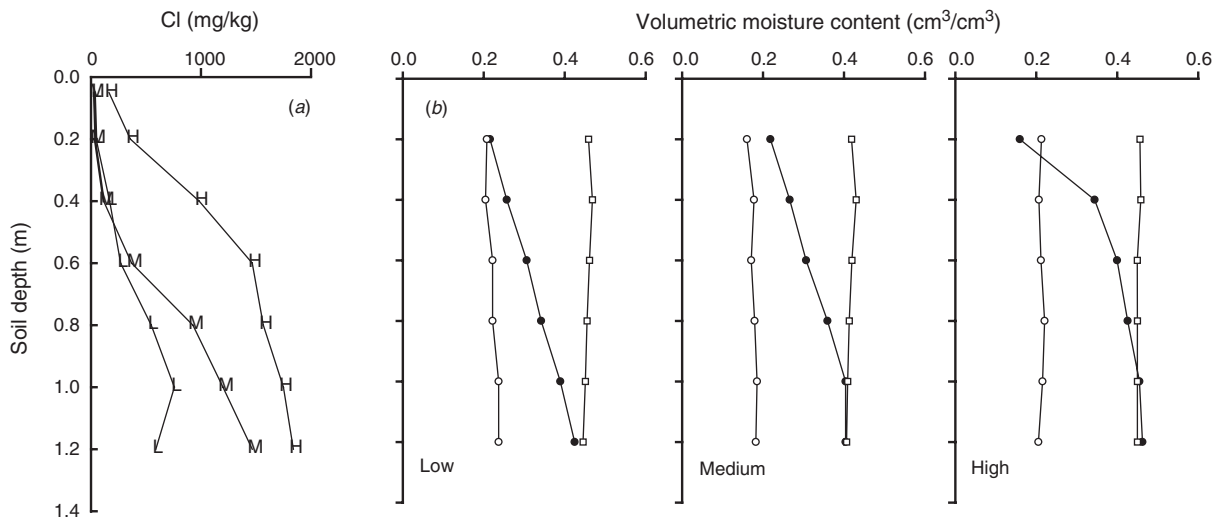


Fig. 5. Soil profile distribution of (a) low (L), medium (M), and high (H) Cl concentration and (b) patterns of soil water extraction of bread wheat (●) and LL15 (○) and starting water (□) on low, medium, and high Cl Vertosols.

water extraction by bread wheat (Fig. 5b) grown on low, medium, and high Cl soil profiles showed that wheat grown at the relatively low subsoil Cl site was able to extract water down to 1.20–1.30 m depth. At the medium subsoil Cl site, mean maximum depth of water extraction was 1.10–1.20 m, whereas at the high subsoil Cl site, mean maximum depth of water extraction was reduced to 1.00 m. The reduced depth of water extraction resulted in increased apparent unused water, hence reduced PAWC and grain yield. For example, for bread wheat grown at the relatively low, medium, and high Cl sites, apparent unused water was 120, 180, and 205 mm, respectively. The resultant wheat grain yields were 2.58, 2.08, and 1.26 t/ha, respectively. Similar results were obtained for durum wheat, chickpea, barley, and canola (data not shown).

The APSIM simulation also showed that subsoil constraints accounted for 82% of the observed variability in wheat grain yield with a RMSD of 0.5 t/ha (Fig. 6). Inclusion of functions based on Cl, EC_{se} , or ESP to restrict root development (via the root expansion factor) did not improve the simulation results further, suggesting these are already accounted for by increasing CLL and thus reducing the PAWC (Hochman *et al.* 2007).

Extent of subsoil constraints

Regional mapping

The subsoil constraint maps available for the northern cropping region have an accuracy that reflects the scale of source data used, which in the project area ranges from 1:50 000 to 1:500 000. Because attribute surfaces are based on averages or estimates for each soil attribute within particular mapping units, they must be regarded as indicative only. Therefore, they are suitable only for regional scale estimates and not applicable at a 'paddock scale'.

A large proportion of the grain cropping region of Queensland is affected by subsoil constraints (Fig. 7). On the basis of the threshold values in 0–1.30 m soil depth ($ESP > 15$, $EC_{se} > 6$ dS/m, $Cl > 600$ mg/kg soil), we estimated that 62% of the cropped land in Queensland is affected by 1 or more of those

