

# Sustainable expansion of irrigated agriculture and horticulture in Northern Adelaide Corridor: Task 1 - baseline soil properties

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Goyder Institute for Water Research  
Technical Report Series No. 19/14



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### Citation

Oliver, D.P., Forouzangohar, M., Johnston, C., Ouzman, J., and Barry, K. (2019) *Sustainable expansion of irrigated agriculture and horticulture in Northern Adelaide Corridor: Task 1 – baseline soil properties*. Goyder Institute for Water Research Technical Report Series No. 19/14, Adelaide, South Australia.

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## Executive summary

Adelaide's Northern Corridor is under consideration for expansion of irrigated horticulture following the planned extension of the Virginia pipeline scheme delivering 'Class A' recycled water to the region. In the case of irrigated horticulture, any expansion should be preceded by a compilation of baseline information about the various resources (including soils and water sources) underpinning the planned development. To do this, the range of existing soil conditions, and water sources of different qualities, were investigated and various impact scenarios modelled to establish the likely sustainability of irrigating different soil-crop combinations in the proposed region of expansion in the Northern Adelaide Plains (NAP). The overall aim of the project was to use modelling to identify irrigation scenarios that may potentially limit the long-term viability of irrigated agriculture in the region and identify issues of concern, such as possible limiting soil constraints, before the expansion occurs. This will allow informed management decisions to ameliorate any soil and water constraints prior to the commencement of irrigation.

The aim of this report for Task 1 was to determine baseline soil physical and chemical properties to be used in the impact modelling undertaken in Task 2.

The current irrigation region is focussed around the township of Virginia. The region for expansion of irrigated agriculture was still being finalised at the time of the soil collection but is expected to be north of Two Wells. For the purposes of soil sample collection, a focus area was defined extending north of Two Wells to the Light River and east towards Boundary Rd. Soil samples were collected from seven soil pits (NAP 1-7) and from thirteen hand-augered cores (NAP 8-20). Soils were collected at the depths of: 0-10 cm, 10-30 cm, 30-60 cm, 60-90 cm and, where possible, 90-120 cm. Historical soil samples (CL014, CL015 and CL050), previously collected for soil classification in the region, were also included in the analyses. In addition to direct analysis of chemical and physical soil properties, a novel methodology based on infra-red (IR) spectroscopy scanning was developed for rapid determination of soil properties. The validated IR technique has been used for predicting physical and chemical properties in the sampled soils. This approach was validated against 'wet chemistry' analysis of a subset of the soil samples and enabled the large study area to be covered with limited resources. Selection of the subset for validation of the IR data was based on the IR spectra obtained from scanning all the soils. The following physical properties of soils were determined using IR predictions: saturated hydraulic conductivity (Ks) and water retention at a range of matric potentials. The chemical properties determined using IR predictions were: total carbon (TC) (%), organic carbon (OC) (%), total nitrogen (N) (%), ammonium (NH<sub>4</sub>-N) (mg/kg), particle size (%), calcium carbonate (CaCO<sub>3</sub>) (%), exchangeable calcium (Ca<sup>2+</sup>) (cmol(+)/kg), exchangeable magnesium (Mg<sup>2+</sup>) (cmol(+)/kg), exchangeable sodium (Na<sup>+</sup>) (cmol(+)/kg), exchangeable potassium (K<sup>+</sup>) (cmol(+)/kg) and cation exchange capacity (CEC) (cmol(+)/kg). From the exchangeable cations data the exchangeable sodium percentage (ESP %) was determined as an indicator of soil sodicity.

It was not possible to use the IR technique for all chemical properties. Soil pH and electrical conductivity (EC) measurements were made on all soils at all depths and boron (B) concentrations were measured in soils from 0-10 cm, 10-30 cm and 30-60 cm depths. The findings for the major soil properties that are likely to be impacted by long-term irrigation with recycled water or may limit the sustainability and longevity of the expansion of irrigated agriculture in the region, are discussed below.

### **Soil pH**

Soil pH is one of the most important determinants of soil fertility. Different crops have different optimum pH ranges for growth and generally the ideal pH range for plant growth is between 5.5 and 8, and for most vegetables it is  $pH_w$  (1:5 water) 5 to 7. Twenty-three percent of the surface NAP soils (0-10 cm, 10-30 cm and 30-60 cm) analysed had  $pH_w < 8.0$  and 77% had  $pH_w \geq 8$ ; generally,  $pH_w$  increased with depth. Soil  $pH_w > 8.5$  are considered highly alkaline and 52% of the NAP surface soils sampled had  $pH_w > 8.5$ . In the NAP the main concern with regard to pH, is that many of the soils are slightly to highly alkaline and micronutrients required for crop growth (i.e. iron Fe, manganese Mn, copper Cu, zinc Zn) may be unavailable for plant uptake and may need to be supplemented to prevent deficiencies. The addition of micronutrient fertilisers is a current management practice for cereal production in the NAP region. Furthermore, in highly alkaline soils, the concentration of aluminium (Al) and boron (B) in soil solution can increase to levels that may be limiting or toxic for crop growth. Soil management options may need to be implemented for the extremely alkaline soils to provide micronutrients to crops and/or to lower soil pH.

### **Boron (B)**

Boron (B) is a micronutrient that is required by plants in small quantities (<500 g/ha) but it has a narrow concentration range between plant deficiency and toxicity. To better represent the soil solution and environment that plant roots would be exposed to, B was measured in soil solution at maximum water holding capacity, in surface soils only (0-10 cm, 10-30 cm and 30-60 cm). The B in soil solution was < 0.5 mg/L in 72% of surface soils, between 1-2 mg/L in 13% of soils and >2 mg/L in 8% of the soils investigated. It has been suggested that soil solution B concentrations < 0.5 mg/L are not toxic for most plants, but above this value many plants may be adversely impacted. Several of the crops being considered for production in the NAP are sensitive to B (e.g. grape, onion, carrot, potato) and this data suggests that the native (geogenic) B in some of the soils in the region may already be at concentrations that are limiting or toxic to crop growth before any irrigation commences. No relationship could be found between soil group and high soil solution B concentrations but there was a general trend of higher soil solution B concentrations at all depths occurring in two sub-groups of the main soil group, Hard red brown texture contrast soils, namely Loam over red clay and Loam over poorly structured red clay. However, the sample size for the soil sub-groups was small ( $n \leq 3$ ), which made it difficult to determine whether this could be used as a predictor of high native B in soils. While other soil properties, that may be more easily measured, were considered as predictors of high native B in soils, no relationship could be found between soil solution B and the properties considered in this study.

A potential problem in the NAP region is the release of native or geogenic B into solution in areas where a perched water table may prevent B being leached out of the soil root zone. As the surface soil is subjected to wetting-drying cycles involving downward (drainage) and upward (capillary rise) water fluxes, any chemicals in solution including B and soluble salts, located deeper in the profile just below the root zone, may move back into the root zone as a result of capillary rise.

To assess the release of native B into soil solution in a scenario representative of multiple applications of irrigation water, B was sequentially extracted four times from a subset of soils. The extraction solution had a high chloride (Cl<sup>-</sup>) content that represented the Cl<sup>-</sup> concentration found in recycled waste water. This easily extractable B fraction ranged from 19-48% of the total B (mg/kg) within the soils assessed. This data would suggest that with successive extractions, the B in these soils would continue to be mobilised into solution with each irrigation event. This fraction would potentially be available for plant uptake or transport through the soil profile to groundwater. A subset of the soils were also extracted with a low Cl<sup>-</sup> solution and the amount of B released was nearly identical to that obtained with the high Cl<sup>-</sup> solution. It should also be noted that the irrigation water is also an additional source of B.

The soil solution B measurement used in this study may not be commercially available. Consequently, a comparison was made between the commercial measurement (hot 0.01 M calcium chloride (CaCl<sub>2</sub>) extract) and the soil solution B measurement: a strong linear relationship was found between the two measurements.

### **Soil Salinity (EC)**

Several crops are being considered to be grown in the expansion area of the NAP. These include almonds, grapes, onions, potato, bean, carrot and lettuce, all of which are classified with a very low to low soil salinity tolerance rating (saturated paste electrical conductivity: EC<sub>se</sub> < 1.9 dS/m). This classification corresponds to an estimated 10% yield reduction based on published yield response models. Of the soils sampled in this study a yield reduction of 10% for these crops would be expected in 82% of the 0-10 cm depth, 73% of 10-30 cm depth and 94% of the 30–60 cm depth. Further, in the 60-90 cm depth 17% of the soils surveyed would be considered too saline for crop growth (EC<sub>se</sub> > 12.2 dS/m) based on a published classification system for salinity tolerance ratings and yield response models. The impact of soil salinity in the surface soils, however, could be moderated by irrigation management and flushing soluble salts out of the root zone prior to planting, during the growing season or between seasons. The potential impact of an impermeable sub-surface at shallow depth should be considered due to the risk of soluble salts moving back into the root zone as water rises due to capillarity in response to plant transpiration and soil evaporation.

### **Sodicity (exchangeable sodium percentage ESP%)**

In the soils surveyed sodicity increased with increasing depth: 36% of 0-10 cm soils were sodic and 3% highly sodic; 49% of 10-30 cm soils were sodic and 35% highly sodic; and 19% of 30-60 cm soils were sodic and 72% highly sodic. However, the problems of clay dispersion and swelling only arise when the EC value is too low

to maintain the soil clay in a flocculated condition at a given ESP value. An existing classification scheme for the prediction of dispersive behaviour in A horizons of red-brown earth soils, was applied to all the surveyed soils as a guide for determining the proportion of the soils sampled that may potentially be sodic.

In the 0-10 cm depth interval, the majority of soils surveyed were classified as potentially dispersive soils (Class 2A or 2B). Deeper in the profile (10-30, 30-60 and 60-90 cm) the ESP% and salinity (EC) increased and a greater proportion of the soils were categorised as dispersive soils (Class 1). Horticultural practices may require the soil to be worked to a greater extent or frequency than currently occurs under the present agricultural activities of cereal production or pasture, and under the landuse change to horticulture the soil may experience greater mechanical stress. The implications of this potential increased mechanical stress could potentially lead to a greater incidence of soil physical deterioration which could lead to a reduction in infiltration, water logging, etc. Soil sodicity can be managed with applications of gypsum, and various forms of compost, which is a current practice in the existing horticulture area in Virginia.

The expansion of irrigated agriculture in the region, north of the current horticultural production area in Virginia, is an opportunity for South Australia to provide the growing demand for premium food and agribusiness products. However, prior to any expansion occurring, further baseline soil analyses would be required to identify and, as required, remediate any soil constraints to ensure sustainability of the region. While this study has delivered an unprecedented set of valuable soil data, the heterogeneity in soil properties makes it difficult to extrapolate the current results based on a relatively small number of samples to the entire NAP region. Where new agriculture developments are planned, site-specific soil investigations are encouraged as these would provide the best information for decision making. The outputs from Task 1 can serve as a guide as to which risk parameters to focus on and what the most cost-effective tools are for data collection.

Soil data from this project will be available for integration within existing South Australian data repositories.

## Acknowledgments

This research was funded jointly by the Goyder Institute for Water Research and CSIRO Land and Water. We are grateful to the landholders in the proposed Northern Adelaide Plains (NAP) expansion region that participated in this project by allowing us to sample soil on their properties. Thanks also to Brian Hughes, PIRSA, for allowing sampling from soil pits at sites NAP1-7. The assistance of Dirk Mallants, Vinod Phogat, Nigel Fleming, Melanie Kah, Matt Wilson and Will Kemp during the soil sampling was greatly appreciated. The reviewers are also thanked for their constructive comments that greatly improved the quality of this report. Dr Joanne Vanderzalm is thanked for her assistance with the final formatting of the report.

# 1 Introduction

Adelaide's Northern Corridor is under consideration for expansion of irrigated horticulture following the planned extension of the pipeline delivering recycled water in the region. However, in the case of irrigated horticulture, any expansion should be preceded by compilation of information about the resources in the area, and options for development carefully considered. To do this, the range of existing soil conditions and water sources of different qualities need to be considered and various scenarios modelled to establish the likely sustainability of irrigating different locations in the proposed region of expansion in the Northern Adelaide Plains (NAP). The Goyder Institute for Water Research instigated a stocktake of the water resources, both quantity and quality, on the NAP that could be made available for economic development in the region in the short-term (Goyder Institute for Water Research, 2016).

Determining which options to implement is complicated by numerous factors, including:

- (i) various potential options in relation to agricultural production, such as protected cropping, broadacre agriculture and intensive livestock, and the water supply options that are available and best suited to these;
- (ii) potentially competing uses for available land; and
- (iii) potential environmental and social impacts.

In addition, there are several gaps in underlying knowledge that need to be filled in order to enable decisions to be made in an informed manner including a lack of knowledge of:

- (i) current soil attributes;
- (ii) the impact of water from different sources / of different quality on water-soil biochemical interactions;
- (iii) the fate of nutrients from different sources / of different quality on long-term soil health and receiving waters; and
- (iv) the amount of water of different quality that can be supplied at different times of the year.

This project considered a range of existing soil conditions and water sources of different qualities and model various scenarios to establish the potential sustainability of irrigating different locations in the proposed region of expansion in the NAP. The modelling aims to identify any locations or irrigation scenarios that may potentially limit the long-term viability of irrigated agriculture in the region and identify areas of concern (from an agronomic and/or environmental viewpoint) before the expansion occurs. The area under consideration for expansion of irrigated agriculture is in the Adelaide Plains Council, and it has recently been used for dryland cropping, predominantly wheat, barley, canola and pulses (Brian Hughes, PIRSA, pers. comm.). This area has a significantly lower grain yield potential than the rest of the Lower North district (council areas Adelaide Plains, Light and Barossa Councils) (Michael Wurst, PIRSA, pers. comm.). Due to a combination of lower rainfall and soil type, the NAP area would be estimated to yield approximately 70% of

the Lower North district average. The 5 and 10 year average wheat yield in the NAP area has been estimated by PIRSA to be 2.4 t/ha and 2.3 t/ha, respectively. This is in comparison to the 5 and 10 year average wheat yield for the Lower North District as a whole, which is 3.4 t/ha and 3.25 t/ha, respectively (Michael Wurst, PIRSA, pers. comm.). Furthermore, the north-west part of the NAP area has lower rainfall and highly calcareous sandy loam soil, which is less productive than the soils in the majority of the Lower North district. Therefore, the estimated grain yield production in this area could be less than 2 t/ha (Michael Wurst, PIRSA, pers. comm.). This would suggest that while expansion of irrigation into the region north of Two Wells would address the yield constraint of low rainfall, the soil constraint issues may still exist and need to be managed.

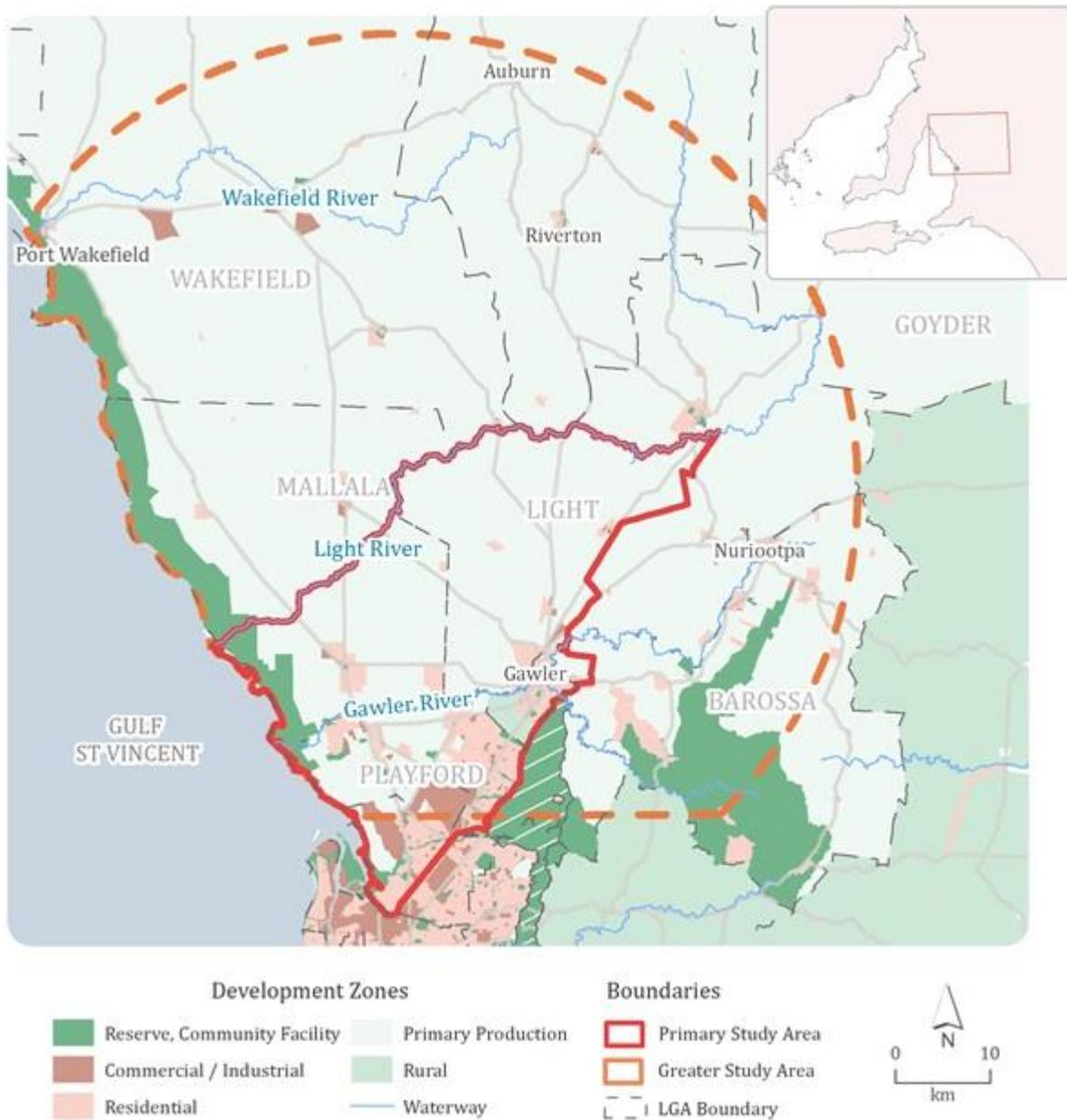
The aim of this project task, 'Task 1 Development and optimisation of modelling domain and impact assessment of irrigation expansion on the receiving environment', was to develop baseline soil physical and chemical properties to be used in the Hydrus modelling planned in Task 2. Task 2 will then assess the likely long-term impacts of irrigation in different regions with irrigation water of different qualities. This report summarises the soils data collected across the focus area for the study and discusses any potential issues with respect to changing land use in the region from broadacre agriculture (primarily cereal cropping and grazing) to irrigated horticulture.

## 2 Materials and methods

### 2.1 Soil sampling

Baseline data describing key soil properties is required for the Hydrus modelling in Task 2. Prior to commencing any soil sampling it was necessary to define the focus area for the study. At the time of commencement of the project the details of the area for expansion of irrigated agriculture north of the existing Virginia horticultural region had not been confirmed, although a primary study area was identified in the Northern Adelaide Plains Water Stocktake (Goyder Institute for Water Research, 2016) (Fig. 1). Subsequently, a decision was made by the project team, after consultation with several government and industry representatives and in consideration of the priority primary production area (SA Government, 2017), to define the focus area for the collection of soil samples as shown in Figs. 2 and 3.

The proportion of the major soil groups in the focus area (Hall et al., 2009) is given in Table 1. When the focus area was limited to the priority primary production area (SA Government, 2017) the four major soil groups were Hard red brown texture contrast (52%), Deep uniform to gradational (13%), Calcareous (12%) and Sand over clay (10%).



**Figure 1. Development zones and primary study area identified for potential expansion of irrigated agriculture in the Northern Adelaide Plains (NAP) region (Goyder Institute for Water Research, 2016). The focus area for the soil sampling in this study is indicated by the area outlined in blue.**

Prior to the project commencing (May 2017), seven soil samples (NAP1 – NAP7) were collected with assistance from PIRSA staff who were collecting soils from soil pits dug for soil mapping purposes. An additional 13 sites (NAP 8 – NAP 20) were sampled once the project commenced. At each sampling location (NAP8-NAP20) two replicates (1 m apart) were manually cored using large hand augers (approximately 30 cm diameter). The sampling locations and major soil groups in the region are given in Fig. 3. The sampling depths were: 0-10 cm, 10-30 cm, 30-60 cm, 60-90 cm and 90-120 cm, however, there were occasions when the deeper layers could not be sampled.

In addition, soil cores were taken for determining soil physical properties, which involved clearing the surface and hammering a large diameter ring (approximately 80 mm diameter) into the soil until it was flush with the surface. Then two smaller rings (approximately 50 mm diameter x 50 mm high) were hammered into the soil surface, one on top of the other, within the larger ring, to a depth of approximately 80 mm. The soil underneath and around the larger ring was excavated using a small chisel and the whole unit was removed intact with the soil underneath “protecting” the intact core in the smaller rings. The samples were placed in sturdy plastic bags and secured for transit to the laboratory. This procedure ensured the core remained intact during transit. This procedure was followed for the 0-10 cm and 10-30 cm depth sampling but was generally impractical for deeper depths in the soil profile, except for the sandy soils. Where possible, large clods were sampled for the depths below 30 cm. However, often in the calcareous soils the friable nature of the soil meant collecting a clod was impractical. Consequently, soil physical properties were determined on a smaller number of soils compared with the chemical properties.

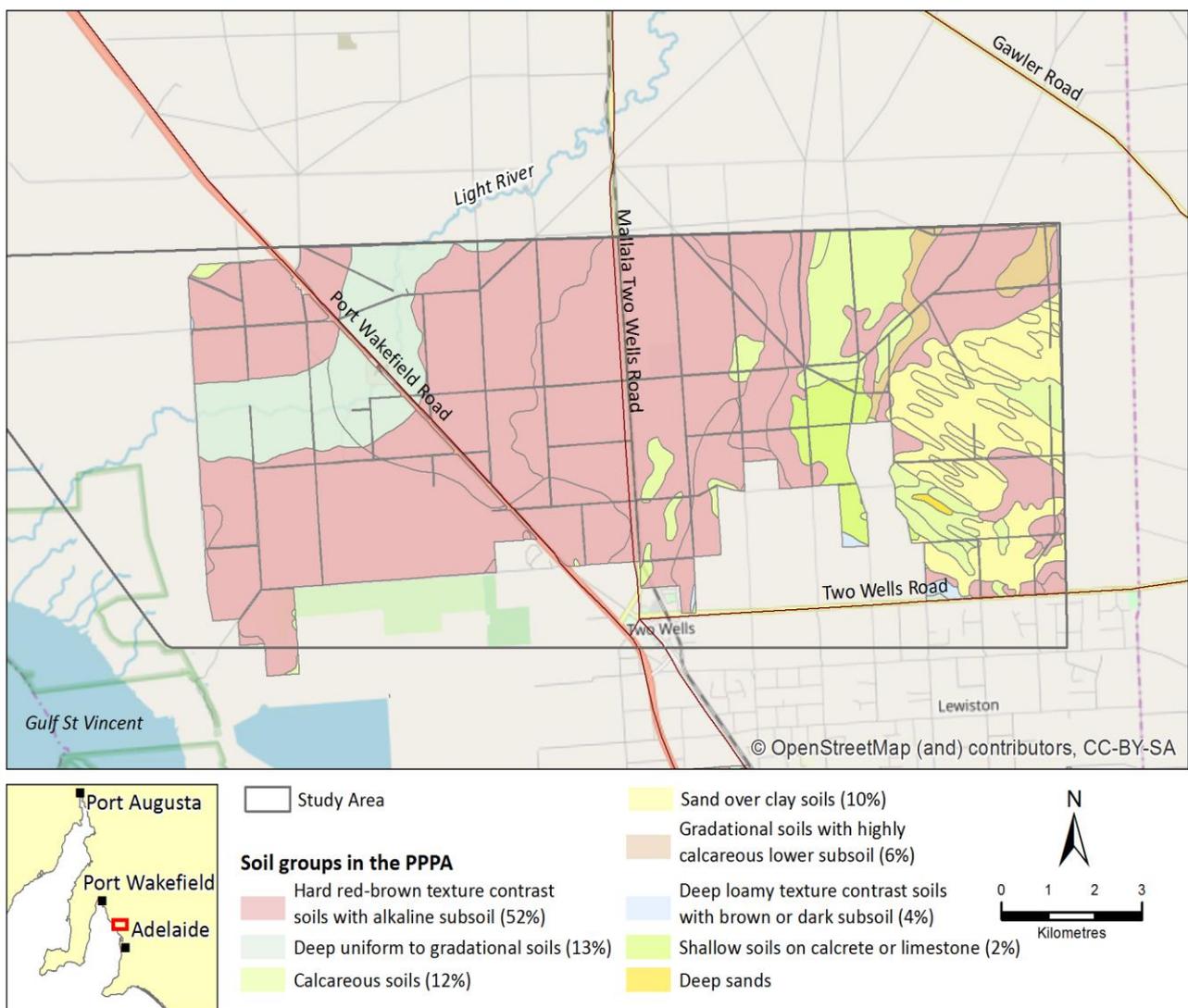


Figure 2. Major soil groups (Hall et al., 2009) in the project focus area for the soil sampling when clipped to the primary production priority areas (SA Government, 2017).