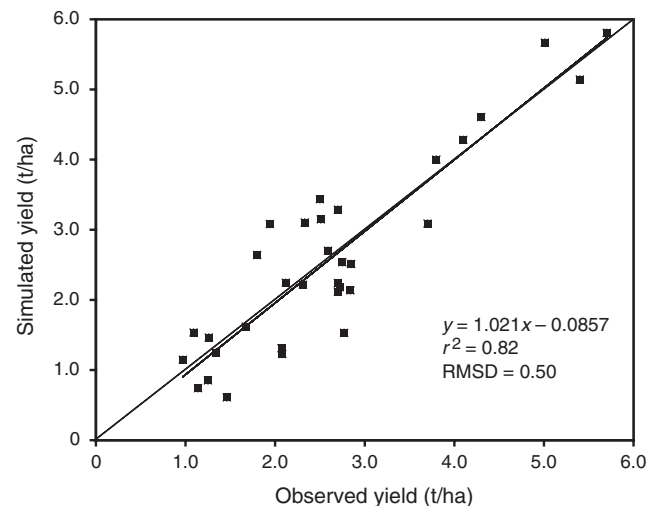


Fig. 6. Simulated and observed wheat yields at 33 sites with various levels of EC, Cl, and exchangeable Na and ESP in the northern grains region using CLL to account for the impact of the subsoil constraint (reproduced from Hochman *et al.* 2007).

3 subsoil constraints. For Cl concentrations, 20% of the cropped land had Cl levels > 600 and ≤ 1000 mg/kg, and a further 26% had > 1000 mg Cl/kg in subsoil. The main sources of salts and in particular Cl accumulation in the landscape are considered to be parent material and rainfall (SalCon 1997), along with the use of groundwater containing mainly sodium bicarbonate for irrigation (Cassidy 1971). Transpiration through vegetation concentrates salts in root-zone. Since the evaporative demand is 3–5 times higher than precipitation, soil dries from the top down, resulting in little leaching of salts below root-zone (Shaw 1997), and hence in high concentrations of salts in the region. The mapped spatial distribution of subsoil acidity ($pH < 5.5$) and alkalinity ($pH > 8.5$) represented 9% and 26%, respectively, of the cropping region. A significant proportion of cropping land in

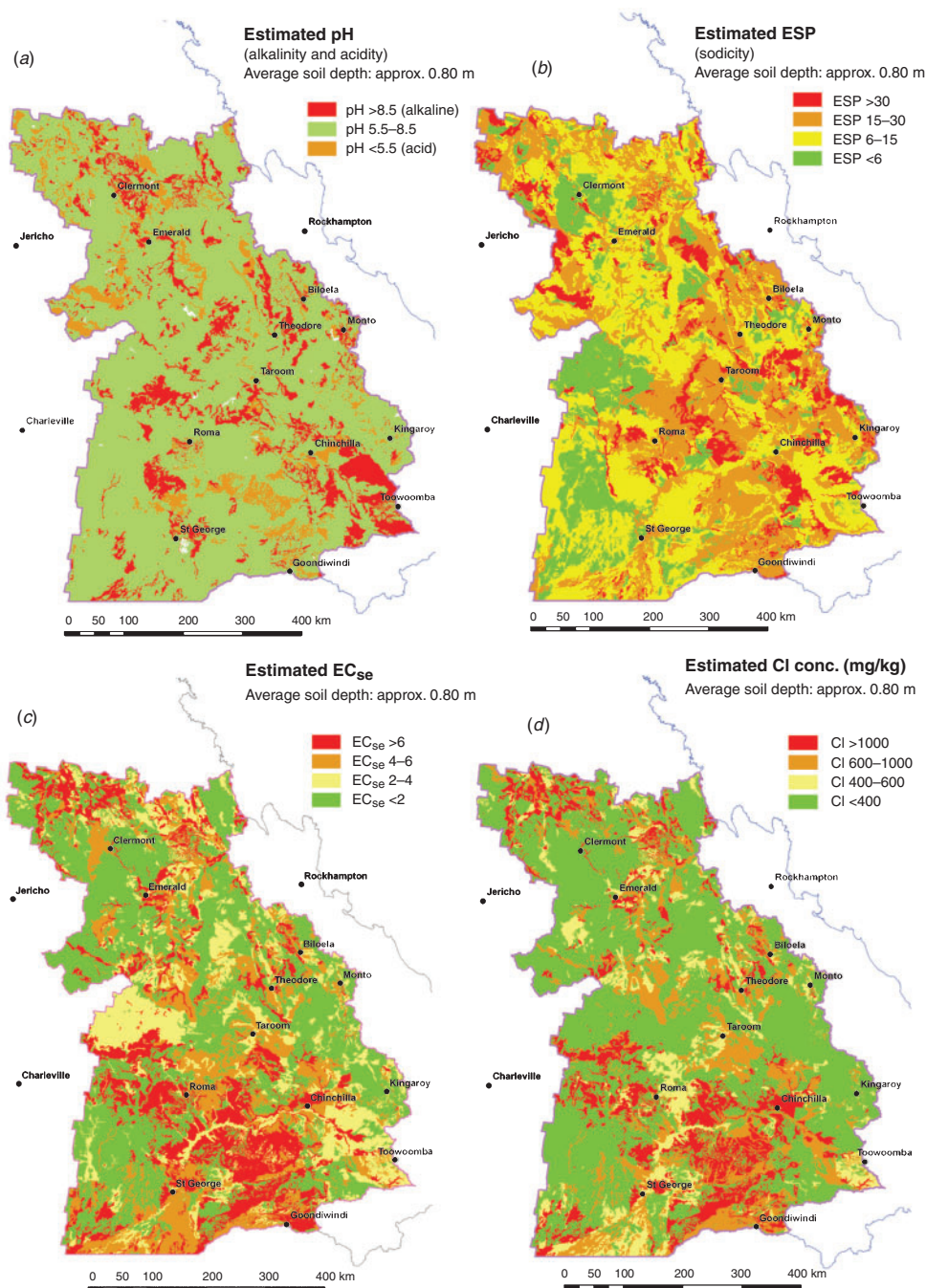


Fig. 7. Estimated distribution of (a) pH (subsoil acidity and alkalinity), (b) ESP (subsoil sodicity), (c) EC_{se} (subsoil salinity), and (d) subsoil Cl concentration, in the northern grains region of Queensland.

Queensland is established on clay soils that formerly supported forests of brigalow (*Acacia harpophylla*). Although these soils are normally alkaline in their upper levels, they are almost invariably strongly acid in the deeper subsoil (Isbell 1962).

Farm or paddock-scale mapping

The apparent electrical conductivity (EC_a) of soil profile was significantly correlated with weighted mean volumetric soil

water content, clay content, EC_{se}, and Cl for all 4 sites in this study (Table 2). The Cl concentrations were better correlated with EC_a than with EC_{se} values and EC_{1:5} values in the soil profile. Step-wise regression analysis indicated that soil Cl and volumetric soil moisture contents accounted for 83–93% of the variation in the EC_a in 3 of the 4 sites (Table 3). Step-wise regression for combined values of 4 sites indicated that EC_a was a function of soil Cl concentration and volumetric moisture

Table 2. Coefficient of determination (r^2) of selected soil properties with EC_a values at 4 locations in southern Queensland

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; n.s., not significant; θ_v , available water (cm^3/cm^3); Cl, soil chloride concentration (mg/kg); $EC_{1:5}$, electrical conductivity in 1:5 soil:water solution; EC_{se} , electrical conductivity of saturated extract

EC_a :	Site 1	Site 2	Site 3	Site 4
$EC_{1:5}$ (dS/m)	0.25*	0.39*	n.s.	n.s.
EC_{se} (dS/m)	0.36*	0.34*	0.25*	0.21*
Cl (mg/kg)	0.51**	0.36**	0.59***	0.34*
Clay (%)	0.29*	0.80***	0.78***	0.48**
θ_v (cm^3/cm^3)	0.36*	0.94***	0.63***	0.61***

contents. There are many reports of strong relationships between soil moisture and EC_a (e.g. Kachanowski *et al.* 1988; Hedley *et al.* 2004).

We also examined the feasibility of using EM38 coupled with yield maps and remotely sensed NDVI images to identify areas with possible subsoil constraints (Fig. 8). High-yielding areas (bottom right hand corner, Fig. 8a) on the yield map tended to match with low EC_a values (Fig. 8b) and also with more actively growing vegetation, as indicated by dark green areas in NDVI map (Fig. 8c). Low-yielding areas on the yield map had significantly higher concentrations of Cl in soil profile. The distribution of Cl in 0–1.50 m soil profile was 328–1660 mg Cl/kg in low-yielding areas and 12–550 mg Cl/kg in high-yielding areas. Wheat grain yield had a negative linear relationship with EC_a ($R^2 = 0.17$, $P < 0.01$), whereas NDVI values had a positive linear relationship with the wheat grain yield ($R^2 = 0.59$, $P < 0.001$). At the paddock or farm scale, EM surveys, yield maps, aerial photographs, and remote sensing for

Table 3. Step-wise multiple regressions relating soil properties and EC_a values at 4 locations in southern Queensland

θ_v , Available water at sowing (cm^3/cm^3); Cl, soil chloride concentration (mg/kg); $EC_{1:5}$, electrical conductivity in 1:5 soil:water solution