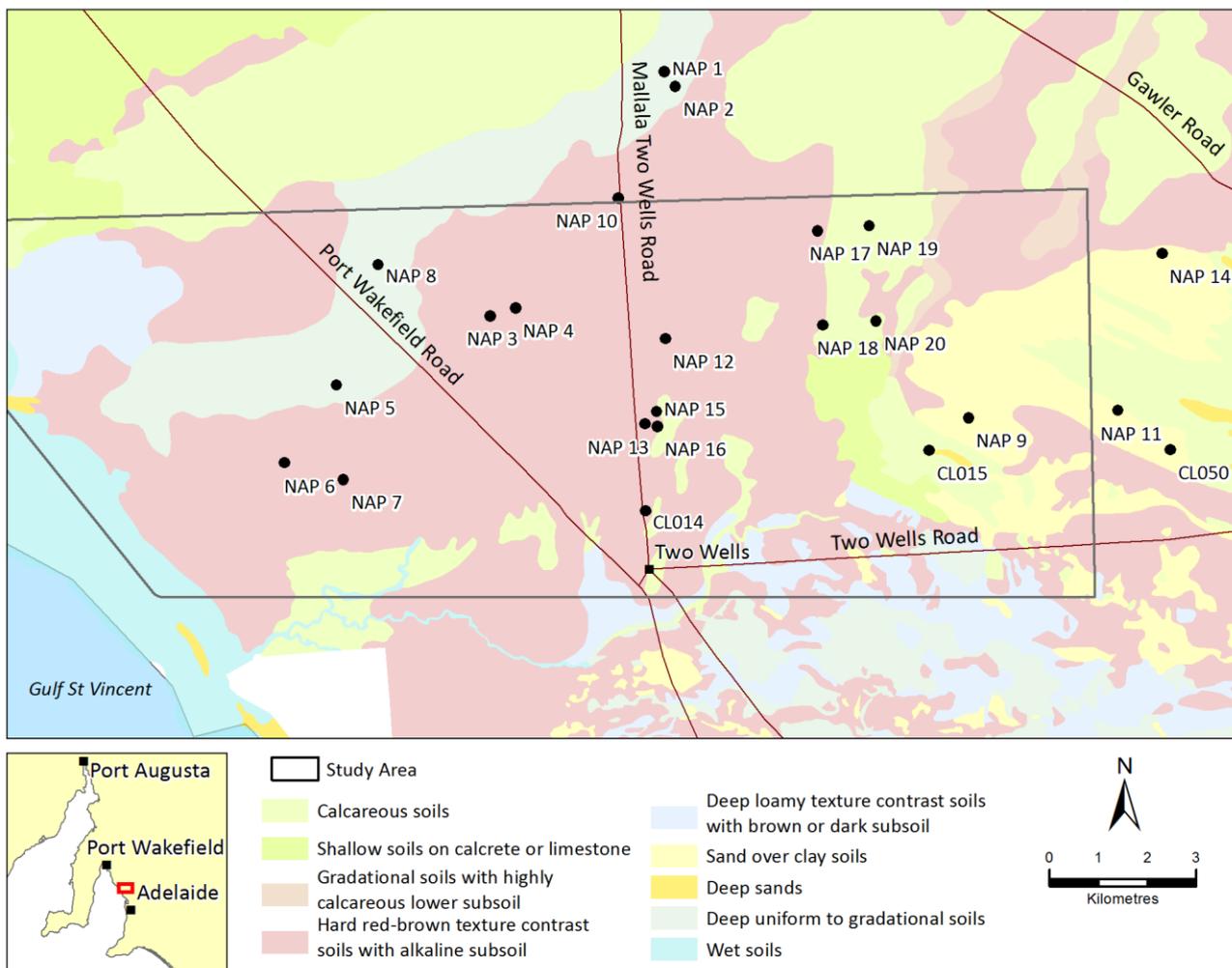


Figure 3. Soil sampling locations used in the determination of soil properties for the modelling and the major soil groups (Hall et al., 2009). The project focus area for soil sampling purposes is outlined in black.

Table 1. Percentage coverage of the major soil groups in the NAP focus soil collection area based on the Australian soil classification system (Hall et al., 2009).

Major soil group	Hard red brown texture contrast	Deep uniform to gradational	Calcareous	Sand over clay	Gradational soils with highly calcareous subsoil
Whole focus area	43%	13%	11%	7%	4%
Area clipped to the priority primary production area <sup>1</sup>	52%	13%	12%	10%	6%

<sup>1</sup>SA Government (2017)

## 2.2 Soil pre-treatment before analyses

Soils for chemical analyses were oven-dried at 40 °C and then sieved to <2 mm. Soils were then stored in plastic containers at room temperature in preparation for scanning for IR analysis or classical analyses. Soils for physical analyses were kept in rigid containers or in the plastic bags at 5 °C.

## 2.3 Infrared (IR) analyses

The area considered for expansion of irrigated agriculture is large, making the conventional sampling and analysis approach cost-prohibitive. Therefore, a rapid soil assessment technique (i.e. IR spectroscopy) was used for determining the current baseline status for the specific parameters identified. Validation, using classical physical and chemical analytical techniques, was made using a sub-set of soils (20%). Rapid and cost-effective IR techniques combined with partial least-squares regression (PLSR) for predicting physical and chemical properties were used to predict attributes in unknown soils. This approach enabled the large study area to be covered with limited resources. Existing archived samples from the ASRIS soil collection (<http://www.asris.csiro.au/soilsiteportal/>) and from the South Australian collection (<https://data.environment.sa.gov.au/NatureMaps/Pages/default.aspx>), were initially planned to be used to derive the models for the specific parameters required. However, the IR spectra of the 23 soils collected in the focus area (Fig. 3) were on the outer border of the spectral cluster of the archived soils. Consequently, the differences in IR spectra between the NAP sampled soils and archived soils meant that the latter could not be used in the development of the prediction models.

The following chemical properties were determined using IR predictions: total carbon (TC) (%), organic carbon (OC) (%), total nitrogen (N) (%), ammonium (NH<sub>4</sub>-N) (mg/kg), particle size (%), calcium carbonate (CaCO<sub>3</sub>) (%), exchangeable calcium (Ca<sup>2+</sup>) (cmol(+)/kg), exchangeable magnesium (Mg<sup>2+</sup>) (cmol(+)/kg), exchangeable sodium (Na<sup>+</sup>) (cmol(+)/kg), exchangeable potassium (K<sup>+</sup>) (cmol(+)/kg) and cation exchange capacity (CEC) (cmol(+)/kg). From the exchangeable cations data the exchangeable sodium percentage (ESP %) was determined as:

$$\text{ESP} = [\text{Na (cmol(+)/kg)} / \text{CEC (cmol(+)/kg)}] \times 100 \text{ (Hazelton and Murphy, 2007).}$$

The following physical properties were determined using IR predictions: saturated hydraulic conductivity (K<sub>s</sub>) and water retention at the following matric potentials (0.01, 4, 8, 33, 60, 100 and 1500 kPa). A subset were also analysed for the hydraulic properties using traditional methods (Mackenzie et al., 2002). Details of the IR approach and the regressions between the predicted and reference data are given in Appendix A.

## 2.4 Chemical analyses using traditional methods

To validate the IR predictions of the soil chemical data a subset (20%) of the soils was analysed using traditional wet chemistry methods. Selection of the subset for validation of the IR data was based on the broad IR spectra obtained from scanning all the soils. This ensured that the subset selected covered the complete cross-section of soils sampled. Not all soil properties could be predicted using IR spectra so the following properties were determined for all soils sampled using a traditional method:  $\text{pH}_w$  (1:5 soil:water),  $\text{pH}_{Ca}$  (1:5 soil:0.01 M  $\text{CaCl}_2$ ) and electrical conductivity (EC). In addition, boron (B) was determined on a subset of soils (0-10 cm, 10-30 cm and 30-60 cm). Details of the traditional chemistry methods for pH, EC, TC, OC, N,  $\text{NH}_4\text{-N}$ , particle size (%),  $\text{CaCO}_3$ , exchangeable  $\text{Ca}^{2+}$ , exchangeable  $\text{Mg}^{2+}$ , exchangeable  $\text{Na}^+$ , exchangeable  $\text{K}^+$  and CEC are given in Appendix B.

### **Boron (B) in soil solution**

Boron (B) in soil solution was determined at maximum water holding capacity (MWHC) based on McLaughlin et al. (1997). This method was selected since others (Aitken and McCallum, 1988; Mertens et al., 2011) had shown that soil solution B concentration was better correlated with plant B concentration and was not affected by soil texture, compared with the traditional hot 0.01 M calcium chloride,  $\text{CaCl}_2$ , extractable fraction method (Appendix C). Different solutions were used to bring the soils to MWHC, namely a solution with a high chloride ( $\text{Cl}^-$ ) content (550 mg  $\text{Cl}^-/\text{L}$ ) and one with low  $\text{Cl}^-$  content (4 mg  $\text{Cl}^-/\text{L}$ ). The high  $\text{Cl}^-$  solution was based on the highest concentration in the reclaimed water from the dissolved air flotation and filtration (DAFF) treatment plant and the lowest was based on the  $\text{Cl}^-$  content in rainwater (Crosbie et al., 2012). Boron in soil solution was determined only on soils from 0-10 cm, 10-30 cm and 30-60 cm depths.

### **Determination of boron sorption coefficient**

Sorption coefficients ( $K_d$  values) were determined for B using the OECD 106 standard protocol for the adsorption – desorption of chemicals using a batch equilibrium method (OECD/OCDE, 2000). Briefly, the procedure involved weighing 2 g of soil into plastic vials in triplicate. There was an initial pre-equilibration for 24 h with 9.5 mL of 0.01 M  $\text{CaCl}_2$ , after which a known volume (0.5 mL) of a spiking solution of B was added to give an initial concentration of 0.5 mg B/L. The solution was shaken again for 24 h on an end-over-end shaker and the concentration remaining in solution was measured, after filtration, using an inductively coupled plasma optical emission spectrometer (ICP-OES). The soils selected for determining  $K_d$  values for B were chosen to cover a range of soil textures, soil pH and native (geogenic) B concentrations.

The sorption coefficients ( $K_d$ ) values were calculated as:

$$K_d = \frac{\text{Concentration of the chemical sorbed by soil (mg/kg)}}{\text{Equilibrium concentration in solution (mg/L)}}$$

Equilibrium mass was corrected for native B that came into solution when blank soils were shaken in 1:5 ratio in 0.01 M  $\text{CaCl}_2$ .

### **Sequential extraction of boron (B) from soils**

To assess how readily B was mobilised sequential extractions were done on a subset of soils. Sequential extractions were done in duplicate with a high  $\text{Cl}^-$  (550 mg  $\text{Cl}^-/\text{L}$ ) solution in a 1:5 ratio. The high  $\text{Cl}^-$  solution was selected to represent the highest concentration in the reclaimed water from the dissolved air flotation and filtration (DAFF) treatment plant. This reclaimed water is currently provided to growers in the existing irrigation area in Virginia. The soils selected had been found to have relatively high B in soil solution and the sequential extractions were performed to determine whether B would continue to come into solution with each successive extraction. The samples were shaken on an end-over-end shaker for 24 h, then centrifuged at 3000 rpm for 15 mins. The extract was then decanted and a fresh solution was added and the extraction repeated four times. The B extracted was determined by ICP-OES.

### **Total boron (B) concentration in soils**

The standard USEPA method for microwave assisted acid digestion of soils (USEPA, 2007) was used to determine the total B concentration in the subset of soils that were used in the sequential extraction of B. Briefly, 7.5 ml nitric acid,  $\text{HNO}_3$ , and 2.5 ml hydrochloric acid,  $\text{HCl}$ , (total volume 10 mL) were added to 0.25 g of soil and allowed to cold digest overnight before close vessel microwaving the samples the next day. The samples were then diluted to 50 mL with high purity (MQ) water, filtered and the B concentration was measured by ICP-OES.

## **2.5 Analyses of soil physical properties using traditional methods**

The soil hydraulic properties were determined on a set of surface (predominantly 0-10 cm and 10-30 cm) soils (57 samples) to validate the IR predictions. The soil core, within the inner ring of the field-sampled cores, was carefully removed and fitted with a thin porous base to allow, firstly, saturated hydraulic conductivity,  $K_s$ , via a constant head method (Youngs, 2001), and secondly, volumetric water retention on porous ceramic plates at the following matric potentials (0.01, 4, 8, 33, 60, 100 and 1500 kPa) according to standard methods outlined by Townend et al. (2001).

## 3 Results and discussion

All the chemical and physical data determined in soils can be found in Appendix D. Selected chemical properties, that may be problematic for the expansion of irrigated agriculture into the region north of the current horticultural region around Virginia, are discussed in more detail below.

### 3.1 Soil pH

Soil pH is one of the most important determinants of soil fertility through its influence on the solubility of metal ions, such as aluminium (Al), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn) and molybdenum (Mo), its effect on the supply of nutrient cations and anions, and its influence on microbes present in soil and their activity. Acidic soils are often associated with nutrient deficiencies of the base cations calcium (Ca), magnesium (Mg) and potassium (K), and deficiencies of phosphorus (P) (Heil and Sposito, 1997). At  $pH_{Ca} < 5$  clay mineral decomposition results in Al and Mn compounds becoming increasingly soluble, which can limit crop growth, since  $Al^{3+}$  and  $AlOH^{2+}$  are phytotoxic. As the soil pH increases the cations  $Fe^{3+}$ ,  $Mn^{2+}$ ,  $Zn^{2+}$  and  $Cu^{2+}$ , can form insoluble hydroxides and become less available to plants, and at  $pH_w > 8$  B decreases in availability as the borate anion can be adsorbed to clay surfaces. However, B increases in availability with  $pH_w > 9$  (Goldberg and Su, 2005).

Different crops have different optimum pH ranges for growth and generally the ideal pH range for plant growth is between 5.5 and 8, and for most vegetables it is  $pH_w$  5 to 7 (Hazelton and Murphy, 2007). The range of soil pH within each depth for the soils sampled from the NAP is summarised for the major soil groups in Appendix D. Generally,  $pH_w$  of the sampled soils were  $\geq 7$  irrespective of soil group or depth, though one surface (0-10 cm) Hard red brown soil was  $pH_w$  5.9. Generally, soil  $pH_w$  also increased with depth. In the NAP soils surveyed 96% had  $pH_w > 7$  in the surface soils (0-10, 10-30 and 30-60 cm) and 77% had  $pH_w > 8$  (Fig. 4). The spatial distribution of soil  $pH_w$  at each sampling depth is shown in Figs. 5a and 5b. Causes and amelioration of different pH ranges is given in Appendix E (Slattery et al., 1999).

In the soils in the NAP region the main concern, with regard pH, is that many of the soils are slightly to highly alkaline and micronutrients required for crop growth (e.g. Fe, Mn, Cu, Zn) will be unavailable for plant uptake and will need to be supplemented to prevent deficiencies. Cereal growers in this region currently are applying micronutrients to wheat to overcome deficiencies. In soils with  $pH_w > 9$  aluminium concentrations have been found to be high and to have toxic effects on wheat growth (Ma et al., 2003). The role of pH on B availability is discussed later. At extremely high soil pH values ( $pH_w > 8.5$ ), where exchangeable sodium (Na) dominates and free sodium bicarbonate ( $NaHCO_3$ ) and carbonates are present, the soil is likely to have a very poor nutritional and structural status (Hazelton and Murphy, 2007). Of the soils surveyed 37% surface soils (0-10 and 10-30 cm) had  $pH_w > 8.5$  with the highest proportion in the calcareous (75%) and sand over clay (57%) soils. Inclusion of the 30-60 cm depths increased those with  $pH_w > 8.5$  to 52% (Fig. 4). In some cases,

a soil may become alkaline with time because of additions of  $\text{Na}^{2+}$  through irrigation water (Slattery et al., 1999). So, expansion of irrigated agriculture into the NAP focus area should monitor pH since this region already has highly alkaline soils.

An investigation in the current irrigation area in Virginia, was conducted into the condition of broad acre cropping soil after irrigation with recycled water (RW) for 14 years (Ryan and Kelly, 2014). In the surface soils (0-20 cm) they found  $\text{pH}_w$  were higher (approximately 8.7) under virgin sites that had never been irrigated, compared with approximately  $\text{pH}_w$  8.1 in those soils that had been irrigated with RW and  $\text{pH}_w$  approximately 7.7 in those soils irrigated with bore water. They concluded that overall, irrigation with RW had not led to a significant decline in soil pH in broad acre agriculture. Soils sampled under polyhouses showed no significant differences at each sampling depth between the different irrigation sources, though generally the soils receiving mains water had lower pH values (Ryan and Kelly, 2014).

Stevens et al. (2004a) investigated the effect of soil additives under field conditions on the soil properties and vegetable production in the NAP region. They found kiln dust increased soil  $\text{pH}_w$  (0-15 cm) from 5.9 to approx. 7.5, resulting in a significant increase in the number of forked carrots (i.e. decrease in quality) grown in a loamy sand. Similarly, in a medium clay, where the treatment raised  $\text{pH}_w$  (0-15 cm) from 7.5 to 8, they found maturation of tomatoes was delayed, which was attributed to decreased availability of some nutrients. While the number of surface sandy soils (0-10 cm and 10-30 cm) assessed in this survey of the NAP area was limited, 3 out of 4 sites had  $\text{pH}_w > 7.5$ .

These results indicate that a large number of soils in the NAP region are already highly alkaline, and issues with micronutrient deficiency and Al toxicity will need to be monitored and mitigation strategies implemented.

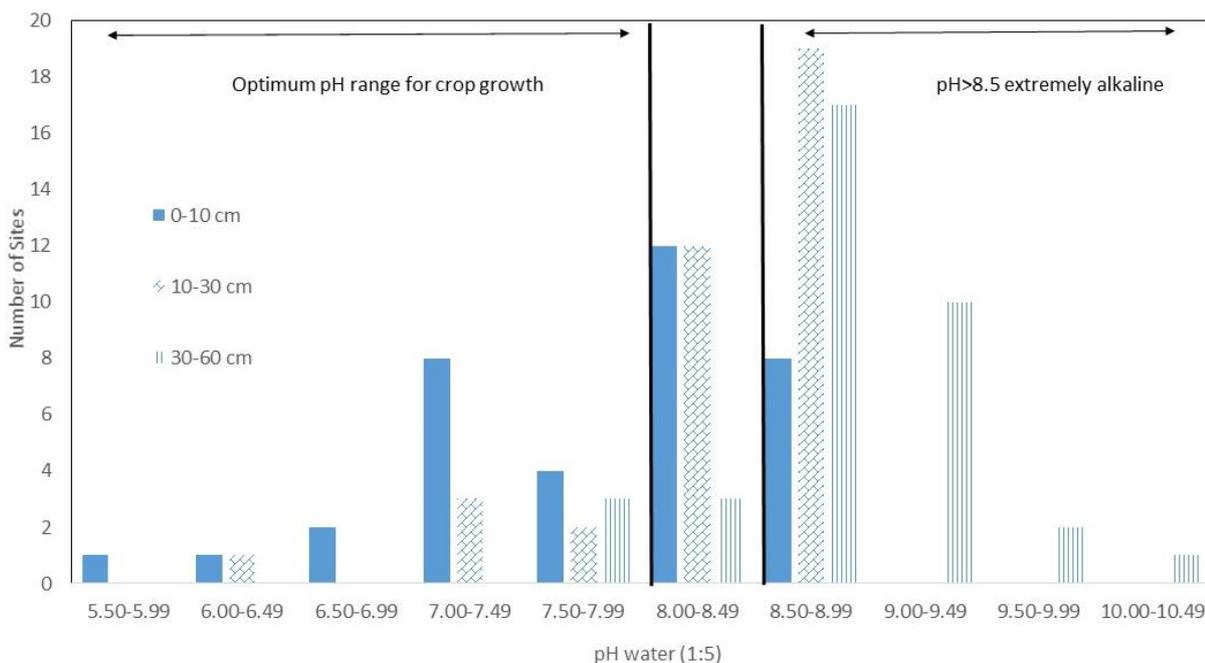


Figure 4. Distribution of  $\text{pH}_w$  (1:5 water) in the surface soils sampled across the NAP region.

a)

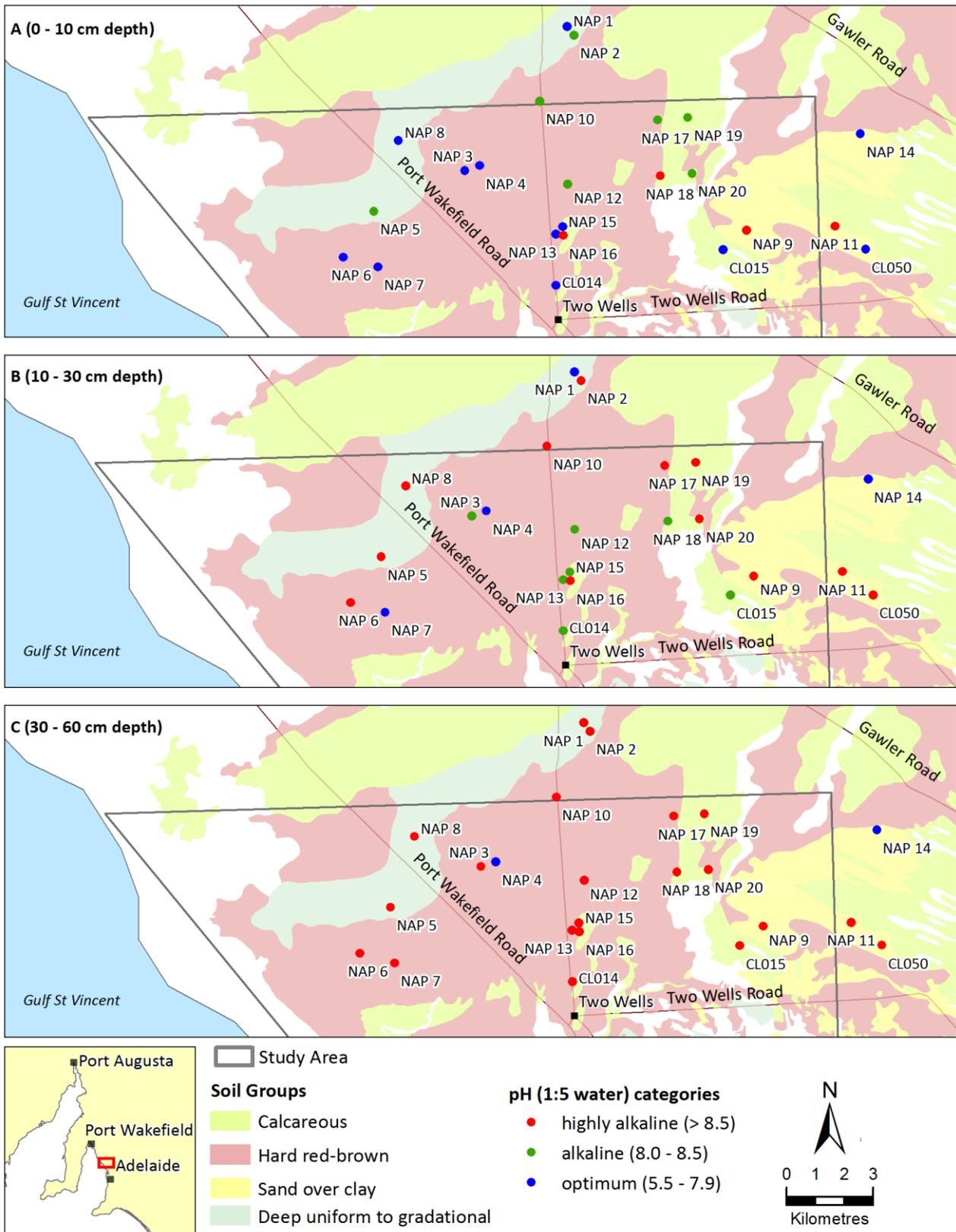


Figure 5. Spatial distribution of pH<sub>w</sub> (1:5 water) in a) 0-10 cm, 10-30 cm and 30-60 cm depth and b) in 60-90 cm and 90-120 cm depth across the NAP focus region.