EC_a (mS/m) EM site 1	$= -100.2 + 0.149 \text{ Cl} + 1170 \theta_v - 4.4 \text{ Clay}$ $R^2 = 0.65$; $P = 0.001$; s.e. = 26.1, $n = 15$
EC_a (mS/m) EM site 2	$= -110.5 + 0.0048 \text{ Cl} + 801 \theta_v$ $R^2 = 0.93$; $P = 0.001$; s.e. = 11.8, $n = 15$
EC_a (mS/m) EM site 3	$= -69.2 + 0.1006 \text{ Cl} + 637 \theta_v$ $R^2 = 0.90$; $P = 0.001$; s.e. = 15.2, $n = 11$
EC_a (mS/m) EM site 4	$= -235.0 + 0.0365 \text{ Cl} + 1105 \theta_v$ $R^2 = 0.83$; $P = 0.001$; s.e. = 18.1, $n = 15$
EC_a (mS/m) all 4 EM sites	$= -130.4 + 0.0559 \text{ Cl} + 1053 \theta_v + 2.04 \text{ Clay}$ $R^2 = 0.80$; $P = 0.001$; s.e. = 22.5, $n = 56$

biomass (using NDVI data) can be used to delineate the areas of possible subsoil constraints for targeted soil sampling. However, ground-truthing by soil sampling and analysis at key sites is necessary to accurately define subsoil constraints (Dang *et al.* 2008b). For managing poor-performing areas of the paddock, test strips of potential management options needs to be evaluated for economic, environmental, and social issues (Robertson *et al.* 2007).

Economic impact of subsoil constraints

In general, the percent decrease in gross margins was higher for crops grown in Queensland than NSW, reflecting, in general, the impact of lower ICR and hence lower grain yields in the former. The percent decrease in gross margin followed the order: safflower < bread wheat < barley < durum = canola = faba bean. Grain legumes (excluding faba bean) suffered the greatest decline in gross margins (Table 4).

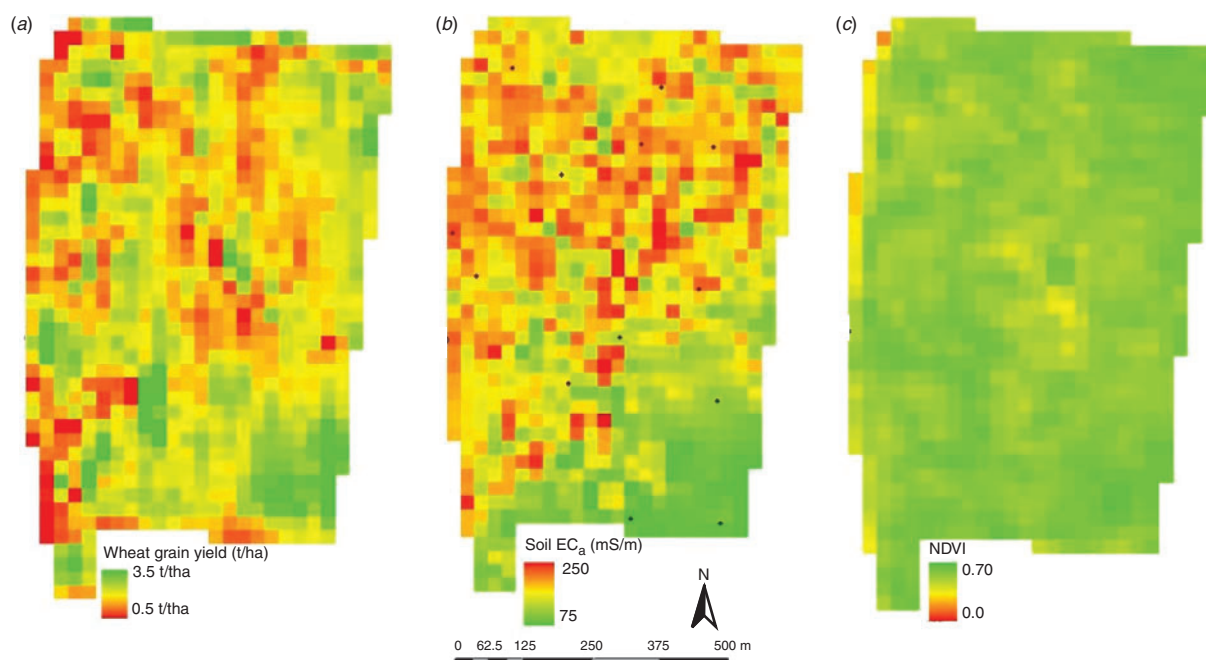


Fig. 8. Comparison of (a) wheat grain yield map with (b) EM38 map and (c) NDVI map derived from satellite imagery on 56-ha paddock in southern Queensland.