b)

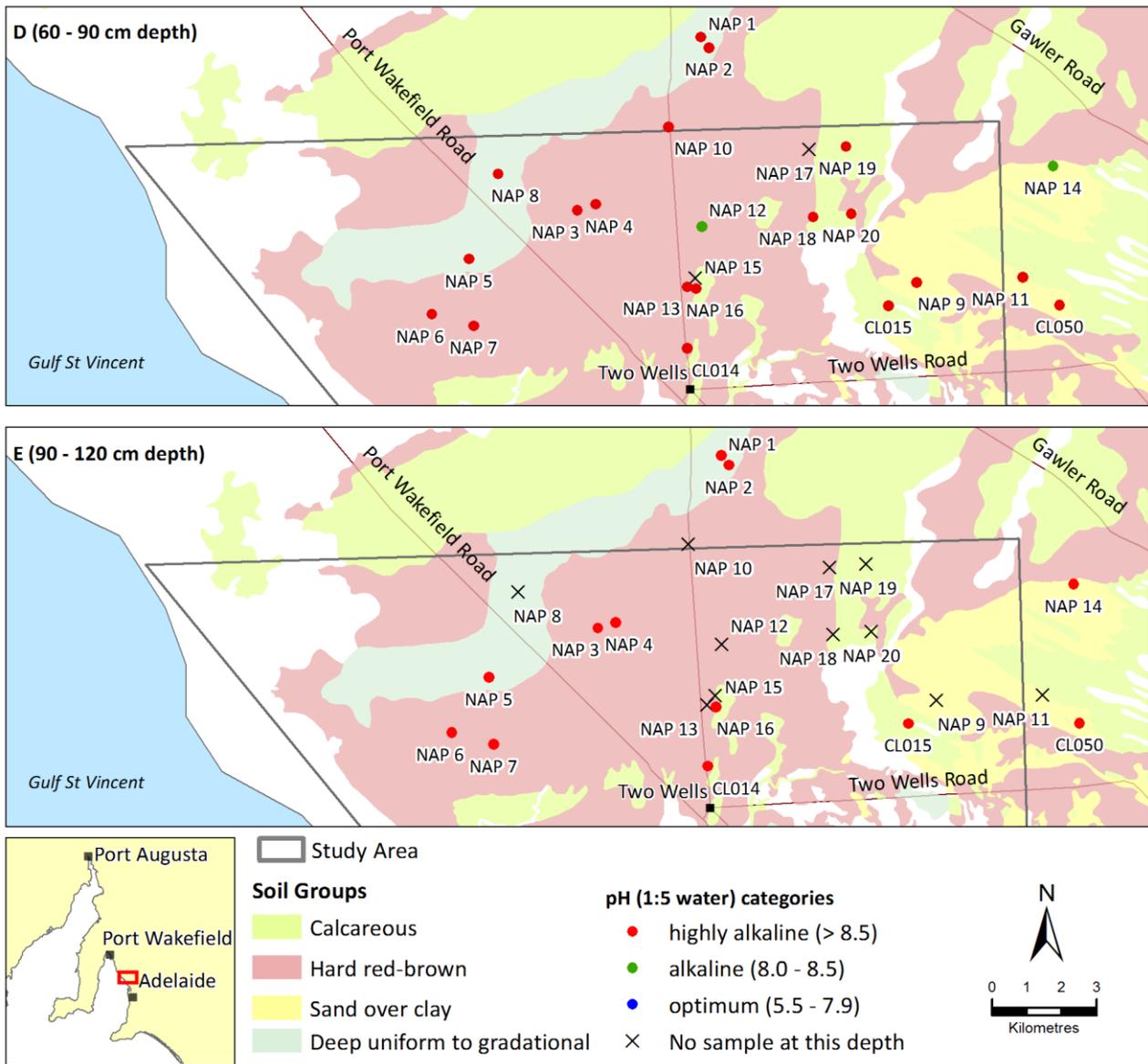


Figure 5 cont. Spatial distribution of pH<sub>w</sub> (1:5 water) in a) 0-10 cm, 10-30 cm and 30-60 cm depth and b) in 60-90 cm and 90-120 cm depth across the NAP focus region.

## 3.2 Boron (B)

Boron (B) has been raised in previous studies as a concern with regards the use of recycled water for irrigation (Leyshon and Jame, 1993; Stevens et al., 2004a). The B concentration in the recycled wastewater from the DAFF treatment plant ranged from 0.16 – 0.55 mg/L and had a median value of 0.33 mg/L over the period 2012 – 2016 (data provided by SA Water). The long-term trigger value for B in irrigation water is 0.5 mg/L (ANZECC/ARMCANZ, 2000).

Boron is a micronutrient that is required by plants in small quantities (<500 g/ha) (Shorrocks, 1997) and since B is relatively immobile in plants, once utilized in actively growing tissues, it is not re-translocated to other parts. Therefore, it is necessary to have a rather continuous source of B available to the plant throughout its growth cycle. Boron is required for the formation of new tissues but not the maintenance of older tissues, so actively growing plants require larger amounts of B than slowly growing or mature plants (Adriano, 2001). The dominant species of B in soils at low pH values is the unionised form,  $B(OH)_3$ , and consequently there is relatively low sorption in soils. As the soil pH increases the concentration of the borate ion,  $B(OH)_4^-$ , increases, and while the hydroxide ion ( $OH^-$ ) concentration is relatively low, the amount of B adsorbed increases (Goldberg and Glaubig, 1985; Adriano, 2001). However, further increases in pH result in increased  $OH^-$  concentration relative to  $B(OH)_4^-$  and consequently B adsorption decreases due to competition with  $OH^-$  for sorption sites (Goldberg and Glaubig, 1985; Adriano, 2001). Consequently, soil adsorption of B has been found to be pH dependent, with a maximum at pH 6 to 8 for Al-oxides and pH 7 to 9 for Fe-oxides (Goldberg and Glaubig, 1985; Goldberg et al., 1993) (Appendix F).

Boron deficiency commonly occurs in sandy soils which have low CEC and organic matter (OM) content, where leaching and heavy cropping have diminished the soil B reserves (Adriano, 2001). Boron toxicity usually is seen in soil of marine sediment, in those soils derived from parent material rich in B, and in arid and semi-arid soils (Adriano, 2001).

The fraction of B in soil that is available for plant uptake is termed the phytoavailable fraction. Total B is an unreliable measure of the bioavailable fraction in soils and often an extractant, such as water or 0.01 M  $CaCl_2$ , is used as an index of the phytoavailable fraction (Adriano, 2001). Aitken and McCallum (1988), showed that the relationship between B concentrations measured in sunflowers and the hot 0.01 M  $CaCl_2$ -extractable fraction was dependent upon the soil texture (Appendix C). They found a stronger relationship with the soil solution fraction measured at maximum water holding capacity (MWHC) (termed B in soil solution) and plant uptake. Plants have varying degrees of tolerance to B in soil solution and Adriano (2001) suggests B concentrations <0.5 mg/L in soil solution are tolerable for most plants, but many plants may be adversely affected when B concentrations are in the range of 0.50 to 5.0 mg/L. Threshold concentration ranges for B in soil solution, based on Leyshon and Jame (1993), are given in Table 2. To better represent the soil solution composition following irrigation the B in soil solution was measured using a solution with a  $Cl^-$  concentration

equivalent to that found in recycled waste water, which is one of the primary irrigation water sources being considered. The Cl<sup>-</sup> concentration in the recycled waste water was 550 mg/L, compared with 4 mg/L in rain water. There was almost a 1:1 relationship between B concentrations in soil solution as determined using the high (550 mg/L) and low (4 mg/L) Cl<sup>-</sup> solution (Appendix F) so only data for the high Cl<sup>-</sup> solutions are discussed below.

## **Boron in NAP soils**

Of the NAP soils assessed (surface layers 0-10, 10-30 and 30-60 cm) 72% had <0.5 mg/L B in soil solution, indicating low native (geogenic) plant-available B in these soils. However, 13% had >1 mg/L and 8% had >2 mg/L B in soil solution. Several of the crops being considered for production in the NAP are sensitive to B (Table 2 and Appendix F) and this data suggests that the native B in some of the soils in the region may already be at concentrations that are limiting or toxic to crop growth before any irrigation commences. The distribution of B in soil solution at the three sampling depths for the soils sampled across the NAP region is shown in Fig. 6. The spatial distribution of B in soil solution in the surface soils (0-10 cm, 10-30 cm and 30-60 cm) is given in Fig. 7.

Stevens et al. (2004a) recommend special care is needed in the management of B because there is only a small concentration range between plant deficiency and toxicity for this micronutrient. In 28% of the soils surveyed in the NAP region the native B is already above the threshold concentration for sensitive and moderately sensitive crops before any additional applications of B are made through the irrigation water. Furthermore, excess B can accumulate in the root zone if it is not leached down through the soil, leading to toxicity problems. Stevens et al. (2004b) analysed soils from the current irrigation region around Virginia comparing those soils irrigated with recycled water (RCW) and bore water. They found that after long-term (>28 years) irrigation with the RCW the B (1:5 water extract) in surface (0-10 cm) soils had increased to an average of 0.25 mg/L compared with approximately 0.1 mg/L in non-irrigated soil. In the 10-20 cm depth the difference was slightly greater: 0.38 mg/L in RCW-irrigated soils compared with 0.2 mg/L in the non-irrigated soil. However, at lower depths the B concentrations were similar between the RCW-irrigated and non-irrigated soils. One of the difficulties with utilising critical B toxicity values is that often the data are derived from sand cultures and the criteria monitored for impact may be a vegetative measure and not a yield effect, which is often due to experimental and financial limitations in obtaining yield data. However, the high B (>2 mg/L) in soil solution of some of the surface soils assessed in this study would suggest that B concentrations in soils be included in a comprehensive soil assessment prior to the expansion of the irrigated agriculture north of Virginia.

## Relationship between soil solution B and other soil features

The relationship between B in soil solution and other soil properties was assessed to determine whether another soil property could be used as a predictor or surrogate of B in soil solution. This may be a useful tool to identify areas of concern for cropping to enable targeted management/mitigation programs. These relationships are shown in Appendix F. Unfortunately, no soil property showed a strong relationship with B concentrations in soil solution.

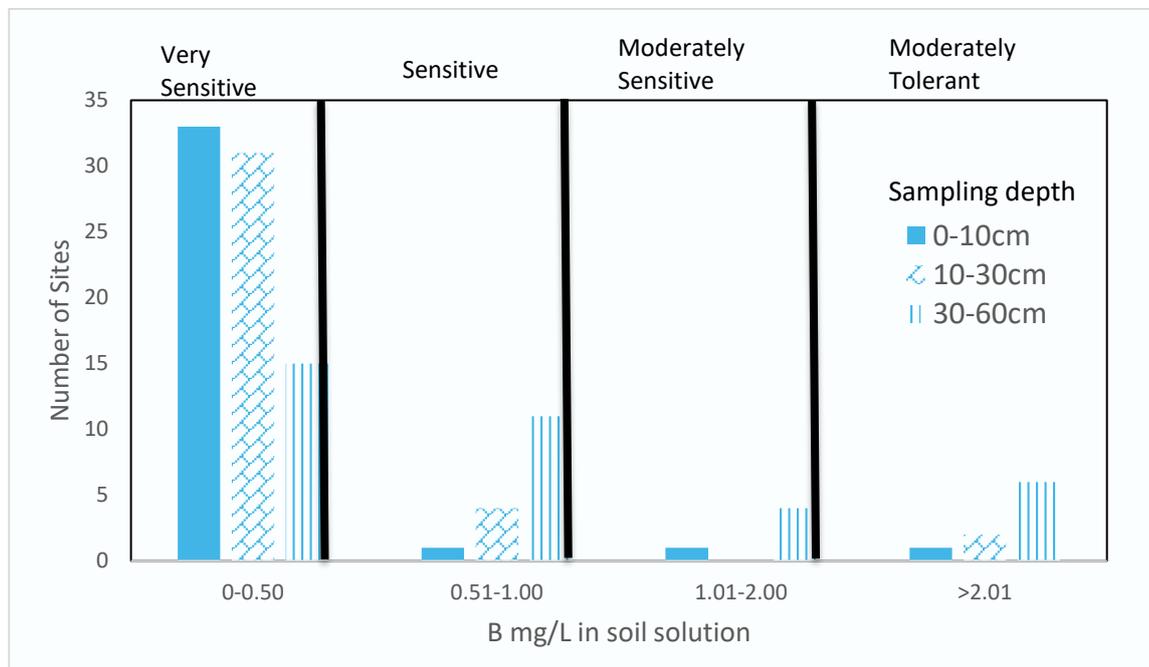
While there was a higher frequency of “high” soil solution B concentrations (>1.0 mg/L) in those soils with ESP >15% or  $\text{pH}_w > 8.5$ , these properties were not conclusive determinators, since not all soils in these ranges had B in soil solution >1.0 mg/L. The possibility of using the IR data to predict soil solution B was explored, but the prediction error was very large for the B concentrations in the range encountered in the region.

While those soils that had B in soil solution >1.0 mg/L were found predominantly in areas where the main soil group was Hard red brown texture contrast soils (Fig. 8a), the trend was not consistent. Some sampling locations in areas with this main soil group did not have high soil solution B concentrations. So this was also not a definitive discriminator. Consequently, the relationships between B in soil solution at different depths and the soil sub groups was also assessed. Although this was made difficult by the small sample size in each soil sub-group, there was a general trend of higher soil solution B at all depths occurring in two sub-groups of Hard red brown texture contrast soils, namely Loam over red clay and Loam over poorly structured red clay (Fig. 8b). There was no relationship found between the geology of the area and the B in soil solution (Appendix F).

**Table 2. Proportion of total samples (0-10 cm, 10-30 cm and 30-60 cm) within each threshold concentration range for boron (B) in soil solution determined at field capacity.**

Threshold concentration range for B in soil solution (field capacity basis) <sup>1</sup> (mg B/L)	Number of samples within range	Percentage of total soils (n=109) assessed	Crop species within threshold concentration range being considered in NAP <sup>1</sup>
Very sensitive <0.50	79	72%	
Sensitive 0.51-1.00	16	15%	Fig Grape Walnut Onion Garlic
Moderately sensitive 1.01-2.00	5	5%	Broccoli Red pepper Carrot Potato Cucumber
Moderately tolerant /tolerant >2.01	9	8%	Lettuce Tomato

<sup>1</sup> Leyshon and Jame (1993)



**Figure 6. Distribution of boron (B) concentrations in soil solution determined at field capacity for 0-10 cm, 10-30 cm and 30-60 cm depths for soils sampled from the NAP region. Threshold concentrations for the crop tolerances to B (Leyshon and Jame, 1993) are shown.**

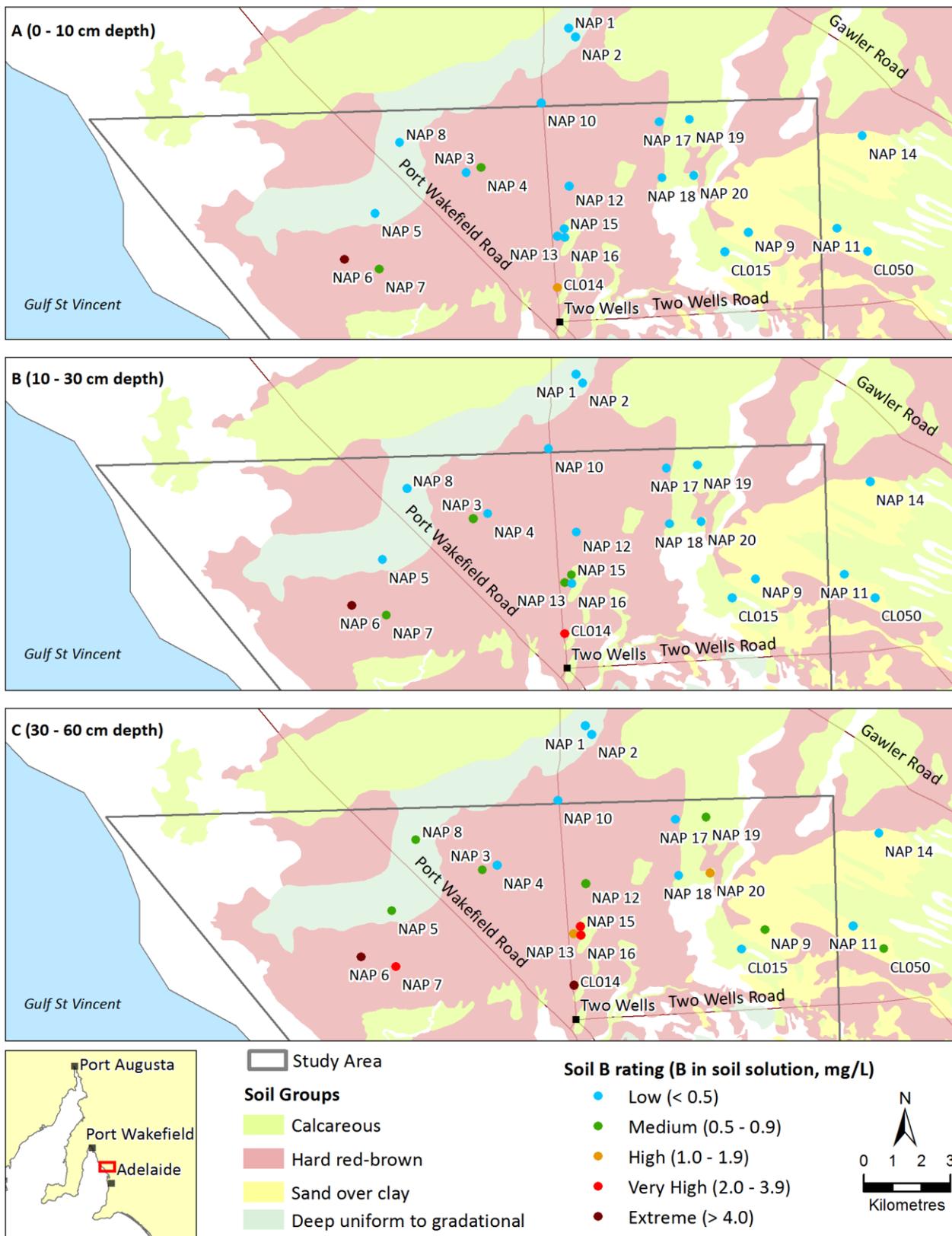
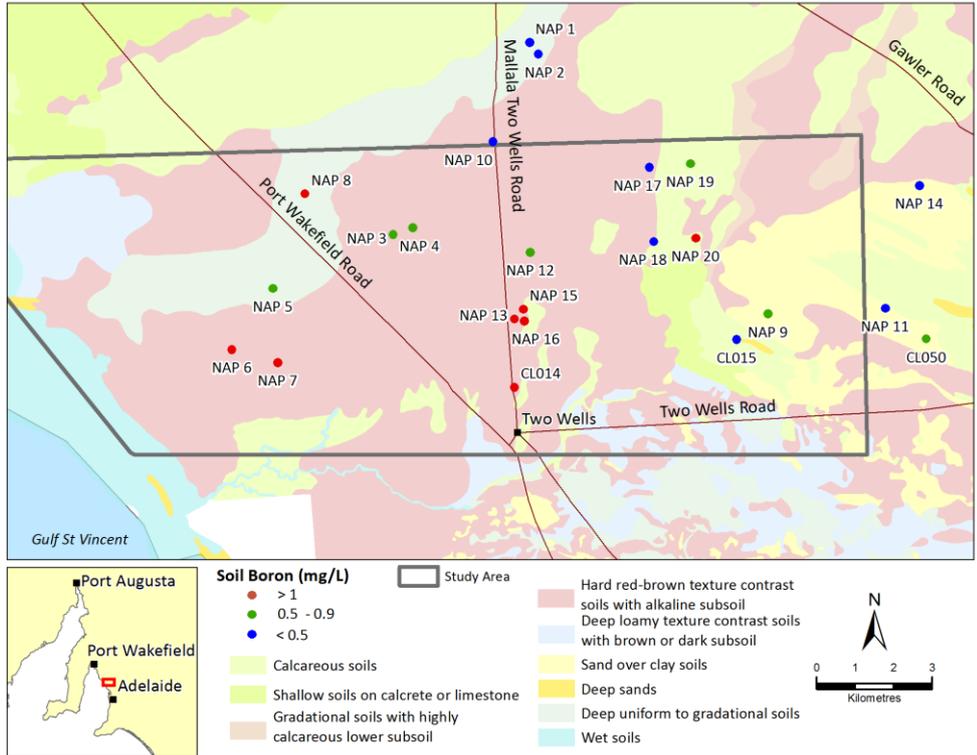


Figure 7. Spatial distribution of boron (B) concentrations in soil solution determined at field capacity for 0-10 cm, 10-30 cm and 30-60 cm depths for soils sampled from the NAP region. Threshold concentrations (<0.5, 0.5 – 0.9 and >1.0 mg B/L) for the crop tolerances are from Leyshon and Jame (1993).

a)



b)

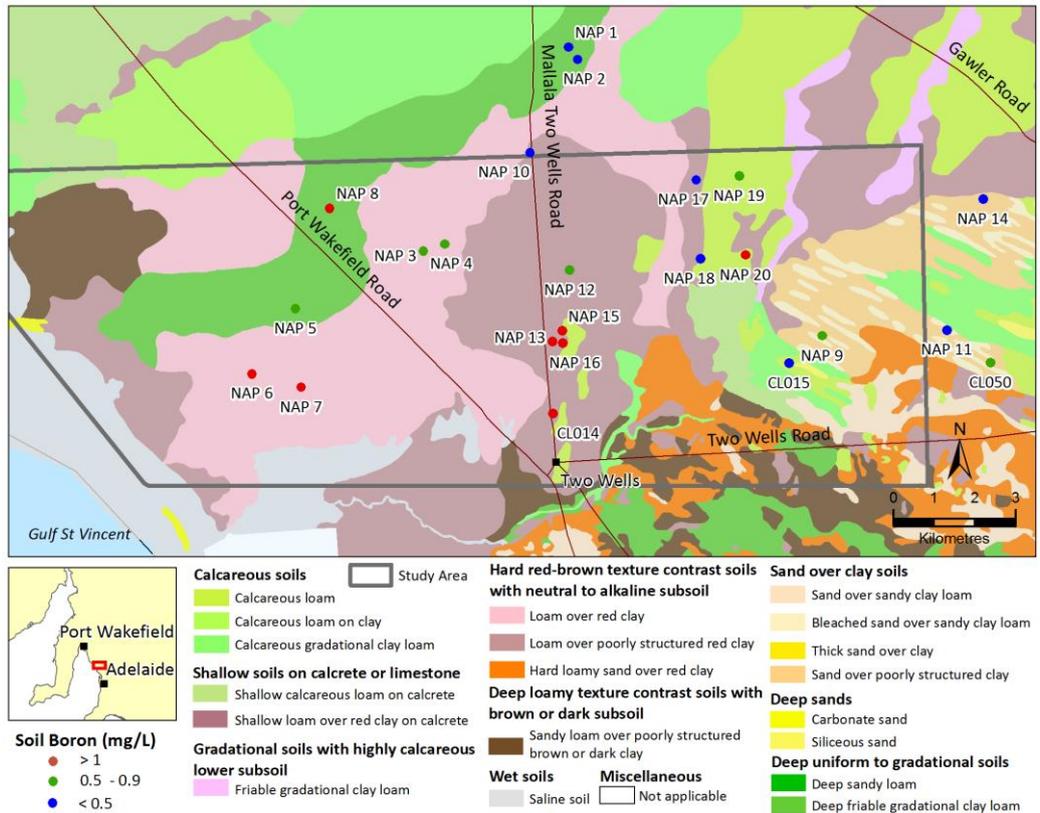


Figure 8. Sampling sites with soil solution boron (B) concentrations <0.5, 0.5 – 0.9 or >1.0 mg B/L at one or more of the surface depths (0-10 cm, 10-30 cm and 30-60 cm) and the a) major soil groups or b) major soil sub groups within the focus area.

## Relationship between soil B measurements

A strong relationship was found ( $R^2 = 0.80$ ) between soil B concentrations measured using hot 0.01 M  $\text{CaCl}_2$  extract and B in soil solution (Fig. 9) indicating that growers could utilise the commercially available method (hot 0.01 M  $\text{CaCl}_2$  extraction) for determining potential plant-available B. Based on the regression equation in Fig. 10, and the soil:solution ratio 1:2 for the hot 0.01 M  $\text{CaCl}_2$  extraction method (Rayment and Lyons, 2011), the extractable-B concentrations in mg/kg were converted to mg/L to allow comparison with the threshold concentrations of B in soil solution from Leyshon and Jame (1993). From this conversion, the threshold concentrations for the hot 0.01 M  $\text{CaCl}_2$  extractable B were 6.4 mg/L (equivalent to 2 mg/L B in soil solution) for sensitive to moderately sensitive crops, approximately 13 mg/L (equivalent to 4 mg/L B in soil solution) for moderately tolerant crops and approximately 19 mg/L (equivalent to 6 mg/L B in soil solution) for tolerant crops (Fig. 10).

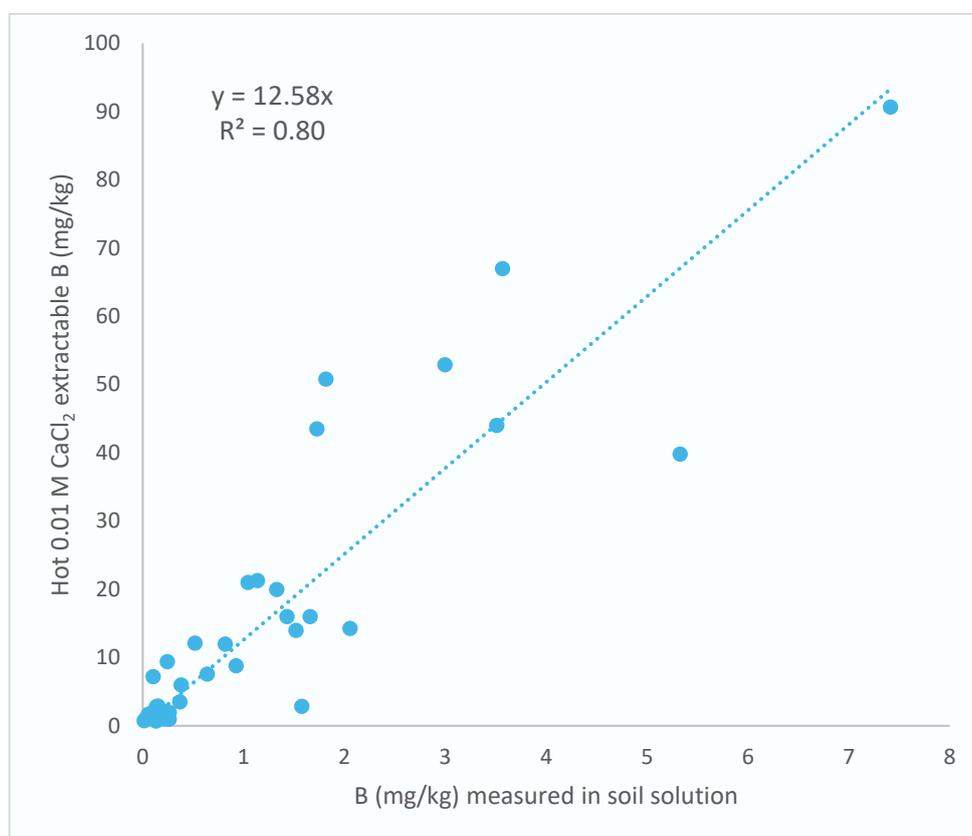
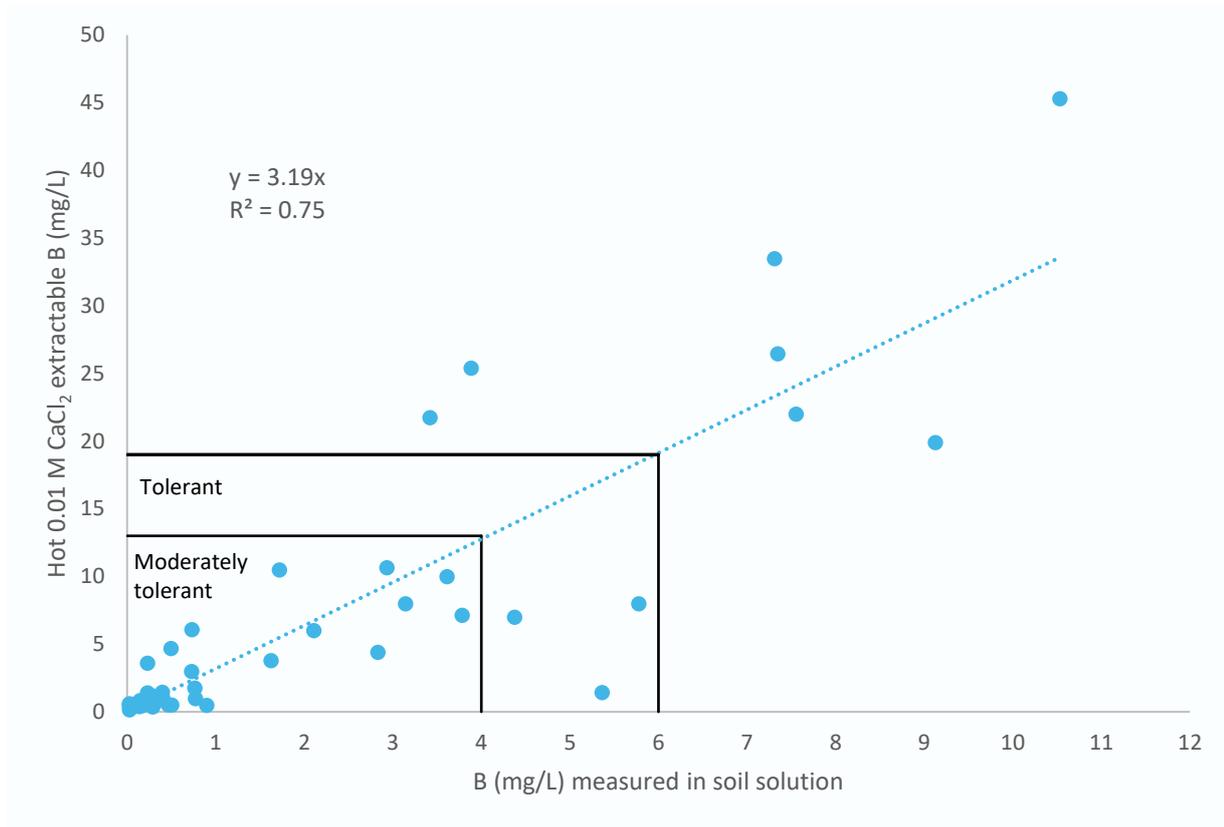


Figure 9. Comparison of boron (B) (mg/kg) measured using hot 0.01 M  $\text{CaCl}_2$  extraction and B (mg/kg) measured in soil solution using a high chloride (550 mg  $\text{Cl}^-/\text{L}$ ) solution.



**Figure 10.** Comparison of boron (B) (mg/L) measured using hot 0.01 M CaCl<sub>2</sub> extraction and B (mg/L) measured in soil solution using a high chloride (550 mg Cl<sup>-</sup>/L) solution. The threshold for moderately tolerant and tolerant crops (Leyshon and Jame, 1993) are shown.

### Sorption coefficients ( $K_d$ values) for B

The sorption coefficient ( $K_d$  value) is the distribution of the chemical between the solid and solution phases in soils. It is a measure of the degree of chemical sorption and hence mobility within soil. A high  $K_d$  value indicates that the chemical is strongly sorbed to the soil and is unlikely to easily move through the profile. Generally, the average  $K_d$  values for B in the NAP soils were low (compared with  $K_d$  values for other metals and metalloids) ranging from 0.44 to 5.16 L/kg (Appendix F). A plot of  $K_d$  against pH showed that a maximum  $K_d$  value was reached for a soil with  $pH_w$  8.5 but decreased with increasing pH values (Appendix F). This sorption data are used in the Hydrus modelling in Task 2. This data also indicates, that in the alkaline soils in this region, B would not be strongly sorbed to solid phases.

### Occurrence of B in sodic soils

A potential problem in the NAP region is the release of native or geogenic B into solution in areas where a perched water table may prevent B being leached out of the soil root zone. As the surface soil is subjected to wetting-drying cycles involving downward (drainage) and upward (capillary rise) water fluxes, any chemicals in solution including B and soluble salts, located deeper in the profile just below the root zone, may move back into the root zone as a result of capillary rise.

An indicator of potential perched water tables and restricted water infiltration is soil sodicity, as indicated by exchangeable sodium percentage (ESP %). The ESP of those soils that were found to have a high native B (>0.5 mg/L) in soil solution is given in Table 3 for the surface soils and in Table 4 for the subsoils. In the surface soils with B >0.5 mg/L, 25 (93%) had ESP >6%, which is considered sodic and 19 (70%) had ESP >14%, which is considered highly sodic (Hazelton and Murphy, 2007) (Table 3). The effects of soil sodicity are also moderated by the salt content in soil (discussed in later sections). Increased addition of water through irrigation of these soils may potentially leach salts from the root zone resulting in increased occurrence of the effects of sodicity, namely dispersion and slaking, in the surface soils.

**Table 3. Exchangeable sodium percentage (ESP), clay content (%) and EC for surface soils (0-10 cm, 10-30 cm and 30-60 cm) with high boron (B) (>0.5 mg/L) in soil solution determined at field capacity.**

Location code	Major soil group	Field rep	Sampling depth (cm)	B <sup>1</sup> mg/L	ESP <sup>2</sup> (%)	EC (1:5) (dS/m)	Clay content (<0.002 mm) (%)
NAP 4	Hard red brown	1	0-10	0.50	<b>8.6</b>	<b>0.115</b>	14
NAP 9	Sand over clay	1	30-60	0.55	4.0	0.109	11
NAP 9	Sand over clay	2	30-60	0.56	<0.1	0.103	8
NAP 8	Deep uniform to gradational	1	10-30	0.60	<b>10.6</b>	<b>0.211</b>	26
NAP 8	Deep uniform to gradational	2	30-60	0.65	25.2	0.523	27
NAP 19	Calcareous	2	30-60	0.67	<b>12.9</b>	<b>0.170</b>	14
NAP 13	Hard red brown	1	30-60	0.69	<b>12.2</b>	<b>0.125</b>	45
CL050	Hard red brown	1	28-50	0.73	<b>19.2</b>	<b>0.199</b>	25
NAP 3	Hard red brown	1	30-60	0.73	<b>15.9</b>	<b>0.223</b>	45
NAP 5	Deep uniform to gradational	1	30-60	0.76	<b>16.4</b>	<b>0.152</b>	27
NAP 7	Hard red brown	1	0-10	0.77	<b>10.0</b>	<b>0.156</b>	9
NAP 12	Hard red brown	1	30-60	0.80	16.7	0.730	45
NAP 12	Hard red brown	2	30-60	0.81	18.6	0.629	37
NAP 19	Calcareous	1	30-60	0.83	<b>15.1</b>	<b>0.181</b>	14
NAP 7	Hard red brown	1	10-30	0.90	<b>11.7</b>	<b>0.124</b>	8
NAP 8	Deep uniform to gradational	1	30-60	1.21	25.5	0.262	23
NAP 13	Hard red brown	2	30-60	1.43	<b>15.9</b>	<b>0.219</b>	43
NAP 15	Hard red brown	1	30-60	1.55	27.7	0.630	55
NAP 20	Hard red brown	2	30-60	1.58	18.8	0.296	45
NAP 16	Calcareous	2	30-60	2.41	22.6	0.227	18
NAP 15	Hard red brown	2	30-60	2.45	18.4	0.710	53
NAP 16	Calcareous	1	30-60	2.86	28.8	0.233	19
CL014	Hard red brown	1	10-30	3.42	<b>14.7</b>	<b>0.144</b>	51
NAP 7	Hard red brown	1	30-60	3.78	20.8	0.703	33
CL014	Hard red brown	1	30-50	7.55	27.1	0.550	33
NAP 6	Hard red brown	1	10-30	9.13	16.8	0.321	27
NAP 6	Hard red brown	1	30-60	10.53	21.3	0.397	44

<sup>1</sup> B in soil solution determined at maximum water holding capacity using a high chloride (550 mg/L) solution based on the maximum chloride content in DAFF recycled water. The values in bold are soils with both high ESP (> 6) and low EC (<0.25 dS/m) which are more likely to disperse. <sup>2</sup>From Hazelton and Murphy (2007) ESP> 6 sodic; ESP>14 highly sodic

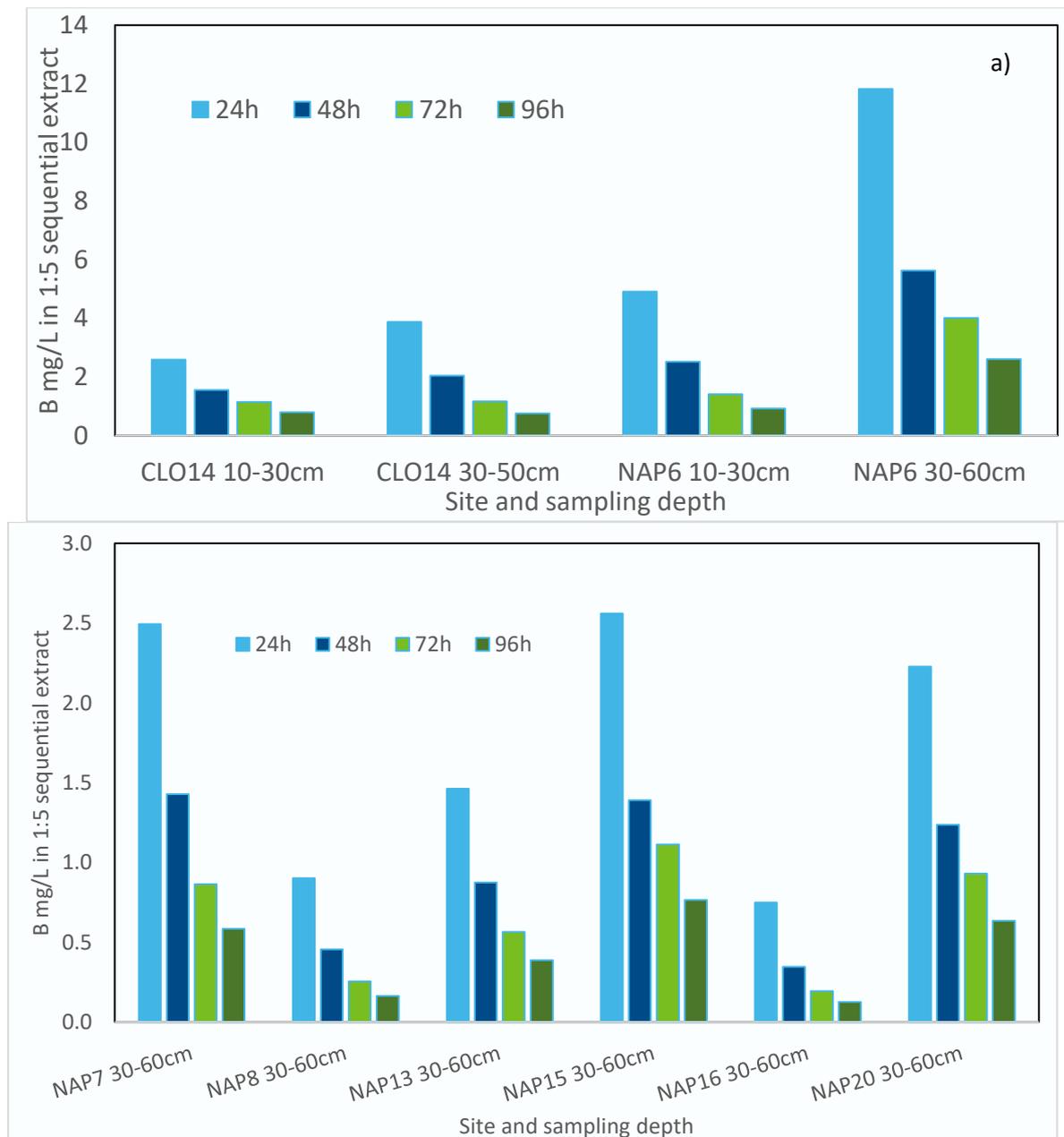
**Table 4. Exchangeable sodium percentage (ESP), clay content (%) and EC of sub-surface (30-60 cm and 60-90 cm) for those soils with high boron (B) (>0.5 mg/L) in soil solution determined at field capacity.**

Location code	Major soil group	Field rep	Depth	ESP (%)	EC (1:5) (dS/m)	Clay content (<0.002 mm) (%)
NAP 3	Hard red brown	1	60-90	26.7	0.662	49
NAP 3	Hard red brown	1	90-120	28.3	1.030	36
NAP 4	Hard red brown	1	60-90	31.0	0.292	37
NAP 4	Hard red brown	1	90-120	29.7	0.328	29
NAP 5	Deep uniform to gradational	1	60-90	12.1	0.182	60
NAP 5	Deep uniform to gradational	1	90-120	24.6	0.422	52
NAP 6	Hard red brown	1	60-90	47.9	0.983	29
NAP 6	Hard red brown	1	90-120	33.8	0.961	21
NAP 7	Hard red brown	1	60-90	44.2	1.080	26
NAP 7	Hard red brown	1	90-120	<0.1	1.182	22
NAP 8	Deep uniform to gradational	1	60-90	45.0	1.190	19
NAP 8	Deep uniform to gradational	2	60-90	39.9	1.253	23
NAP 9	Sand over clay	1	60-90	10.4	0.155	31
NAP 9	Sand over clay	2	60-90	20.5	0.171	37
NAP 12	Hard red brown	1	60-80	23.7	3.712	37
NAP 12	Hard red brown	2	60-80	27.7	1.472	32
NAP 13	Hard red brown	1	60-80	18.0	0.215	47
NAP 13	Hard red brown	2	60-80	20.8	0.244	47
NAP 16	Calcareous	1	60-90	34.0	0.738	18
NAP 16	Calcareous	1	90-120	32.2	1.268	20
NAP 16	Calcareous	2	60-90	46.9	0.616	15
NAP 19	Calcareous	1	60-80	15.3	0.368	13
NAP 19	Calcareous	2	60-76	22.6	0.335	12
NAP 20	Hard red brown	2	60-70	34.3	0.299	31
CL014	Hard red brown	1	50-75	18.0	1.309	53
CL014	Hard red brown	1	75-100	22.1	1.480	41
CL050	Hard red brown	1	50-85	18.0	0.448	29
CL050	Hard red brown	1	85-100	22.7	0.296	32

NAP 15 was not sampled below 60 cm; NAP 16 Rep 2 was not sampled below 90 cm.

## Sequential extraction of geogenic or native B

The sequential extraction of B from a subset of soils showed, irrespective of depth, there was a significant ( $P < 0.001$ ) exponential decreased in release of B with each extraction (Fig. 11). The rate of B extracted however, varied with each soil, and the B concentration at which the slope reached a plateau varied from approximately 0.15 mg/L to 2.5 mg/L. This would be expected since the initial extractable concentration measured after 24 h varied between the soils. The concentration extracted after 96 h was expressed as percentage of the extractable B after 24 h and this ranged from 18-35% (Table 5).



**Figure 11. Release of native (geogenic) boron (B) from selected soils with successive extractions with high chloride (550 mg Cl/L) solutions. Soils selected had 'high' native B. Data is presented for a) CLO14 and NAP6 and b) NAP7, NAP8, NAP13, NAP16 and NAP20.**

**Table 5. Exponential relationship between boron (B) extracted (y) over time for sequential extractions of a subset of soils.**

Soil code	Depth (cm)	Polynomial regression (y=B mg/L and x = hours)	R <sup>2</sup>	Approximate B in solution (mg/L) as the amount released plateaus (96h)	Approximate B in solution (mg/L) as the amount released plateaus. Data expressed as % of the initial extractable B after 24h
CLO14	10--30	$y = 0.0003x^2 - 0.0598x + 3.8295$	0.99	~0.8	31%
CLO14	30-50	$y = 0.0006x^2 - 0.1171x + 6.311$	1.00	~0.8	21%
NAP13	30-60	$y = 0.0002x^2 - 0.0362x + 2.2203$	1.00	~0.4	27%
NAP15-1	30-60	$y = 0.0003x^2 - 0.057x + 3.4671$	0.98	~0.8	35%
NAP15-2	30-60	$y = 0.0004x^2 - 0.0758x + 4.3326$	0.97	~0.8	28%
NAP20	30--60	$y = 0.0003x^2 - 0.0573x + 3.3939$	0.98	~0.6	27%
NAP16-1	30-60	$y = 0.0002x^2 - 0.0287x + 1.4271$	0.99	~0.15	18%
NAP16-2	30-60	$y = 0.0001x^2 - 0.0231x + 1.1276$	0.99	~0.15	23%
NAP6	10--30	$y = 0.0008x^2 - 0.1532x + 8.0839$	1.00	~1.0	20%
NAP6	30--60	$y = 0.0021x^2 - 0.3708x + 19.307$	0.98	~2.5	21%
NAP7	30--60	$y = 0.0003x^2 - 0.0672x + 3.8995$	1.00	~0.6	24%
NAP8	30--60	$y = 0.0002x^2 - 0.0285x + 1.4905$	1.00	~0.16	18%

The total amount of B extracted (mg/kg), after 4 washes with the high chloride (550 mg Cl<sup>-</sup>/L) solution (96 h), was then compared to the total B (mg/kg) in the soil (Table 6). The total extractable B (mg/kg) ranged from 19-48% of the total B (mg/kg) within the soils studied. This data would suggest that with successive extractions, the B in these soils would continue to come into solution with each irrigation event. This fraction would potentially be available for plant uptake. Furthermore, under current irrigation practices, where a volume of water is applied to leach salts out of the root zone, it is highly likely that the easily extractable fraction of B will move down through the soil profile. This mobile fraction of B could potentially move into groundwater. Alternatively, in profiles with a sodic subsoil, this mobile fraction of B may move through the soil profile until an impermeable layer is reached. While only 15% of the surface soils assessed in this study had high B (>1.0 mg B/L), this data demonstrates that there is a significant proportion of the native B in these highly alkaline soils that is easily extracted, potentially mobile and may impact crop growth.