Table 4. Average gross margin (\$AU/ha) across all sites for the winter crops grown in the northern grains region
Low Cl sites, <600 mg Cl in 0.1–1.3 m soil depth; High Cl sites, >600 mg Cl/kg in 0.1–1.3 m soil depth

	New South Wales		Queensland	
	Low Cl	High Cl	Low Cl	High Cl
Barley	617 ± 47 (588–726)	506 ± 49 (464–577)	295 ± 29 (254–331)	145 ± 81 (73–239)
Bread wheat	466 ± 88 (358–599)	418 ± 52 (281–480)	301 ± 52 (198–354)	184 ± 102 (57–330)
Durum wheat	461 ± 37 (298–577)	304 ± 38 (224–362)	224 ± 44 (173–265)	88 ± 33 (57–117)
Chickpea	427 ± 47 (110–744)	139 ± 109 (29–270)	330 ± 123 (143–435)	78 ± 76 (–7–186)
Faba bean	519 ± 34 (227–812)	285 ± 62 (101–469)	–	–
Field pea	240 ± 78 (68–367)	84 ± 30 (5–173)	–	–
Canola	189 ± 86 (125–250)	141 ± 58 (92–190)	120 ± 6 (114–127)	24 ± 33 (–9–55)
Safflower	429 ± 82 (334–525)	387 ± 76 (182–593)	–	–

Management of subsoil constraints

Various options to manage subsoil constraints were evaluated, including plant adaptation through tolerant cultivars, cultural practices, chemical, mechanical treatments, and matching N-nutrition.

Plant adaptation

Subsoil constraints restrict the ability of roots to obtain water from soil, by increasing osmotic potential and Cl toxicity, and nutrient imbalances which all act to reduce rooting depths, resulting in reduced grain yield. We evaluated water extraction potential, maximum depth of water extraction, and grain yields of various winter and summer crop species. Since ICR was generally average to below-average at most trial sites during the course of this study, all the crops grown in our trials relied heavily on access to subsoil water.

Winter crop species

Water extraction potential of winter crop species varies greatly. Figure 9 shows the depth distribution in mean values of PAWC of 5 Vertosols with various combinations of subsoil constraints in southern Queensland. Of the 5 crops studied, bread wheat, barley, and canola had higher PAWC throughout the soil profile than durum wheat and chickpea. Average PAWC (0.10–1.30 m) for soils with various combinations of subsoil constraints varied for crop species: bread wheat 124 mm, canola 122 mm, barley 116 mm, durum wheat 98 mm, and chickpea 82 mm (l.s.d. $P=0.05$, 32.9).

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 subsoil constraints in the northern grains region than wheat (Whish *et al.* 2007). Differences in the tolerance of crop species to high subsoil Cl suggests that excluding sensitive crop species, such as durum wheat and legume crops especially chickpea and field pea, from crop rotations on these soils may be an effective way of mitigating negative impact of subsoil constraints.

Cultivars of different winter crop species also showed some minor differences in sensitivity to increasing concentrations of subsoil Cl (Schwenke 2007). Variation across sites was high; therefore, most wheat and barley varieties yields were not significantly different from cv. Baxter. Of the barley varieties,

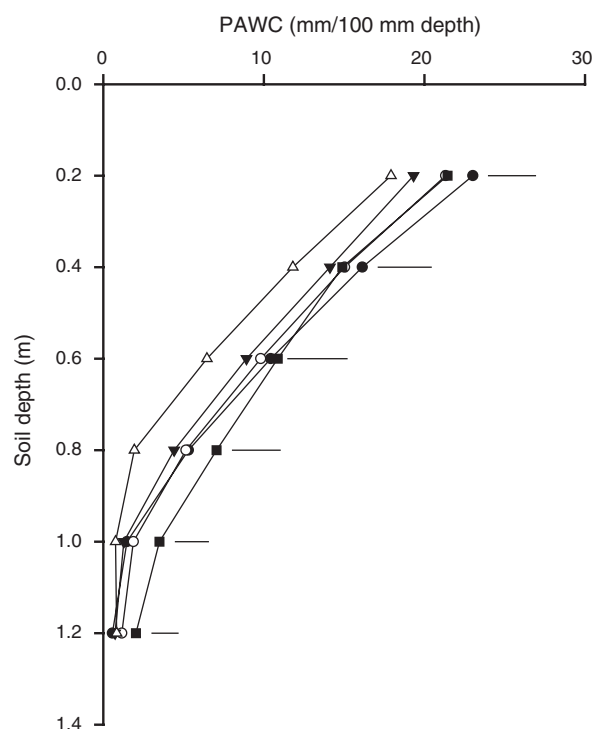


Fig. 9. Mean values of plant-available water capacity of the soil (PAWC) under bread wheat (●), barley (○), durum wheat (▼), chickpea (△), canola (■) grown during 2004 on 5 Vertosols in southern Queensland. Horizontal bars shows l.s.d. at $P=0.05$ (reproduced from Dang *et al.* 2006a).

cv. Binalong, cv. Fitzroy, and cv. Grout generally yielded more on soils with high to very high subsoil Cl than cv. Gairdner and cv. Mackay. Yield differences between high Cl and low Cl sites for other species were not consistent across the whole grains region, presumably due to confounding effects of ICR across the region.