**Table 6. Total extractable boron (B) (mg/kg), after 4 washes (96 h) with high chloride (550 mg Cl<sup>-</sup>/L) solution, total B (mg/kg) as measured by aqua regia digest and the extractable fraction expressed as % of total B.**

Soil code	Depth (cm)	Total extractable B (mg/kg), after 4 washes (96 h)	Total B (mg/kg) measured by aqua regia digest	Total extractable B (96 h) as fraction of total B (mg/kg) (%)
CLO14	10--30	30.5	117.9	26
CLO14	30-50	39.3	104.8	37
NAP13	30-60	16.4	72.5	23
NAP15-1	30-60	26.7	68.0	39
NAP15-2	30-60	31.6	106.9	30
NAP20	30--60	25.1	64.7	39
NAP16-1	30-60	8.0	36.6	22
NAP16-2	30-60	6.1	31.7	19
NAP6	10--30	48.9	138.3	35
NAP6	30--60	120.4	256.2	47
NAP7	30--60	26.9	78.7	34
NAP8	30--60	8.9	34.4	26
Average (± std dev)				31 ± 9

### 3.3 Electrical conductivity (EC)

Salinity is the presence of soluble salts, mainly chlorides and sulfates of sodium, magnesium and calcium, in waters or soils and results from the transport of salts by hydrologic processes and accumulation where there is preferential loss of water by evaporation or evapotranspiration (Sumner et al., 1998). Salt is very widely distributed in Australian soils, since all except the most permeable soils show some salt accumulation. The degree of salt accumulation in a soil depends on the degree of leaching of a soil (permeability), the presence of vegetation (evapotranspiration) and the amount and seasonal distribution of rainfall. Low- permeability soils also tend to be sodic in the root zone which has probably derived from the presence of shallow sodic water tables in the past (Shaw, 1999). Soil salinity levels are usually determined by measuring electrical conductivity (EC) of soil/water suspensions. Traditionally the EC of saturated extracts was used (EC<sub>e</sub>) but these measurements are time-consuming and difficult to determine, so commonly EC is determined more rapidly on a 1:5 soil:water suspension (EC 1:5) (Hazelton and Murphy, 2007). Shaw (1999) gives a detailed description of the conversion of EC 1:5 to EC<sub>e</sub> and a conversion table based on soil texture is given in

Appendix G. The NAP soils surveyed have been assessed against these tolerance thresholds based on clay content (Appendix G; Shaw, 1999) for the 0-10, 10-30, 30-60 and 60-90 cm depth profiles (Table 7). This assessment is also represented spatially across the region surveyed in Figs. 12a and 12b.

Within the 0-10 cm depth 41% of soils sampled in the NAP focus area would be categorised as low soil salinity and 41% as medium soil salinity. In the 10-30 cm depth 40% and 33% of the soils sampled were rated as low or medium soil salinity, respectively (Table 7). This classification corresponds to an estimated 10% yield reduction based on published yield response models. From this existing classification scheme (Shaw, 1999) soils with a medium or low salinity rating would impact crops that are considered moderately tolerant or moderately sensitive, respectively. Salt tolerance of some agricultural crops is given in Appendix H. Some of the crops being considered to be grown in the expansion area of the NAP are almonds, grapes, onions, and potato and these crops are classified in the category of moderately sensitive ( $EC_e 0.95 - 1.9 \text{ dS/m}$ ) (Appendix H), which equates to an EC 1:5 range of  $0.07 - 0.3 \text{ dS/m}$  (Shaw, 1999; Appendix G). Results from this survey of soils in the focus area would suggest that current salt levels in the surface soils would impact on crop growth of these horticultural crops.

The impact of soil salinity in the surface soils however, could be moderated by irrigation management and flushing soluble salts out of the root zone with better quality water (provided such a source of water was available) prior to planting and during the growing season. The impact of an impermeable sub-surface however would need to be considered due to the risk of soluble salts moving back into the root zone with water rising with capillary action as the surface soil dries. Consideration of impermeable sub-surface layers is discussed further in the section on sodicity. The irrigation and management practices in the proposed NAP area are expected to be similar to those in the existing horticulture area in Virginia. Consequently, the findings of Ryan and Kelly (2014) are relevant to the proposed NAP area. These authors found, after 14 years of irrigation with recycled water in the Virginia area, no significant difference in the salinity of the 0-20 cm soils for un-irrigated broadacre, and soils irrigated with bore water or recycled water (RW). Below 20 cm depth however, soils irrigated with bore water had lower EC values compared with un-irrigated soils and those irrigated with RW. In soils up to 60 cm depth there was little difference in EC values between the latter two. Below 60 cm however, the EC values in the un-irrigated soils were approximately 1.5 x that in the soils irrigated with RW. They concluded that salinity would not be a major yield limiting parameter for potatoes or olives, but levels were bordering on thresholds for yield declines for grape vines and almonds under RW irrigation (Ryan and Kelly, 2014). This would suggest that the current management practices by growers in Virginia are providing a suitable leaching fraction to avoid salt build-up in the root zone. It is expected that, due to the close proximity of Virginia to the proposed expansion region, irrigation management practices would be similar between the two regions.

**Table 7. Number (% of total) soils from NAP survey (0-10 cm, 10-30 cm, 30-60 cm and 60-90 cm) within each clay (%) and 1:5 EC threshold (dS/m) range based on soil salinity criteria (Shaw, 1999, Appendix G).**

Depth cm	Plant response	Soil salinity rating	Total <sup>1</sup>	EC 1:5 Range	10-20% clay	EC 1:5 Range	20-40% clay	EC 1:5 Range	40-60% clay	EC 1:5 Range	60-80% clay
0-10	Sensitive	Very low	5 (17%)	<0.07	2 (11%)	<0.09	3 (30%)	<0.12		<0.15	
	Moderately sensitive	Low	12 (41%)	0.07-0.15	5 (28%)	0.09-0.19	6 (60%)	0.12-0.24	1 (100%)	0.15-0.3	
	Moderately tolerant	Medium	12 (41%)	0.15-0.34	11 (61%)	0.19-0.45	1 (10%)	0.24-0.56		0.3-0.7	
	Tolerant	High		0.34-0.63		0.45-0.76		0.56-0.96		0.7-1.18	
	Very tolerant	Very high		0.63-0.93		0.76-1.21		0.96-1.53		1.18-1.87	
	Too saline <sup>2</sup>	Extreme		>0.93		>1.21		>1.53		>1.87	

Table 7 contd. Number (% of total) soils from NAP survey (0-10 cm, 10-30 cm, 30-60 cm and 60-90 cm) within each clay (%) and 1:5 EC threshold (dS/m) range based on soil salinity criteria (Shaw, 1999, Appendix G).

Depth cm	Plant response	Soil salinity rating	Total <sup>1</sup>	EC 1:5 Range	10-20% clay	EC 1:5 Range	20-40% clay	EC 1:5 Range	40-60% clay	EC 1:5 Range	60-80% clay
10-30	Sensitive	Very low	8 (27%)	<0.07	1 (10%)	<0.09	3 (25%)	<0.12	2 (33%)	<0.15	2 (100%)
	Moderately sensitive	Low	12 (40%)	0.07-0.15	3 (30%)	0.09-0.19	5 (42%)	0.12-0.24	4 (67%)	0.15-0.3	
	Moderately tolerant	Medium	10 (33%)	0.15-0.34	6 (60%)	0.19-0.45	4 (33%)	0.24-0.56		0.3-0.7	
	Tolerant	High		0.34-0.63		0.45-0.76		0.56-0.96		0.7-1.18	
	Very tolerant	Very high		0.63-0.93		0.76-1.21		0.96-1.53		1.18-1.87	
	Too saline <sup>2</sup>	Extreme		>0.93		>1.21		>1.53		>1.87	

**Table 7 contd. Number (% of total) soils from NAP survey (0-10 cm, 10-30 cm, 30-60 cm and 60-90 cm) within each clay (%) and 1:5 EC threshold (dS/m) range based on soil salinity criteria (Shaw, 1999, Appendix G).**

Depth cm	Plant response	Soil salinity rating	Total <sup>1</sup>	EC 1:5 Range	10-20% clay	EC 1:5 Range	20-40% clay	EC 1:5 Range	40-60% clay	EC 1:5 Range	60-80% clay
30-60	Sensitive	Very low	2 (6%)	<0.07		<0.09	1 (6%)	<0.12	1 (9%)	<0.15	
	Moderately sensitive	Low	14 (40%)	0.07-0.15	2 (29%)	0.09-0.19	8 (47%)	0.12-0.24	4 (36%)	0.15-0.3	
	Moderately tolerant	Medium	10 (29%)	0.15-0.34	5 (71%)	0.19-0.45	3 (18%)	0.24-0.56	2 (18%)	0.3-0.7	
	Tolerant	High	8 (23%)	0.34-0.63		0.45-0.76	5 (29%)	0.56-0.96	3 (27%)	0.7-1.18	
	Very tolerant	Very high	1 (3%)	0.63-0.93		0.76-1.21		0.96-1.53	1 (9%)	1.18-1.87	
	Too saline <sup>2</sup>	Extreme		>0.93		>1.21		>1.53		>1.87	

**Table 7 contd. Number (% of total) soils from NAP survey (0-10 cm, 10-30 cm, 30-60 cm and 60-90 cm) within each clay (%) and 1:5 EC threshold (dS/m) range based on soil salinity criteria (Shaw, 1999, Appendix G).**

Depth cm	Plant response	Soil salinity rating	Total <sup>1</sup>	EC 1:5 Range	10-20% clay	EC 1:5 Range	20-40% clay	EC 1:5 Range	40-60% clay	EC 1:5 Range	60-80% clay
60-90	Sensitive	Very low	1 (4%)	<0.07		<0.09	1 (6%)	<0.12		<0.15	
	Moderately sensitive	Low	6 (23%)	0.07-0.15		0.09-0.19	4 (25%)	0.12-0.24	2 (50%)	0.15-0.3	
	Moderately tolerant	Medium	9 (35%)	0.15-0.34	2 (33%)	0.19-0.45	6 (38%)	0.24-0.56	1 (25%)	0.3-0.7	
	Tolerant	High	3 (12%)	0.34-0.63	2 (33%)	0.45-0.76		0.56-0.96	1 (25%)	0.7-1.18	
	Very tolerant	Very high	3 (12%)	0.63-0.93	1 (17%)	0.76-1.21	2 (13%)	0.96-1.53		1.18-1.87	
	Too saline <sup>2</sup>	Extreme	4 (15%)	>0.93	1 (17%)	>1.21	3 (19%)	>1.53		>1.87	

<sup>1</sup> Total across each clay content (%) within each soil depth for the soil salinity category; <sup>2</sup> Generally considered too saline for crops (Shaw, 1999).



b)

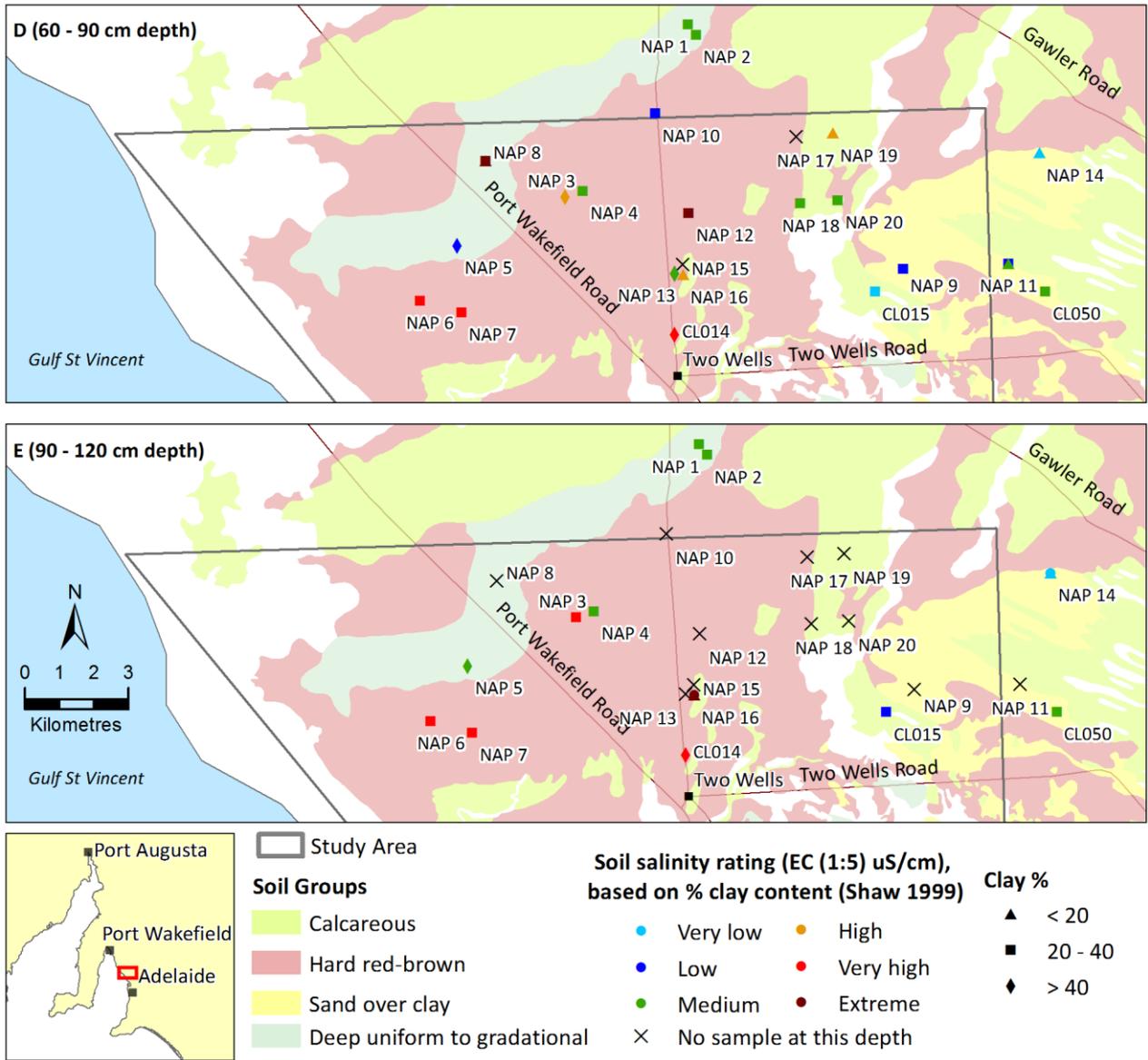


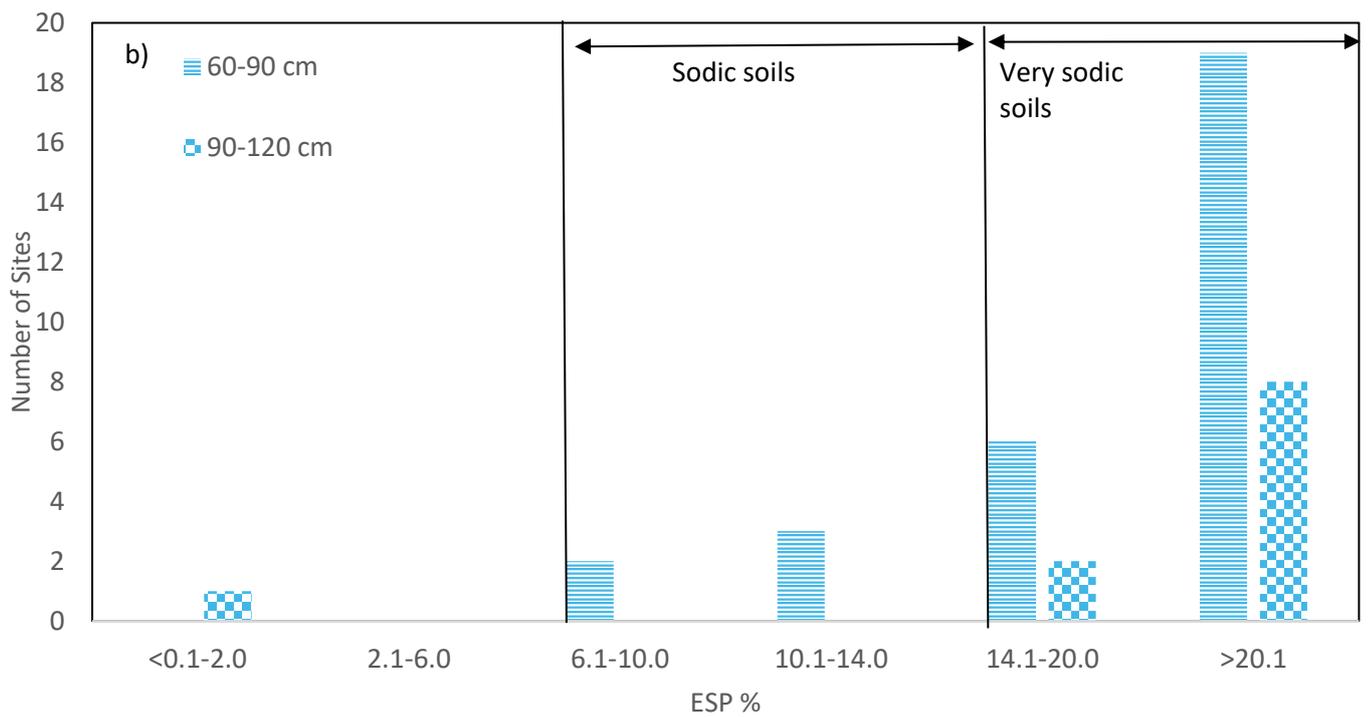
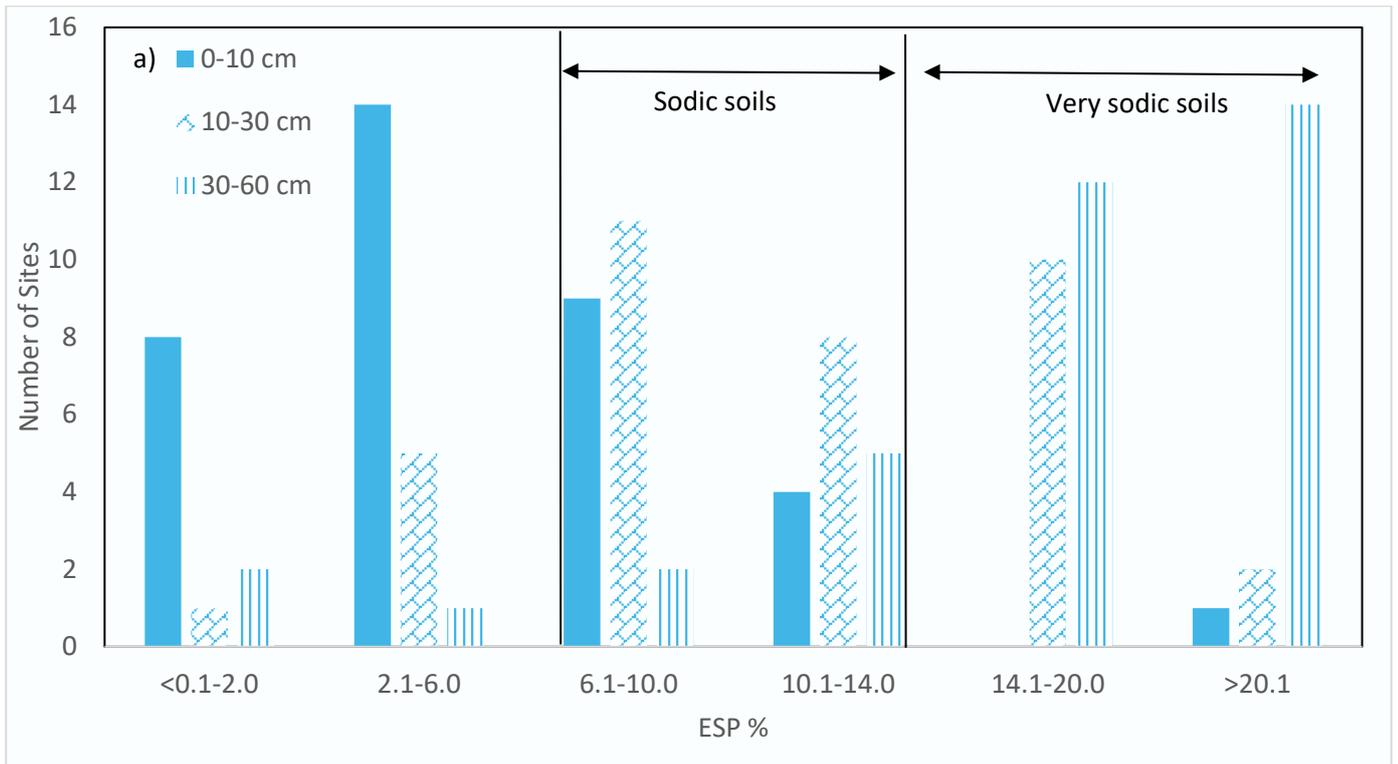
Figure 12 cont. Spatial distribution of salinity category based on EC (1:5) (dS/m) and clay content (Shaw, 1999, Appendix G) for a) surface soils 0-10 cm, 10-30 cm and 30-60 cm and b) sub-surface soils (60-90 cm and 90-120 cm). The number of samples at the lower depth were limited.

### 3.4 Sodicity and exchangeable sodium percentage (ESP %)

Sodicity leads to the deterioration of the physical structure of soils because it causes or enhances swelling and dispersion of clay particles (Sumner, 1993). This leads to waterlogging, crusting and hard-setting resulting in poor water infiltration, decreased plant-available water, poor leaching and perched water tables. These issues are discussed extensively by others (Rengasamy and Olsson, 1993; Levy et al., 1998; Murray and Grant, 2007). In Australia, Northcote and Skene (1972) define sodic soils as having ESP > 6% in the top metre and highly sodic soils having ESP > 14%.

The distribution of ESP in soils in the NAP is given in Fig. 13 and Table 8. This shows increasing occurrence of sodic soils with depth with 36% of 0-10 cm soils being sodic and 3% highly sodic; 49% of 10-30 cm soils sodic and 35% highly sodic; and 19% of 30-60 cm sodic and 72% highly sodic.