Summer crops

Water extraction potential of summer crop species also varied. Of the 5 crops, maize and sorghum had higher PAWC in soil profile than sesame, millet, and mungbean (Fig. 10). Compared with other crops, the soil under mungbean and millet had lowest PAWC below 0.50 m depth. Average PAWC (0.10–1.30 m) for

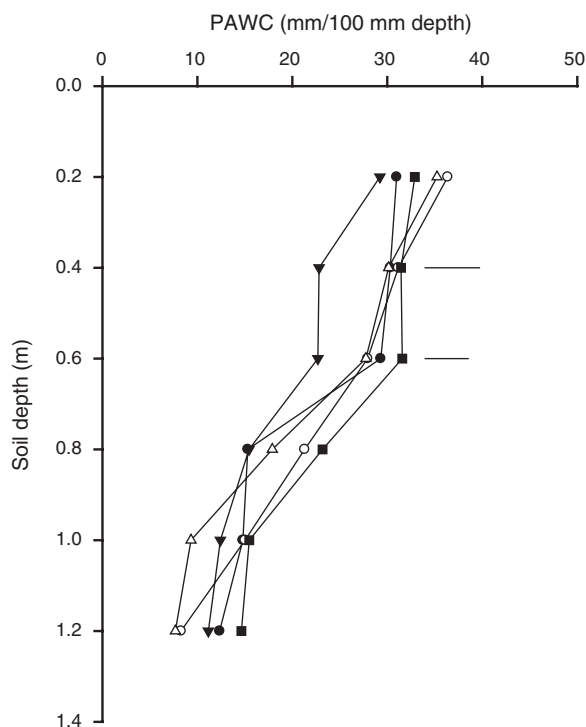


Fig. 10. Mean values of plant-available water capacity of the soil (PAWC) under sesame (●), sorghum (○), millet (▼), mungbean (△), and maize (■) grown during 2005–06 on 2 Vertosols in southern Queensland. Horizontal bars (where significant) shows l.s.d. at $P=0.05$.

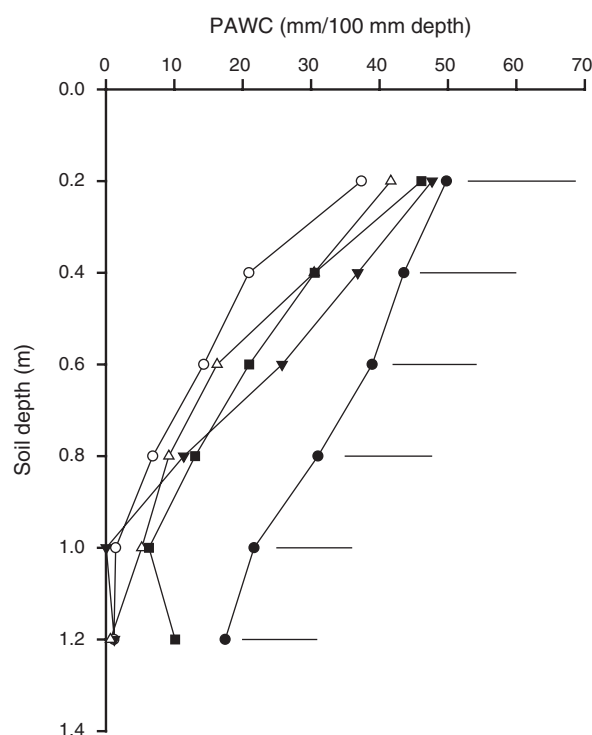


Fig. 11. Mean values of plant-available water capacity of the soil (PAWC) under lucerne (●), lablab (○), butterfly pea (▼), vigna (△), and burgundy bean (■) grown on moderate to high subsoil constrained site during 2004 in southern Queensland. Horizontal bars shows l.s.d. at $P=0.05$.

soils with various combinations of subsoil constraints varied for crop species: maize 149 mm, sorghum 140 mm, sesame 133 mm, mungbean 128 mm, and millet 125 mm (l.s.d. $P=0.05$, not significant). Cultivars of sorghum showed some differences in sensitivity to increasing concentrations of subsoil Cl. Of the 8 cultivars, the percent decrease in the grain yield was higher for cvv. MR 43, Bonus, and 80G08 than Venture, Maxi, Dominator and Buster (Y. P. Dang, B. O’Mara and D. Orange, unpubl. data)

Pasture and forage species

Compared with grain crops, salt tolerant pasture, forage, and fodder crops have been shown to be more successful in increasing ground cover, soil water use, and plant biomass in highly constrained subsoil areas of southern Queensland. Results from a trial conducted on a high Cl (1100 mg Cl/kg in 0.90–1.10 m soil depth) Vertosol in southern Queensland showed lucerne was more effective in extracting soil moisture from deeper subsoil than other legumes, including burgundy bean, perennial lablab, butterfly pea, and *Vigna* species, which showed no significant differences between them (Fig. 11).

Soil amendments

Gypsum

Surface application of gypsum at 2.5–5.0 t/ha significantly improved wheat grain yield on sites with surface soil (0–0.10 m) ESP 8.9 and 12.5 in southern Queensland and NSW (Table 5). ESP >6% is used to define sodic soil (Northcote

Table 5. Effect of surface-applied gypsum on grain yield (kg/ha) of wheat cv. Baxter

Values within a row followed by same letter are not significantly different ($P=0.05$). SQ, Southern Queensland; CQ, central Queensland; NSW, New South Wales; percent response, (grain yield with gypsum – grain yield without gypsum)/grain yield without gypsum

	ESP (0–0.10 m)	No gypsum	Gypsum 2.5 t/ha	Gypsum 5.0 t/ha	Percent response
Site 1 (SQ)	12.5	1447a	1736b	1736b	19.9
Site 2 (SQ)	8.9	1575a	1728b	1730b	9.8
Site 3 (SQ)	5.6	2073a	2109a		1.7
Site 4 (SQ)	4.6	1681a	1752a	1648a	4.2
Site 5 (SQ)	3.2	2082a	2105a	2073a	1.1
Site 6 (CQ)	3.0	880a	902a		3.0
Site 7 (CQ)	3.0	1400a	1613b		15.0
Site 8 (NSW)	0.8	2200a	2200a		0.0
Site 9 (NSW)	4.1	3330a	3310a		0.0

and Skene 1972), and the response to gypsum application in such soils in this study is consistent with earlier studies (McKenzie and So 1989). However, one site in central Queensland with ESP 3% in the 0–0.10 m soil also showed significant increases in wheat grain yield following application of gypsum. This could be due to the fact that the surface soil (0–0.10) had 40.1% exchangeable magnesium percentage (EMgP). The effect of Na on dispersion can be exacerbated

Table 6. Effect of gypsum and deep ripping on grain yields (kg/ha) at 3 sites

Values within a column followed by same letter are not significantly different ($P=0.05$). Site 4, Southern Queensland, ESP (0–0.10 m), 4.6; ESP (0.1–0.3 m), 8.9. Site 6, Central Queensland, ESP (0–0.10 m), 3.0; ESP (0.10–0.30 m), 7.0. Site 9, North-west NSW, ESP (0–0.10 m), 4.1; ESP (0.10–0.30 m), 8.2

	Site 4		Site 6			Site 9
	Wheat 2005	Chickpea 2007	Wheat 2008	Wheat 2005	Wheat 2006	Wheat 2005
Control	2192a	1054a	2511a	880a	1400a	3330a
Gypsum 2.5 t/ha (surface)	2208a	1515b	3061b	902a	1613b	3170a
Ripping only (0.20–0.30 m)	2352a	1413ab	3046a	1178a	1494ab	3550a
Ripping + gypsum 2.5 t/ha	2459a	1500b	3113a	1107a	1650b	3340a
l.s.d. ($P=0.05$)	NS	380	432	n.s.	162	195

by the presence of an excessive EMgP (>25%) (Bakker *et al.* 1973); however, the action of Mg may be apparent until the ESP reaches a value of 12, beyond which the effect of Na becomes dominant.

In another 3 trials comparing gypsum application at surface and subsurface depths, application of gypsum at 2.5 t/ha did not significantly increase wheat grain yield in first year of its application. However, 1 year after gypsum application in central Queensland and 2 years after in southern Queensland, both surface and subsurface applied gypsum significantly increased wheat grain yields (Table 6). This could be because gypsum has very low solubility (15 mM, 2.5 g/L). For dissolving 2.5 t/ha of gypsum, it would require 1.0 ML water, i.e. 100 mm of rain. The dissolution of gypsum will further depend upon the particle size and exchangeable Na contents of soil (Hira and Singh 1980). Ripping alone did not significantly affect grain yield.