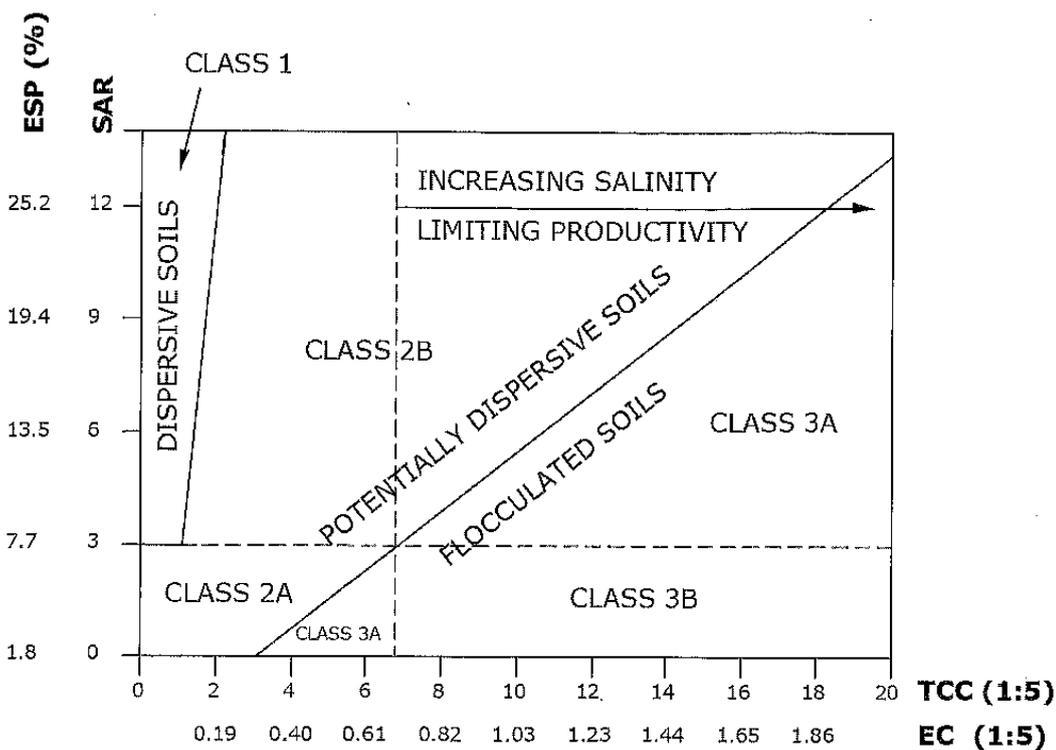
The problems of clay dispersion and swelling only arise when the EC value is too low to maintain the soil clay in a flocculated condition at a given ESP value. Swelling and dispersion of soils is also affected by clay mineralogy, surface charge density and specific surface area of clays (Levy et al., 1998). Consequently, for management purposes Rengasamy et al. (1984) developed a classification scheme for prediction of dispersive behaviour in A horizons of red-brown earths. This was then modified in Hazelton and Murphy (2007) as shown in Fig. 14. While this predictive relationship was developed for red-brown earths it has been applied to all the soils in the NAP focus area as a guide for the proportion of the area that may potentially be problematic regarding sodicity. The definitions of the dispersion classes are given in Rengasamy et al. (1984) and Hazelton and Murphy (2007) but the soils from this study fell into three main classes (1, 2A and 2B) which are defined in Table 9. Briefly, in this existing classification system Class 1 soils are defined as dispersive and Class 2A and 2B soils are defined as potentially dispersive. In the 0-10 cm soils the majority of soils fell into the categories 2A or 2B (Fig. 15A), indicating that they are potentially dispersive soils. Deeper in the profile (10-30, 30-60 and 60-90 cm) the ESP% and EC increased and a greater proportion of the soils were categorised as dispersive soils (Class 1) (Fig. 15B – 15E). The implications for changing the land use in the area to horticulture, where mechanical stress due to working the soil to a greater extent or frequency than currently occurs under the present agricultural activities of cereal production or pasture, could potentially lead to a greater incidence of soil physical deterioration. All data are presented in Appendix I.



**Figure 13. Distribution of ESP (%) across the a) surface and b) subsurface soils sampled in the NAP region. The thresholds for soils considered sodic (6-14%) and very sodic (>14%) are shown.**

**Table 8. Percentage of soils within each depth that are within each exchangeable sodium percentage (ESP %) or ESP and electrical conductivity (EC 1:5) threshold range based on the dispersion categories of Rengasamy et al. (1984).**

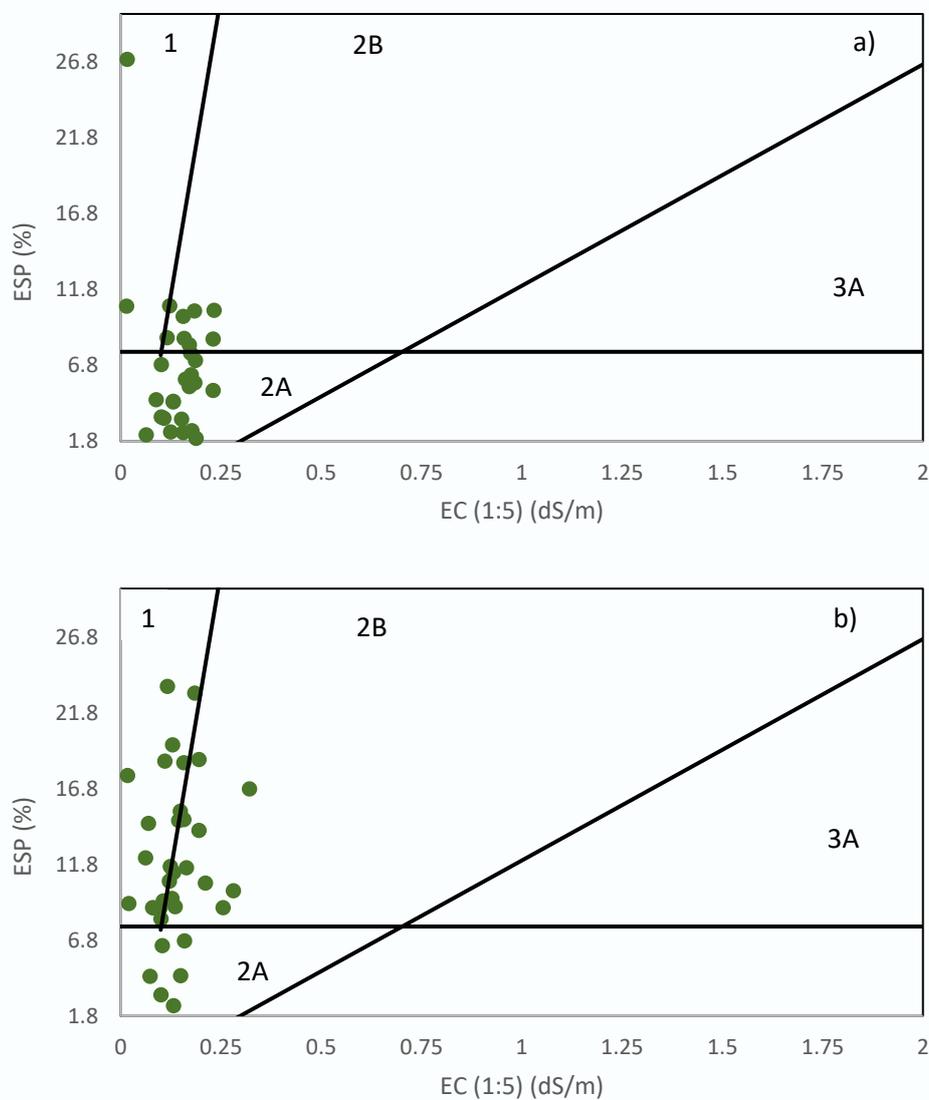
ESP or ESP and EC threshold range	0-10 cm	10-30 cm	30-60 cm	60-90 cm	90-120 cm
Total number of soils	36	37	36	32	11
ESP < 6	61.1%	16.2%	8.3%	0.0%	9.1%
ESP 6-14	36.1%	48.6%	19.4%	15.6%	9.1%
ESP > 14	2.8%	35.1%	72.2%	84.4%	81.8%
ESP > 7.7 & EC 0-0.2 dS/m	22.2%	67.6%	44.4%	21.9%	18.2%
ESP > 7.7 & EC > 0.2 dS/m	5.6%	10.8%	41.7%	71.9%	63.6%
EC > 0.7 dS/m	0.0%	0.0%	8.3%	28.1%	27.3%



**Figure 14. Relationship between ESP (%) and EC (1:5) (dS/m) as a guide for predicting soil dispersion. The classes of dispersion are indicated on each figure. From: Hazelton and Murphy (2007) p95.**

**Table 9. Definition of the main dispersion categories for the soils from the NAP study (Rengasamy et al., 1984; Hazelton and Murphy, 2007)**

Dispersion class	Definition
1	Dispersive soils that disperse spontaneously in water. These are unstable, sodic soils that can have severe management and erosion problems.
2A	Soils that have few structural problems if managed using minimum tillage techniques or if maintained under continuous pasture growth.
2B	Unlike Class 2A soils, these soils become spontaneously dispersive (Class 1) when leached without the addition of calcium compounds, and if there is no generation of electrolytes in the soil due to mineral weathering.



**Figure 15. Distribution of ESP (%) and EC (1:5) (dS/m) for soils from NAP focus area at a) 0-10 cm, b) 10-30 cm, c) 30-60 cm, d) 60-90 cm, and e) 90-120 cm based on the dispersive classes from Rengasamy et al., 1984; Hazelton and Murphy, 2007 and shown in Fig. 13. The dispersive classes, as defined in Table 9, are shown on each figure.**

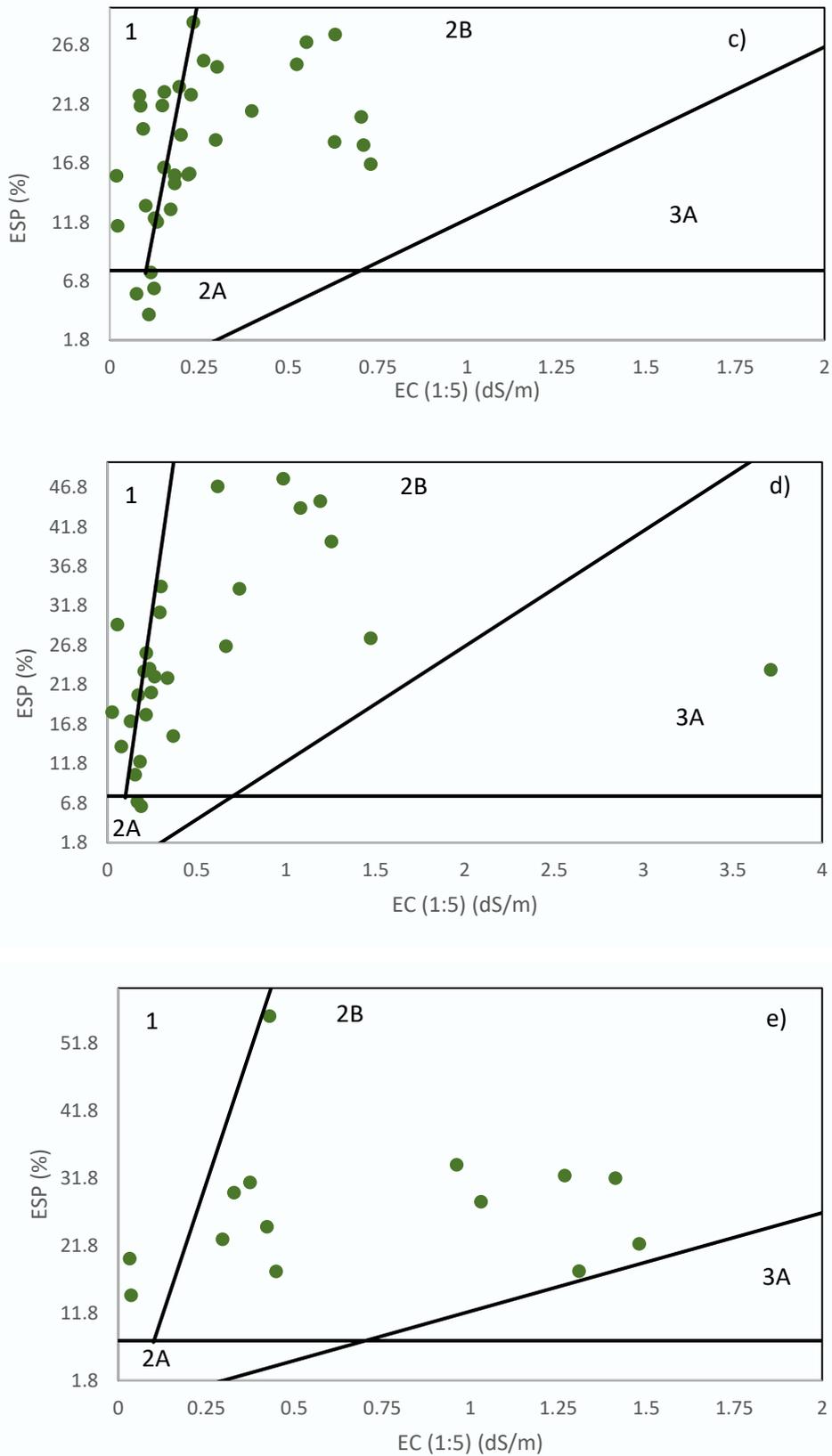


Figure 15 contd. Distribution of ESP (%) and EC (1:5) (dS/m) for soils from NAP focus area at a) 0-10 cm, b) 10-30 cm, c) 30-60 cm, d) 60-90 cm, and e) 90-120 cm based on the dispersive classes from Rengasamy et al., 1984; Hazelton and Murphy, 2007 and shown in Fig. 14. The dispersive classes, as defined in Table 9, are shown on each figure.

## Effect of irrigation water on sodicity

The electrolyte concentration of irrigation water will be an important factor in determining whether the potentially dispersive soils show any deterioration in the physical state of the soil during the irrigation season. The hydraulic conductivity of a soil depends on both  $\text{Na}^+$  and the total salt concentration of the percolating solution. High hydraulic conductivity may be maintained, even at high ESP values, if the solution concentration is above a critical value (Shainberg and Letey, 1984). The impact of irrigation on soil structure has been covered extensively elsewhere (Levy et al., 1998; Murray and Grant, 2007) but briefly, while a soil remains both sodic and saline, dispersion is decreased. However, as the soil becomes even more sodic at a given salinity level, or the salinity decreases, due to leaching with rain or irrigation with a water source of low salinity, the structure of the soil becomes increasingly unstable with increasing likelihood of dispersion occurring.

The capacity of irrigation to impact soil sodicity depends upon a number of factors including soil type, management, time and water quality. The most important water quality factors are total salinity and the sodium adsorption ratio (SAR) where

$$\text{SAR} = [\text{Na}^+] / \text{square root } ([\text{Ca}^{2+} + \text{Mg}^{2+}]) \text{ where concentrations are in milli-moles/L}$$

The SAR of the recycled waste water, currently used in the Virginia horticultural area, ranged from 6.7 to 11.3 with a median of 8.1 from July 2012 to Dec 2016 (Fig. 16). The impact on a soil of water with a high SAR also depends upon the CEC of the soil, the time over which this irrigation water is applied and the management. Irrigation-induced sodicity of soil is complicated by the fact that irrigation with saline/sodic water in spring/summer may alternate with leaching with fresh water during winter rainfall. This may leach salts and decrease soil salinity but have a lesser effect upon sodicity. Consequently, the likelihood of dispersion is at its highest just before the irrigation season commences. Further, management practices such as no mulching, frequent small irrigation events or the use of fine sprays tend to increase both SAR and salinity since these practices increase crop transpiration or evaporation of water from the soil (Rengasamy and Olsson, 1993; Murray and Grant, 2007). Rengasamy and Olsson (1993) summarised findings from several experiments on the effects of saline-sodic irrigation water on soil properties and plant productivity and noted that if the SAR of the irrigation water is  $>3$  and the leaching fraction is below 0.5,  $\text{Na}^{2+}$  accumulates in soil layers. The leaching fraction in subsoils is generally considerably less than in surface soils and consequently, the EC and SAR of subsoils in irrigated soils generally increases to an even greater extent than in surface soils.

## Management of sodic soils

There are numerous articles and guidelines about the management of sodic soils. Rengasamy and Olsson (1993) provide a review of irrigated agriculture in Australia and state most of the irrigated soils in Australia need reclamation of sodicity of soil layers at least in the root zone. For irrigated agriculture to be sustainable,

the sodic soils need to be managed by the application of gypsum, suitable tillage and the addition of artificial drainage. Irrigation without appropriate drainage leads to the buildup of salts in soil solutions and can develop perched watertables.

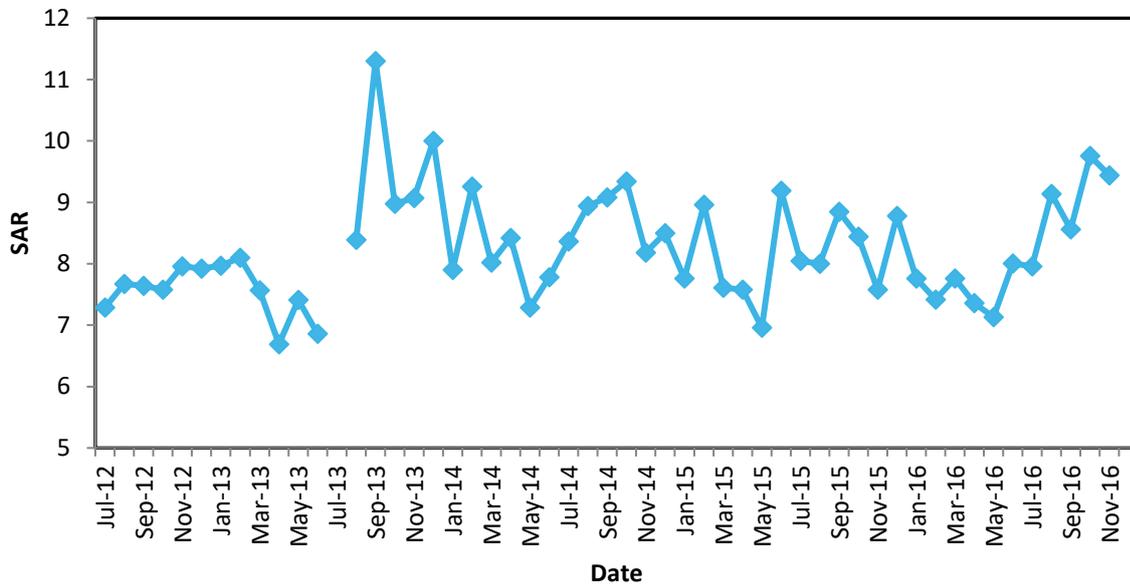


Figure 16. Sodium adsorption ratio (SAR) of recycled waste water after DAFF treatment from July 2012 to Dec 2016. Data provided by SA Water.

## 4 Conclusions

This survey of soils to a depth of between 90-120 cm, across the area under consideration for expansion of irrigated horticulture in the NAP region, has provided critical baseline data that can be utilised in the monitoring of soils over time following irrigation with recycled water, to provide guidance around the main risk parameters to be measured in soil and/or areas not previously studied. The survey has also highlighted several soil constraints that will need to be managed to ensure yields are not adversely impacted over time. Potentially suitable management options are discussed in the Task 2 report.

Different crops have different optimum pH ranges for growth and generally the ideal pH range for plant growth is between 5.5 and 8, and for most vegetables it is  $\text{pH}_w$  5 to 7. Twenty-three percent of the surface NAP soils (0-10 cm, 10-30 cm and 30-60 cm) analysed had  $\text{pH}_w < 8.0$  and 77% had  $\text{pH}_w \geq 8$ ; generally,  $\text{pH}_w$  increased with depth. Soil  $\text{pH}_w > 8.5$  are considered highly alkaline and 52% of the NAP surface soils sampled had  $\text{pH}_w > 8.5$ . Soil management options will need to be implemented for the extremely alkaline soils to provide micronutrients to crops and/or to lower soil pH.

Native soil B concentrations in some locations (predominantly in Hard red brown texture contrast soils) were elevated ( $> 1$  mg/L in soil solution). It has been suggested that soil solution B concentrations  $< 0.5$  mg/L are not toxic for most plants, but above this value many plants may be adversely impacted. Several of the crops being considered for production in the NAP are sensitive to B (e.g. grape, onion, carrot, potato) and this data suggests that the native B in some of the soils in the region may already be at concentrations that are limiting or toxic to crop growth before any irrigation commences. To assess the release of native B into soil solution in a scenario representative of multiple applications of irrigation water, B was sequentially extracted four times from a subset of soils. Sequential extractions of B (representative of multiple irrigations) showed that 19-48% of total soil B was easily extracted. This suggests that native B in some soils in this region will be mobilised into solution and potentially be available for plant uptake or transport through the soil profile to groundwater.

Several crops are being considered to be grown in the expansion area of the NAP. These include almonds, grapes, onions, potato, bean, carrot and lettuce, all of which are classified with a very low to low soil salinity tolerance rating (saturated paste electrical conductivity:  $\text{EC}_{se} < 1.9$  dS/m). This classification corresponds to an estimated 10% yield reduction based on published yield response models. A yield reduction of 10% for these crops would be expected in 82% of the 0-10 cm depth, 73% of 10-30 cm depth and 94% of the 30–60 cm depth, of the soils sampled in this study. Further, in the 60-90 cm depth 17% of the soils surveyed would be considered too saline for crop growth ( $\text{EC}_{se} > 12.2$  dS/m). The impact of soil salinity in the surface soils, however, could be moderated by irrigation management and flushing soluble salts out of the root zone prior to planting, during the growing season or between seasons. The potential impact of an impermeable sub-

surface at shallow depth should be considered due to the risk of soluble salts moving back into the root zone as water rises due to capillarity in response to plant transpiration and soil evaporation

In the soils surveyed sodicity increased with increasing depth: 36% of 0-10 cm soils were sodic and 3% highly sodic; 49% of 10-30 cm soils were sodic and 35% highly sodic; and 19% of 30-60 cm soils were sodic and 72% highly sodic. However, the problems of clay dispersion and swelling only arise when the EC value is too low to maintain the soil clay in a flocculated condition at a given ESP value. An existing classification scheme for the prediction of dispersive behaviour in A horizons of red-brown earths was applied to all the surveyed soils as a guide for determining the proportion of the soils sampled that may potentially be sodic.

In the 0-10 cm depth interval the majority of soils surveyed were classified as potentially dispersive soils (Class 2A or 2B). Deeper in the profile (10-30, 30-60 and 60-90 cm) the ESP% and salinity (EC) increased and a greater proportion of the soils were categorised as dispersive soils (Class 1). Horticultural practices may require the soil to be worked to a greater extent or frequency than currently occurs under the present agricultural activities of cereal production or pasture, the soil may experience greater mechanical stress. The implications of this potential increased mechanical stress, could potentially lead to a greater incidence of soil physical deterioration which could lead to a reduction in infiltration, water logging, etc. Soil sodicity can be managed with applications of gypsum, and various forms of compost, which is current practice in the existing horticulture area in Virginia.

The expansion of irrigated agriculture in the region north of the current horticultural production area in Virginia is an opportunity for South Australia to provide the growing demand for premium food and agribusiness products. However, prior to any expansion occurring, further baseline soil analyses would be required to identify and, as required, remediate any soil constraints to ensure sustainability of the region. While this study has delivered an unprecedented set of valuable soil data, the heterogeneity in soil properties makes it difficult to extrapolate the current results based on a relatively small number of samples to the entire NAP region. Where new agriculture developments are planned, site-specific soil investigations are encouraged as these would provide the best information for decision making. The outputs from Task 1 can serve as a guide which risk parameters to focus on and what the most cost-effective tools are for data collection.

Soil data from this project will be available for integration within existing South Australian data repositories.

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# Appendix A – Analysis of soils using infrared spectroscopy

## Overview of infrared spectroscopy approach

In this study, infrared (IR) spectroscopy was used as an alternative to conventional soil analysis methods to predict physical and chemical properties in a large number of soil samples. IR analysis is rapid and inexpensive compared to conventional wet chemistry methods, especially because it can provide us with simultaneous prediction of various chemical and physical properties using only soil IR spectra (Palm et al., 2007; Forouzangohar et al., 2009). Moreover, the repeatability of IR analysis over time, and its reproducibility among different soil laboratories exceeds the performance of conventional techniques (Palm et al., 2007).