Lime and gypsum

One trial conducted in southern Queensland showed that a lime + gypsum treatment had no effect on wheat grain yield (data not shown). Gypsum plus lime amendment has been shown to improve soil structural stability for a longer period of time than gypsum alone in soils with near neutral or acidic pH (Valzano *et al.* 2001). Valzano *et al.* (2001) suggested that gypsum acts as a useful source of Ca^{2+} during early stages after application and its slight acidifying effect improved dissolution rate of lime to supply Ca^{2+} for a longer period of time than gypsum alone.

Nutrition

Application of both P and Zn in general resulted in increased grain yield for various crop species including wheat, chickpea, barley, canola, and faba bean in both low and high subsoil Cl sites (data not shown). However, percent increase in grain yields of various crops when P + Zn were applied on a high subsoil Cl soil was higher than that on a soil with a low concentration of subsoil Cl, suggesting that improved nutrition helps to alleviate negative impact of high subsoil Cl through nutrient interactions (Singh *et al.* 2006). Supplementary P, Zn, and potassium (K) nutrition has been widely reported to mitigate adverse effects of high salinity on both fruit and grain crop yield and whole plant biomass for various crop plants (Marschner 1995).

Table 7. Optimal N input levels and potential saving by using optimal N decision for a very high subsoil constraint soil

Location and SSC level	Optimal total N (kg/ha)	N applied (kg/ha)	Gross wheat income when N applied at optimal amount (\$/ha)	Potential saving by matching N in presence of high subsoil Cl (\$/ha)
<i>Goondiwindi</i>				
Low SSC	120	87	379	
Mild SSC	120	85	371	
High SSC	120	79	328	
Very high SSC	60	37	180	13
<i>Emerald</i>				
Low SSC	90	59	222	
Mild SSC	90	58	216	
High SSC	60	41	181	
Very high SSC	30	17	100	27

Matching N-input

The results reported here are simulated for a hypothetical situation and must be regarded as indicative only. Estimates of potential saving that could be made by fertilising a very high subsoil Cl soil with an optimal amount of N, rather than the amount that would be optimal for a mild subsoil Cl soil, were \$AU13 and \$27/ha for Goondiwindi and Emerald, respectively (Table 7). Using these values and known areal extents of very high subsoil Cl soil type, the potential saving would be in the order of \$6.6 million and \$2.0 million for Goondiwindi and Emerald districts, respectively.

Conclusions

Single or multiple factors of subsoil constraints are present in many cropping soils of the northern grains region. The identification of the most limiting subsoil constraint and its interaction with other factors is first step in planning a sustainable cropping system. EM38 maps together with historical yield maps may offer more affordable opportunities to identify suspected subsoil constraints at paddock or farm scale; however, ground-truthing is necessary.

The primary impact of variable subsoil constraints was to increase CLL, thereby reducing PAWC and grain yield. Thus, for calculating input requirements of a crop, realistic yield potential needs to be determined, considering yield losses due to the presence of unused water. High concentration of Cl in subsoil was identified as the key indicator of subsoil constraints in the northern grains region. Results suggest that growing legume crops such as chickpea and field pea should be avoided on soil with subsoil Cl >600 mg/kg. In the presence of high to very high subsoil Cl, most cereal and oilseed crops would incur yield penalties depending upon season and ICR. In the presence of very high subsoil Cl, alternate land use such as pastures, forage, or agro-forestry may be more profitable and sustainable but need to be investigated further.

Challenges ahead

Management of subsoil constraints requires a cost-effective platform to detect the presence of subsoil constraints. Proximal sensing using the EM38 appears to offer this at the field scale. Nevertheless, the EM38 remains non-discriminating. EM values appear to match with the total concentration of salts in the soil solution; where the field is relatively homogeneous apart from the salt in question (such as Cl⁻), the technique may provide very useful surrogate data. Further assessment is required to examine if standard calibrations can be used based on clay content and/or moisture. Multi-year yield maps offer a secondary source of spatial data at the field scale. Areas in these maps which vary to a considerable degree, using a temporal coefficient of variation scale, between good and poor years may be highly correlated with the presence of subsoil constraints. However, this technique requires a history of yield-mapping or NDVI imagery along with sophisticated spatial analysis.

Second, further work is needed on the challenge of how to manage and/or ameliorate subsoil constraints in the current farming system. It is still unclear whether gypsum amendments to soil other than ESP >6 in the top 0.1 m depth are yield-enhancing in the northern grains region.

Third, existing cropping models should be adapted to incorporate subsoil constraints into their soil-crop modules. Field data and simulation then form a sound basis for providing growers and advisors with evidence-based decision support systems for managing subsoil constraints economically and with environmentally sustainable practices.

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