A total of 155 soil samples were scanned in 4 replications using an IR spectrometer resulting in a total of 620 soil IR spectra. The 155 samples were coming from 36 soil profiles/sampling points: 10 profiles previously collected as part of previous projects and were utilised in this study, as well as, 13 new soil profiles collected specifically for this study in 2 replications (i.e. 26 soil profiles). The selection of new 13 soil sampling locations was assisted with a soil IR survey across the study landscape. The 26 new soil profiles were divided in various depths, air-dried and passed through a 2 mm sieve in preparation for IR spectral analysis along with the 10 archive soil profiles (i.e. resulting in a total of 155 soil samples).

A representative calibration/validation subset was chosen from the complete set of 155 samples. This subset was subjected to reference analysis of selected soil properties. The results of reference analysis along with corresponding soil IR spectra were used to predict the selected soil properties in the remaining soil samples (i.e. unknowns). The calibration models for making predictions were developed using partial least-squares regression (PLSR) in an R environment (R Core Team, 2017) and using the “pls” package (Mevik and Wehrens, 2007).

## Soil properties

A total of 12 soil properties were selected to be predicted using -IR analysis, namely, total carbon (TC %), total organic carbon (TOC %), total nitrogen (TN), cation exchange capacity (CEC cmol/kg), exchangeable potassium (Exch. K cmol/kg), exchangeable calcium (Exch. Ca cmol/kg), exchangeable magnesium (Exch. Mg cmol/kg), exchangeable sodium (Exch. Na cmol/kg), calcium carbonate (%), clay (%), sand (%), silt (%). In addition, saturated hydraulic conductivity (Ksat) and soil water retention (i.e. volumetric water content at 0.01, 4, 8, 33, 60, 100 and 1500 kPa) were also predicted using IR analysis.

## IR spectroscopy

A handheld FTIR spectrometer (4200 FlexScan by Agilent A2 Technologies, CA, USA) was optimised primarily for the IR range within the electromagnetic radiation spectrum. A diffuse reflection sampling interface was used directly pointed at the surface of 2 mm sieved samples. Spectra were acquired over 6000-650  $\text{cm}^{-1}$  with a resolution of 8  $\text{cm}^{-1}$ . In order to quantify and correct the background signal intensity, a background scan (average of 45 scans) was collected before every sample scan. Similarly, for each soil sample, a total of 45 scans was acquired and averaged to produce a reflectance spectrum of the individual sample and was replicated 4 times.

The optimum spectral range for FlexScan spectra was from 5000-775  $\text{cm}^{-1}$ . Therefore, we removed the two noisy ends of FlexScan spectra, i.e. the regions covering wavenumbers of greater than 5000  $\text{cm}^{-1}$  and smaller than 775  $\text{cm}^{-1}$ . Spectral outliers were then identified and removed from the spectral data followed by baseline-correction and detrend transformation. In order to reduce the noise in the spectra, principal component analysis (PCA) was applied to the data and the spectral data were reconstructed using only the first 10 PCs. After these pre-treatment steps the spectra were ready to be used in the development of IR calibration models.

## Building IR calibration models

A principle component score plot for the spectra from the NAP soils and spectra for South Australian soils from another project was developed to determine whether existing IR calibration models from a GRDC-funded project could be used (Apx Figure 1) but there was insufficient overlap between the spectra of the soils from the NAP and those from the GRDC-funded project to allow the use of the existing models.

The calibration models for predicting soil properties were developed between IR spectra (i.e. predictor variables) and reference soil property values (i.e. response variables) based on the method introduced by Haaland and Thomas (1988). The matrices of corresponding IR spectra and soil properties were regressed, and prediction models were fit in an R environment (R Core Team, 2017). Calibrations were developed using cross validation and segment sizes of 20 to determine the optimal number of PLSR components (Arlot and Celisse, 2010). We then used the resulting models to predict the soil properties from the acquired IR spectra.

## Model validation and calculation of uncertainty

A cross validation technique was used for both model calibration (as mentioned above) as well as model validation. Cross validation divides the data into segments. By selecting the segment size of 20 spectra, we randomly divided the calibration set into 6 groups (i.e. segments), and validation was performed 6 times. In turn, one group was used as a validation set, and the remaining 5 groups formed the calibration set as per the method described elsewhere (Forouzangohar et al., 2008). The performance of the calibration models

was assessed using two widely used and accepted statistics, namely variance explained in prediction as R<sup>2</sup>, and estimated error as RMSEP (i.e. Root Mean Square Error of Prediction).

## Soil IR survey of the study area

The IR tool in this study was also used in a context different from making predictions that is soil variability survey across the study landscape. In this context, IR spectral variability of top soil was considered as a surrogate to soil variability. This approach was used to guide the selection of 13 new sampling sites in the study area. The objective of this step was to enable us in choosing new sampling sites which potentially capture the main soil types across the study area.

A sampling campaign was conducted to collect 32 topsoil samples from the accessible sites over the study area. The soil samples were air-dried in plastic bags and with no further processing were scanned with FlexScan in 4 replications (as per the method explained in section 3). Cluster analysis was performed on the acquired spectra in order to divide the set of 32 samples into 13 classes so that similar spectra were in the same class (i.e. classes of spectral variability). For this exercise, the K-means method of cluster analysis (Miller and Miller, 2005) was used in an R environment.

## IR model validation results

The validity of IR prediction models was tested by cross-validation. As shown in Apx Table 1 and Apx Figure 2, 61-98% of the variation between reference and predicted soil properties was explained by the corresponding IR prediction models. The best goodness of fit belonged to the prediction of calcium carbonate concentration with an R<sup>2</sup> of 0.98, and RMSEP of 2.74. The weakest prediction, on the other hand, was for TOC concentration with R<sup>2</sup> of 0.61 and RMSEP value of 0.82. The relatively weak performance of IR prediction models for TOC was perhaps due to the presence of calcium carbonate and the small size of calibration set (n=30 soil samples). On average, 87% of variation between reference and predicted soil properties was explained by the IR prediction models which showed an acceptable (>60%) performance across the board for the selected 12 soil properties.

**Apx Table 1. Performance statistics of the IR prediction models build by FlexScan spectra for the prediction of soil properties in 2 mm sieved samples.**

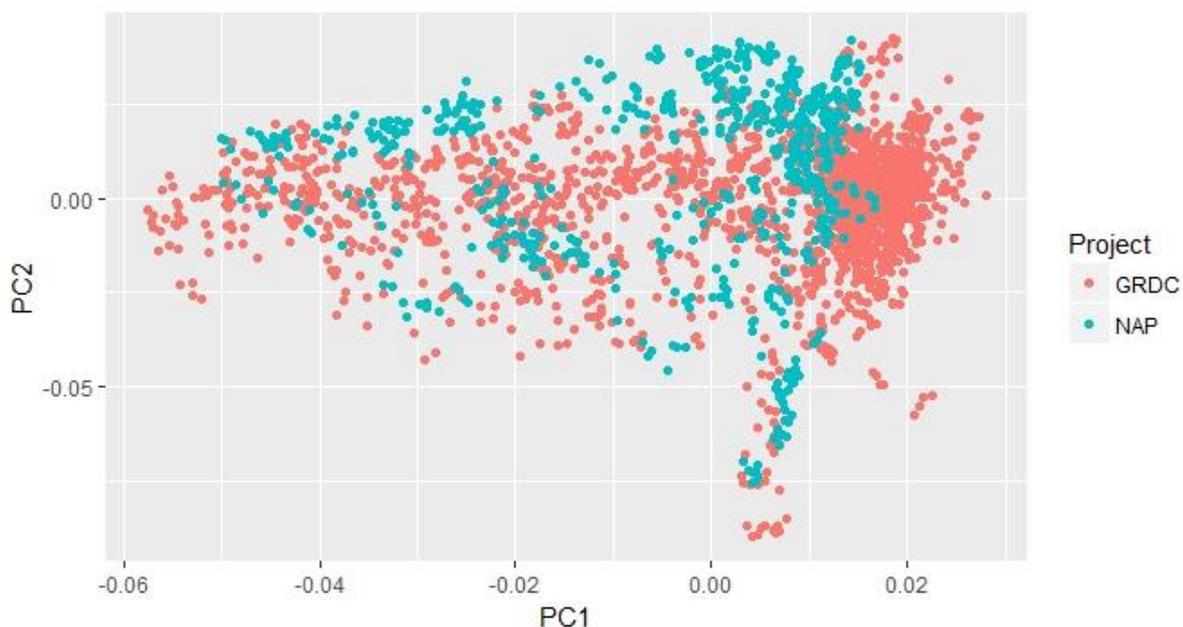
Soil properties	n	R <sup>2</sup>	RMSEP
Total C	35	0.96	0.36
Total N	35	0.83	0.03
Total Organic C	30	0.61	0.82
Clay	33	0.93	3.60
Silt	33	0.86	4.25
Sand	33	0.95	4.21
Exch. Ca	30	0.79	1.97
Exch. Mg	30	0.92	0.92
Exch. Na	30	0.82	0.82
Exch. K	30	0.78	0.41
CEC	30	0.95	1.76
CaCO <sub>3</sub>	30	0.98	2.74
Saturated hydraulic conductivity (Ks)	57	0.77	1 × 10 <sup>-5</sup>
Volumetric water content <sup>1</sup> (0.01kPa)	57	0.79	0.026
Volumetric water content (4kPa)	57	0.73	0.027
Volumetric water content (8kPa)	57	0.95	0.019
Volumetric water content (33kPa)	57	0.95	0.024
Volumetric water content (60kPa)	57	0.95	0.022
Volumetric water content (100kPa)	57	0.96	0.020
Volumetric water content (1500kPa)	55	0.95	0.018

<sup>1</sup> matric potential of measurement given in brackets

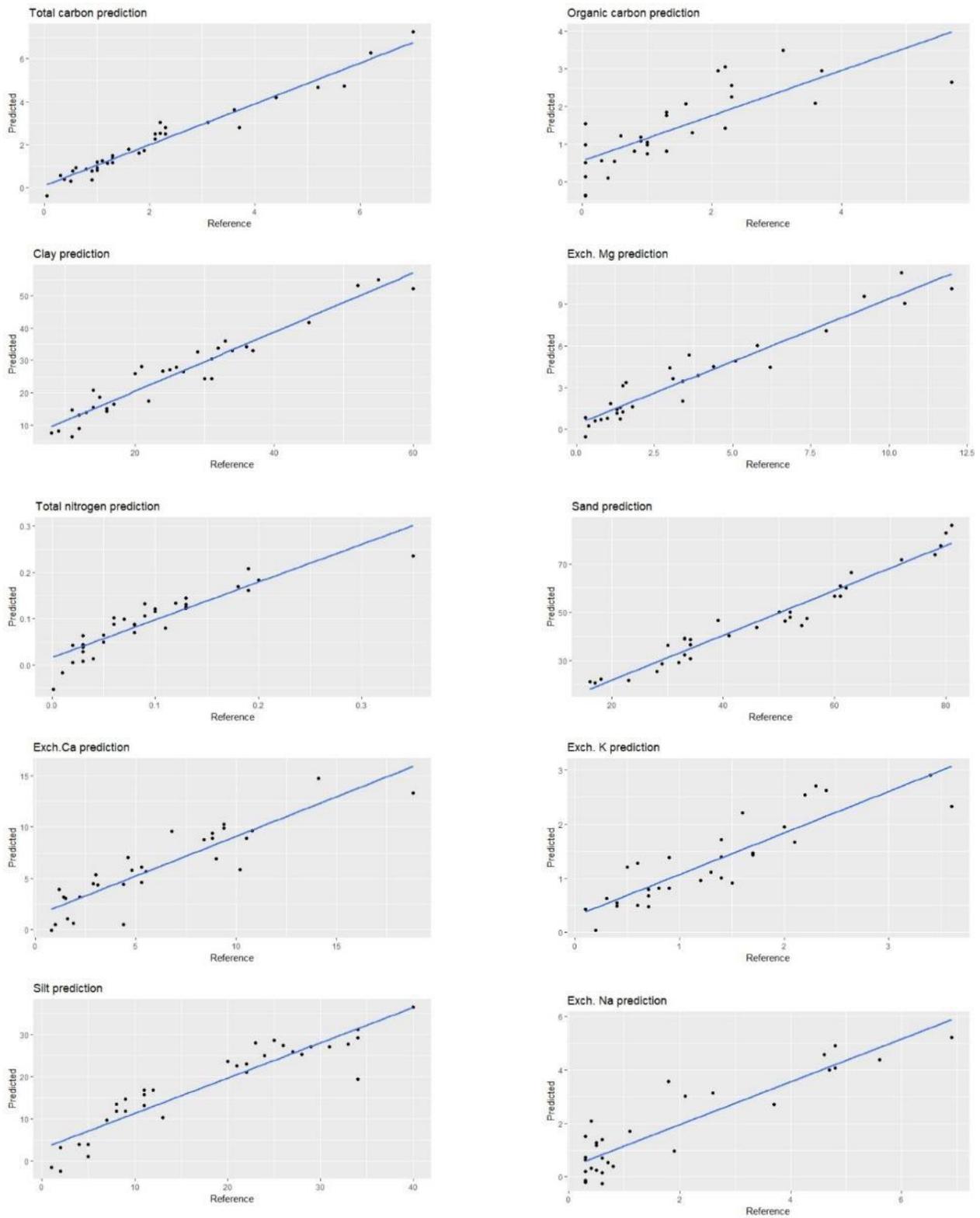
## Correcting for improbable predictions

The mathematical approach used for building IR prediction models provides predicted values that are associated with errors. The average of probable errors in predictions is reported, and that means the predictions could be suffering from over- or under-estimation of values when compared to the reference values. Therefore, at times we encounter predicted values that are improbable based on our knowledge of soil systems. For example, predicted negative silt content in a soil sample that is made up of nearly 100 percent sand. In order to deal with such improbable predictions criteria were developed to adjust the predictions. These criteria needed to be logical and acceptable from a soil science perspective, and were used to correct the improbable predictions. In this study, the following criteria were used:

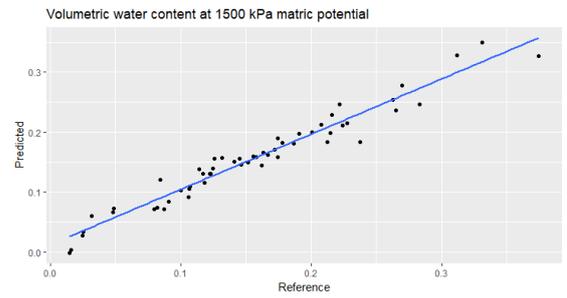
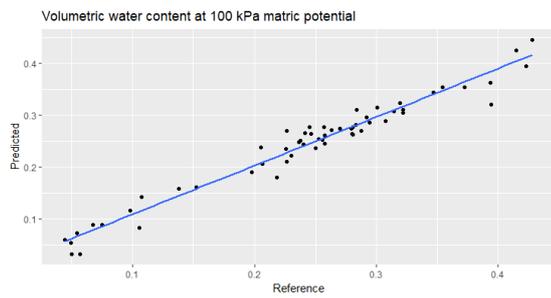
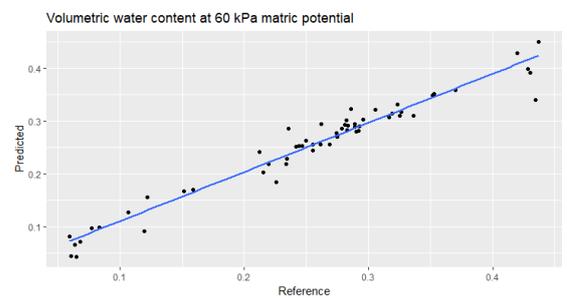
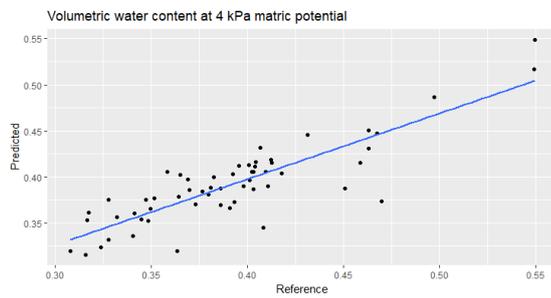
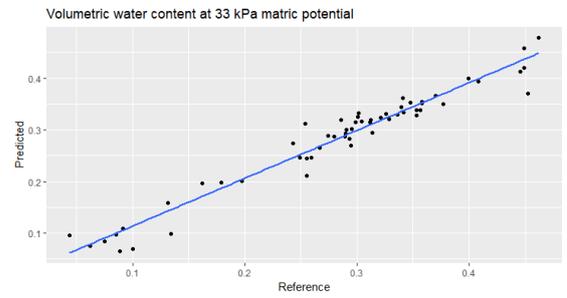
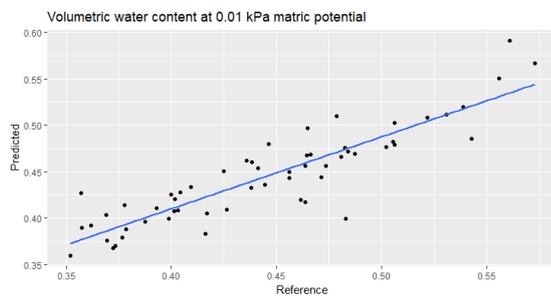
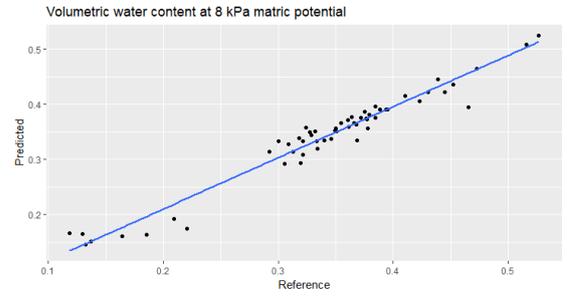
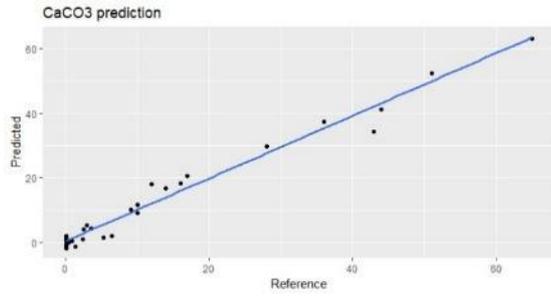
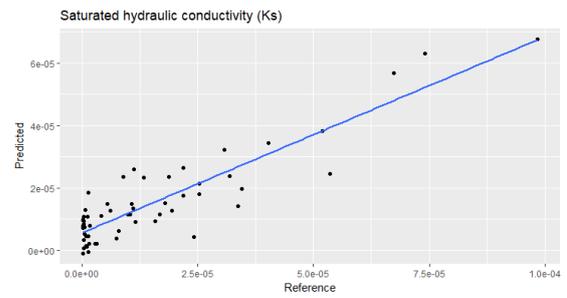
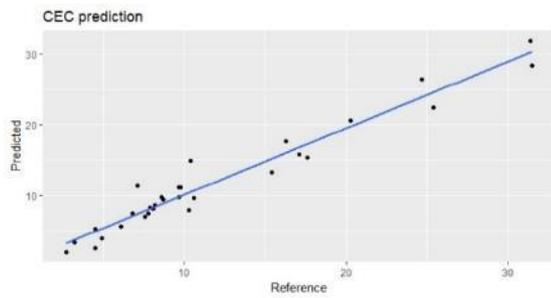
1. When the silt percentage was negative it was presented as zero. For example, in samples coming from the soil NAP 14, the IR model predicted large negative percentages of silt, and in fact, the field observation suggested the soil profile was predominantly sand.
2. Where the sand percentage was greater than 105%, these values were set to 100%.
3. For those samples that had  $TOC > TC$ , the TOC content was adjusted to be equivalent to the TC based on the fact that TC predictions had much higher accuracy (an  $R^2$  of 0.96 and error of 0.36 on average for TC compared with  $R^2$  of 0.61 and average error of 0.82 for TOC). It is worth noting that such cases happened only when the predicted carbonate content as  $CaCO_3$  was very low. This means that in theory we expected TOC and TC values to be very close, but the errors occurring in the prediction of both properties can result in predicted  $TOC > TC$ .



**Apx Figure 1. PCA score plot for PC-1 vs PC-2 for the NAP project soils and GRDC project soils.**



**Apx Figure 2. Regression plots for the prediction of 12 chemical properties and hydraulic conductivity and water retention determined at a range of matric potentials using FlexScan.**



**Apx Figure 2 contd. Regression plots for the prediction of 12 chemical properties and hydraulic conductivity and water retention determined at a range of matric potentials using FlexScan.**

## Appendix B – Details of wet chemistry methods

While all soils sampled in this survey were scanned using IR a subset of soils were selected for analysing using traditional wet chemistry methods for the development of the IR models for predicting selected soil properties. Details of the methods are given below (Apx Table 2).

**Apx Table 2. Summary of traditional wet chemistry methods used for validation of IR predictions of soil properties.**

Soil property	Method	Method <sup>1</sup>
Soil pH <sub>w</sub>	1:5 soil:solution in water	Method 4A1 p 38 Rayment and Lyons (2011)
Soil pH <sub>Ca</sub>	1:5 soil:solution in 0.01 M CaCl <sub>2</sub>	Method 4B2 p 41 Rayment and Lyons (2011)
Electrical conductivity (EC)	1:5 soil:solution in water	Method 3A1 p 20 Rayment and Lyons (2011)
Soil property	Method	Comments and method used for validating IR predictions of soil properties
Total carbon	Leco combustion method	Matejovic (1997)
Organic carbon	Determined by difference	Total organic carbon (TOC) = total carbon (C) – [inorganic C (%carbonate) X 0.12]
Calcium carbonate		Sherrod et al. (2002)
Exchangeable cations		Method 15D2 p 318 Rayment and Lyons (2011)
Cation exchange capacity (CEC)		Method 15D2 p 318 Rayment and Lyons (2011)
Exchangeable sodium percentage (ESP)		ESP (%) = (Exchangeable Na <sup>2+</sup> (cmol/kg) X 100)/cation exchange capacity (CEC) ((cmol/kg)
Total nitrogen	Leco combustion method	Method 7A5 p 110 Rayment and Lyons (2011)
Nitrate and ammonium nitrogen		Method 7C2b p 130 Rayment and Lyons (2011)
Particle size		Mackenzie et al. (2002)
Soil solution measurements		Determined at maximum water holding capacity (MWHC)

<sup>1</sup> Soil pH and EC were not determined by IR

### Soil pH

Soil pH is one of the most important determinants of soil fertility through its influence on the solubility of metal ions, such as Al, Mn, Fe, Cu, Zn and Mo, its effect on the supply of nutrient cations and anions, and its influence on microbes present in soil and their activity. Vines do not perform well when soil pH<sub>w</sub> <5 due to

stunted shoot and root growth (Conradie, 1983; White, 2009) and at  $\text{pH}_w$  4.5 and below root growth ceases (Robinson, 1993). The optimum  $\text{pH}_w$  range for vine growth is 5.5 to 8 (White, 2003).

Soil pH is a measure of the intensity of acidity or alkalinity. The data presented in this report are based on soil pH being measured in a soil/solution ratio of 1:5 with water ( $\text{pH}_w$ ) and 0.01 M  $\text{CaCl}_2$  ( $\text{pH}_{\text{Ca}}$ ) as the solution. The pH values of most soils are lower when determined in a salt solution than at the same soil/solution ratio in water. Usually  $\text{pH}_{\text{Ca}}$  are 0.5 to 1 unit lower than  $\text{pH}_w$  measurements.

## Electrical conductivity (EC)

Salinity is the presence of soluble salts in the plant root zone. Soils are shaken in deionised water in a soil:solution ratio of 1:5. Electrical conductivity is measured at the same time as pH using a combination electrode.

## Soil organic carbon (SOC)

Organic matter (as SOC) is not acquired by plants as a nutrient from the soil, but its cycling is important because of its association with nutrients (N, P and S) and the beneficial contributions that it makes to soil chemical, physical and biological properties (Hoyle et al., 2011). Nutrients may be released into the soil in plant available forms as organic materials are decomposed by microorganisms. Soil OC also contributes to a soils cation exchange capacity, maintains soil structure and provides a food source to soil microorganisms.

Laboratory estimates of soil carbon are restricted to the quantity of organic materials that accompany soil particles that pass through a 2 mm sieve. The data presented in this report are determined by a high-temperature combustion method (Leco furnace method). Inorganic forms of carbon (e.g. charcoal, carbonates, and bicarbonates) need to be removed prior to analysis or be measured and a correction made to determine total organic carbon.

Total organic carbon (TOC) = total carbon (C) – [inorganic C (% carbonate) X 0.12]

## Calcium carbonate (%)

The calcium carbonate fraction was measured to allow the calculation of total organic carbon from the total carbon (inorganic and organic components) measurement as detailed above. The inorganic fraction of carbon is not available for soil microorganisms as a food source.

## Exchangeable cations (Al, Ca, Mg, K, Na)

Measurement of exchangeable cations (positive ions) allows calcium ( $\text{Ca}^{2+}$ ), sodium ( $\text{Na}^+$ ), magnesium ( $\text{Mg}^{2+}$ ) and potassium ( $\text{K}^+$ ) to be monitored in regions where there may be concerns about an increasing

concentration in soil. At low salinity exchangeable cations can be determined without a pre-wash. However, a more accurate measurement of exchangeable cations requires leaching of the soil with a pre-wash solution before exchangeable cations can be determined.

Soils high in Na<sup>+</sup> (more than 5% of all cations bound to clay particles) structural problems begin to occur and soil is termed sodic. High sodicity causes clays to swell excessively when wet and clay particles may separate or disperse (see A2.1) and in surface soils crusts may form preventing water penetration.

## Cation exchange capacity (CEC)

Cation exchange capacity (CEC) is the capacity of the soil (negatively charge clay minerals) to hold and exchange cations (positive ions). The CEC is a major controlling agent of stability of soil structure, nutrient availability for plant growth, soil pH and the soil's reaction to fertilisers and other ameliorants (Hazelton and Murphy, 2007). Especially for soils of  $pH_w < 7$ , the CEC should be measured in a non-buffered solution (at the natural soil pH) because most soils have a pH-dependent component and a CEC measured in a barium chloride-triethanolamine extractant at pH 8.2, for example, will be an over-estimate.

An approximate value for CEC is Effective CEC.

Effective CEC = sum of the five most abundant cations in soils i.e. sum (Na<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup>)

## Total nitrogen

Total nitrogen measures the total amount of nitrogen present in the soil. It is not a very useful measure of the forms of nitrogen available to plants since a large fraction may be in organic matter and it is the mineralised forms of nitrogen (ammonium NH<sub>4</sub><sup>+</sup>, nitrate NO<sub>3</sub><sup>-</sup> and nitrite NO<sub>2</sub><sup>-</sup>) that are the plant-available fractions of nitrogen.

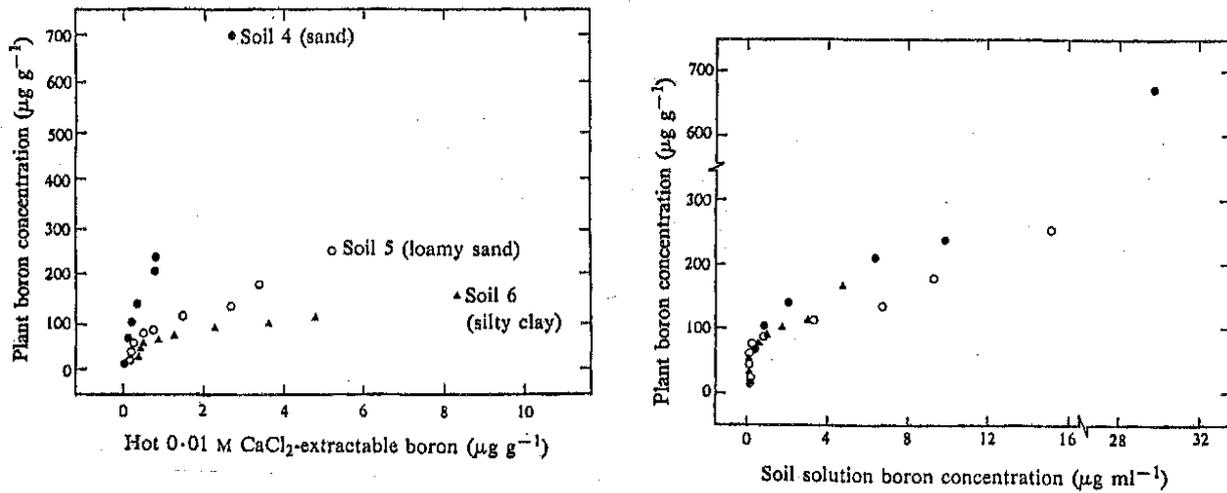
## Nitrate nitrogen (NO<sub>3</sub><sup>-</sup>) and ammonium nitrogen (NH<sub>4</sub><sup>+</sup>)

The forms of nitrogen that are available to plants is generally measured as nitrate (NO<sub>3</sub><sup>-</sup>) or ammonium nitrogen (NH<sub>4</sub><sup>+</sup>). It is difficult to interpret nitrate or ammonium levels in soil however because their levels in soil are affected by:

- Rainfall and level of water stored in the soil
- Time of soil sampling
- Depth over which the soil sample is collected

# Appendix C – Relationship between plant concentration of B and measures of soil solution B

Selection of the method for determining the soil B concentration was determined based on the findings of Aitken and McCallum (1988) and Mertens et al. (2011) that plant B concentration was better related to a soil solution measurement of B rather than a traditional measurement, namely hot 0.01 M CaCl<sub>2</sub> extraction as shown in Apx Figure 3.

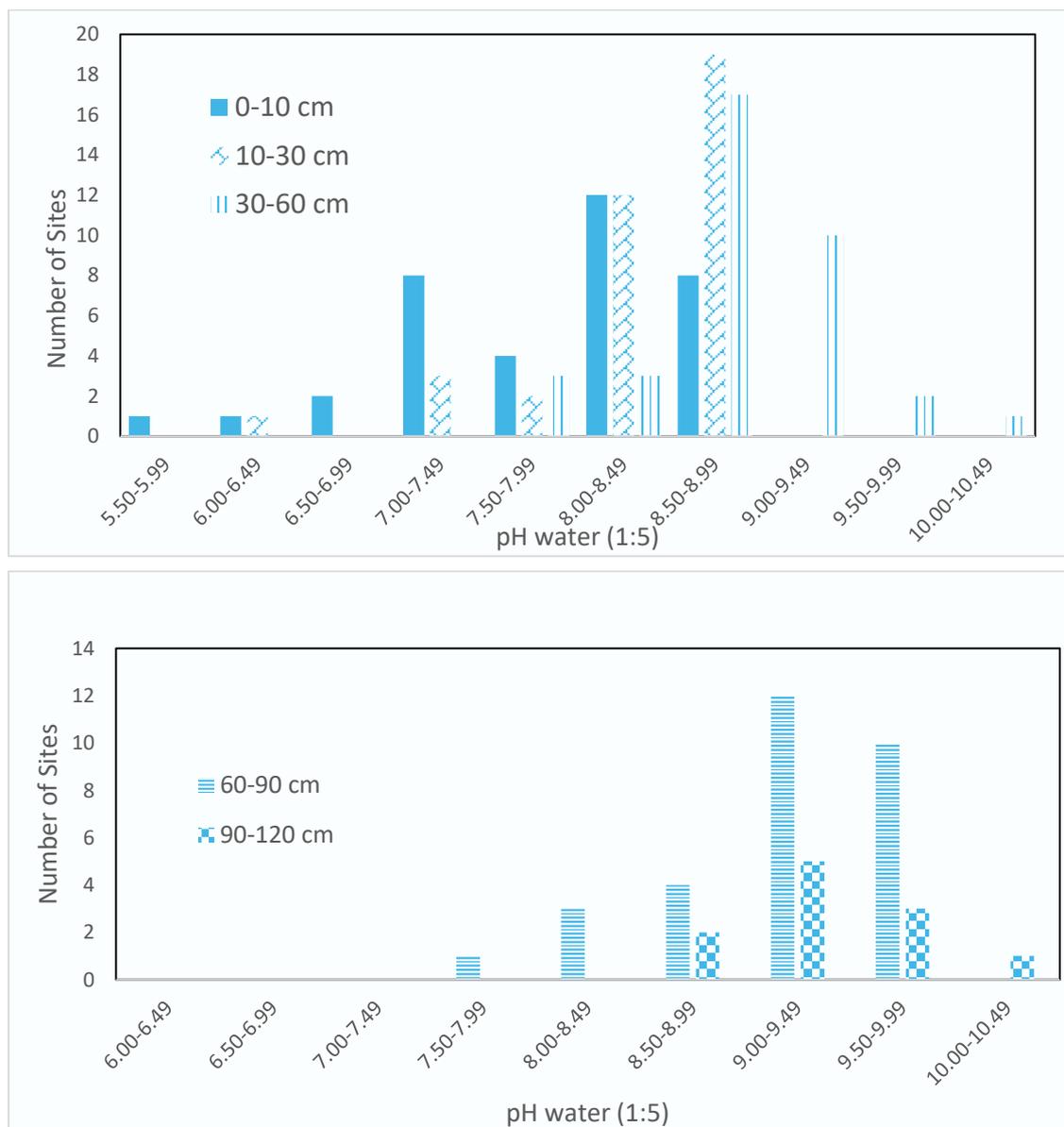


Apx Figure 3. Relationship between plant boron concentration and A) hot 0.01 M CaCl<sub>2</sub> extractable boron or B) soil solution boron concentration in three soils (reproduced from Aitken and McCallum, 1988).

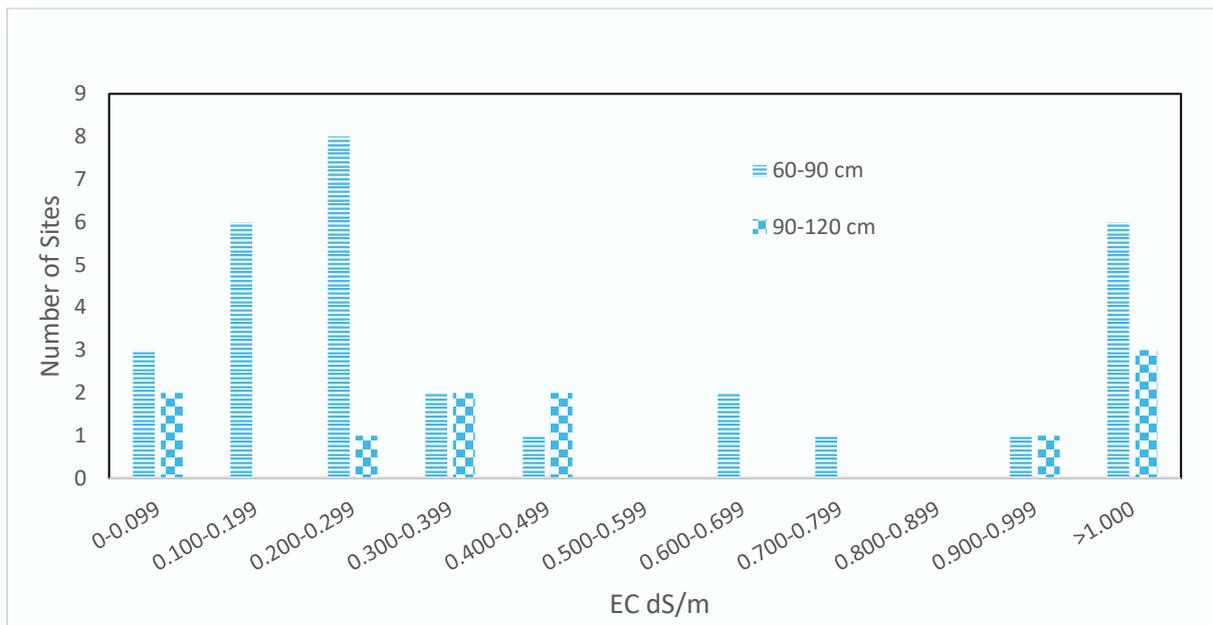
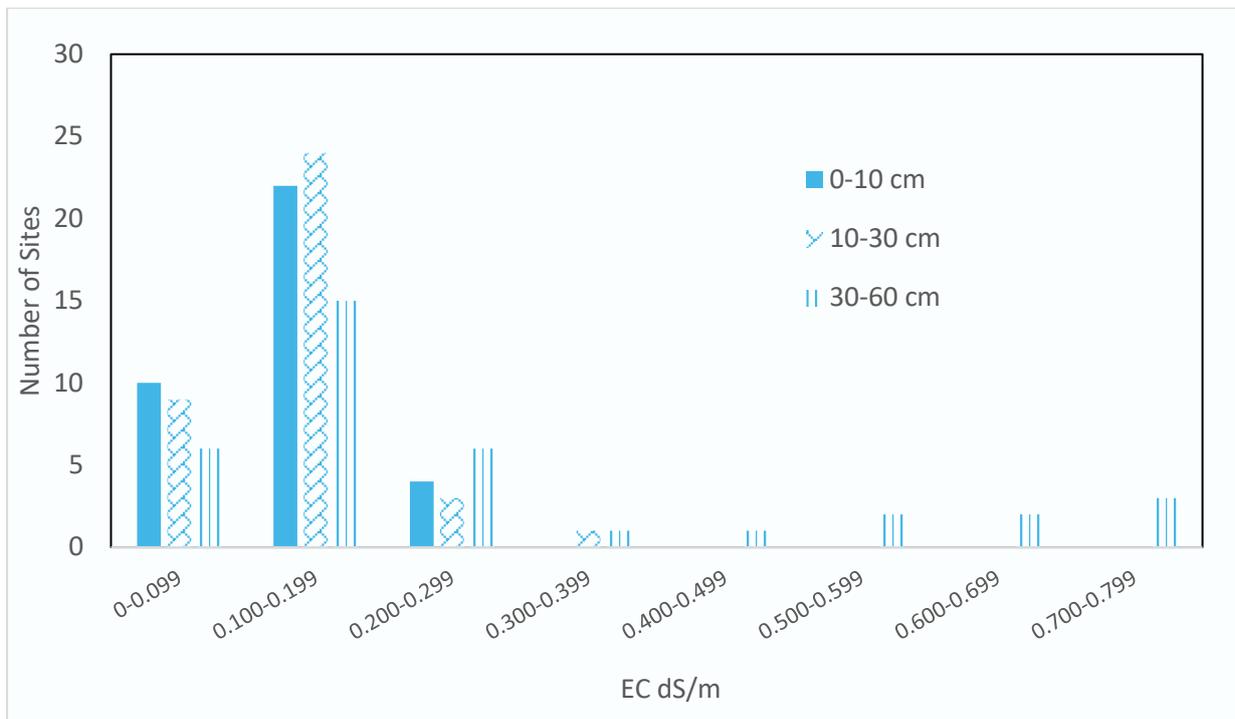
# Appendix D – Frequency distributions of the soil properties across the soils sampled in the NAP region.

## Distribution of soils data across the NAP focus area

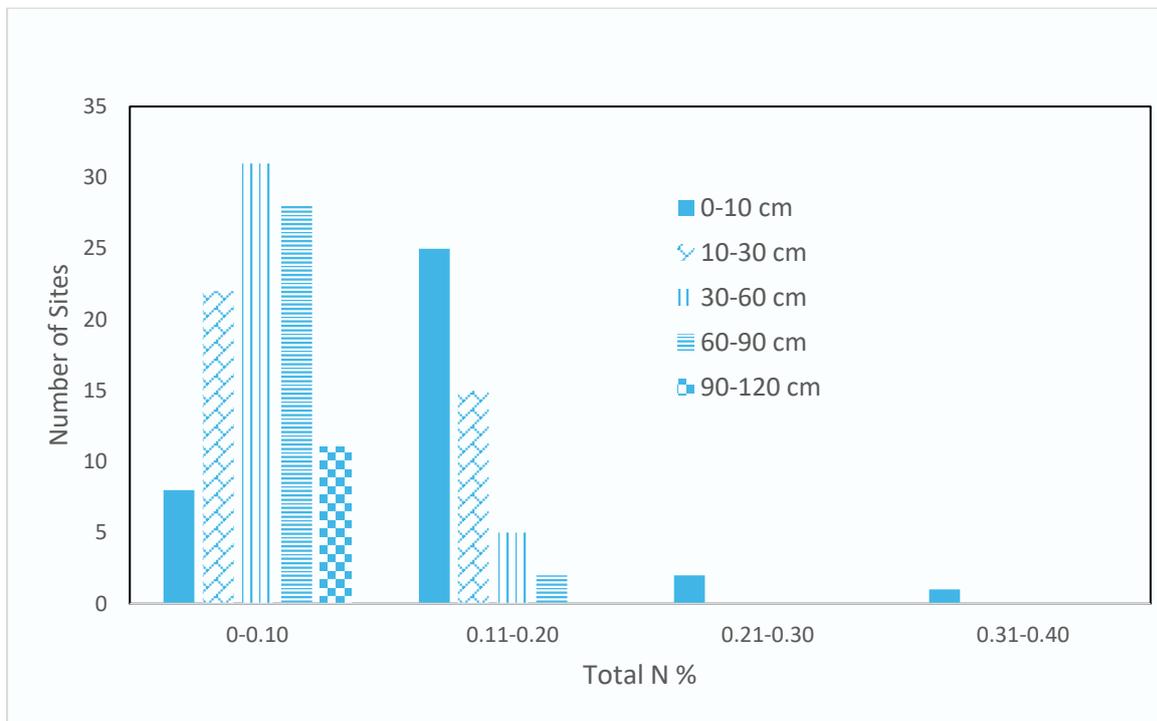
The distribution of each soil property at each sampling depth (0-10 cm, 10-30 cm, 30-60 cm, 60-90 cm and 90-120 cm) across the sampling sites in the focus area is given below (Apx Figs. 4 –14). In some cases, such as data for 90-120 cm, there are limited data.



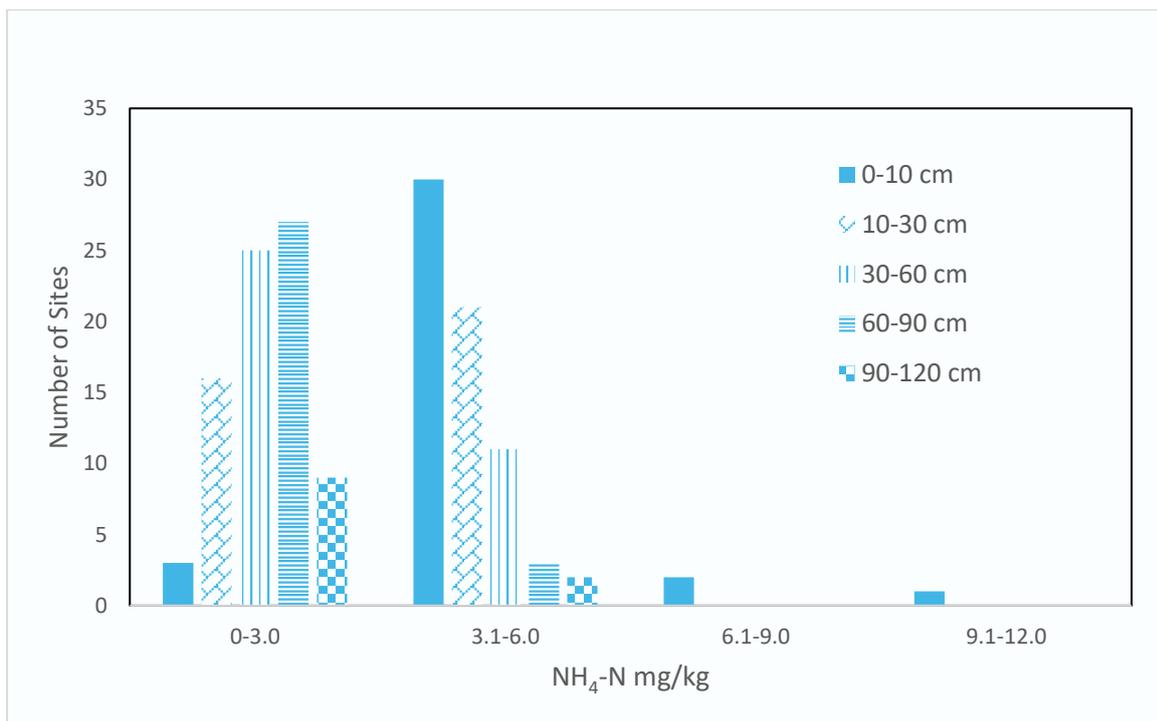
**Apx Figure 4. Distribution of soil pH (1:5, soil: water) in soils at the specified depth for the sampling sites in the study area.**



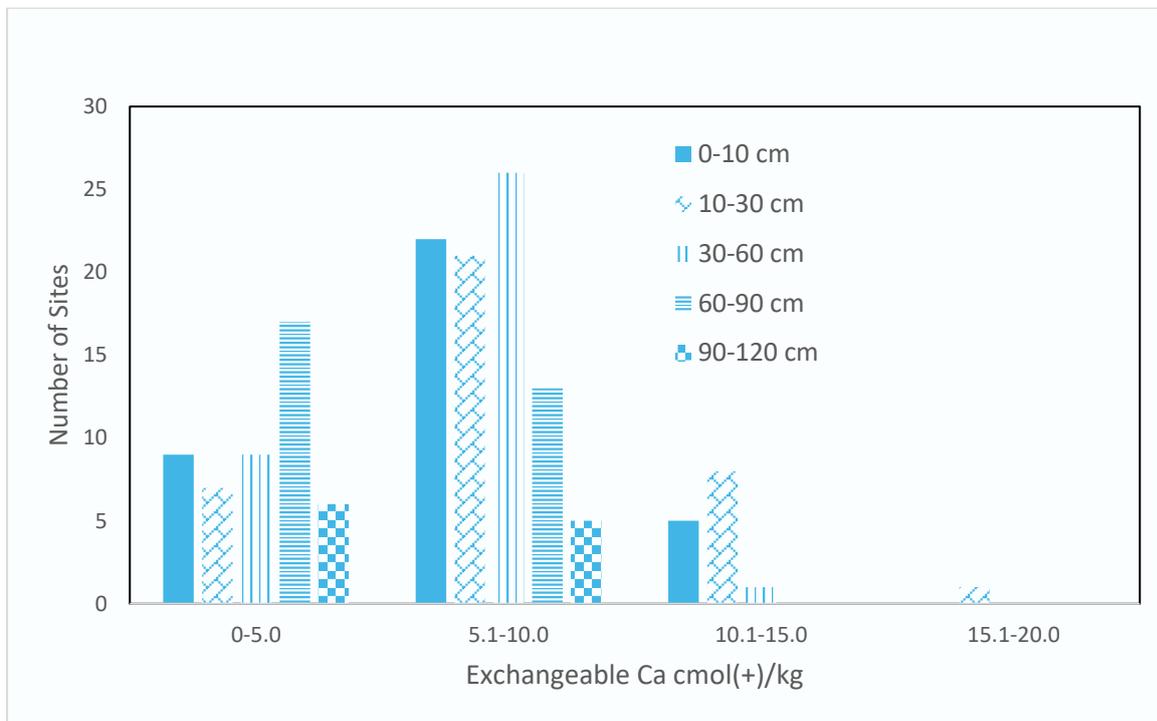
**Apx Figure 5. Distribution of soil EC (1:5 soil:water, dS/m) in soils at the specified depth for the sampling sites in the study area.**



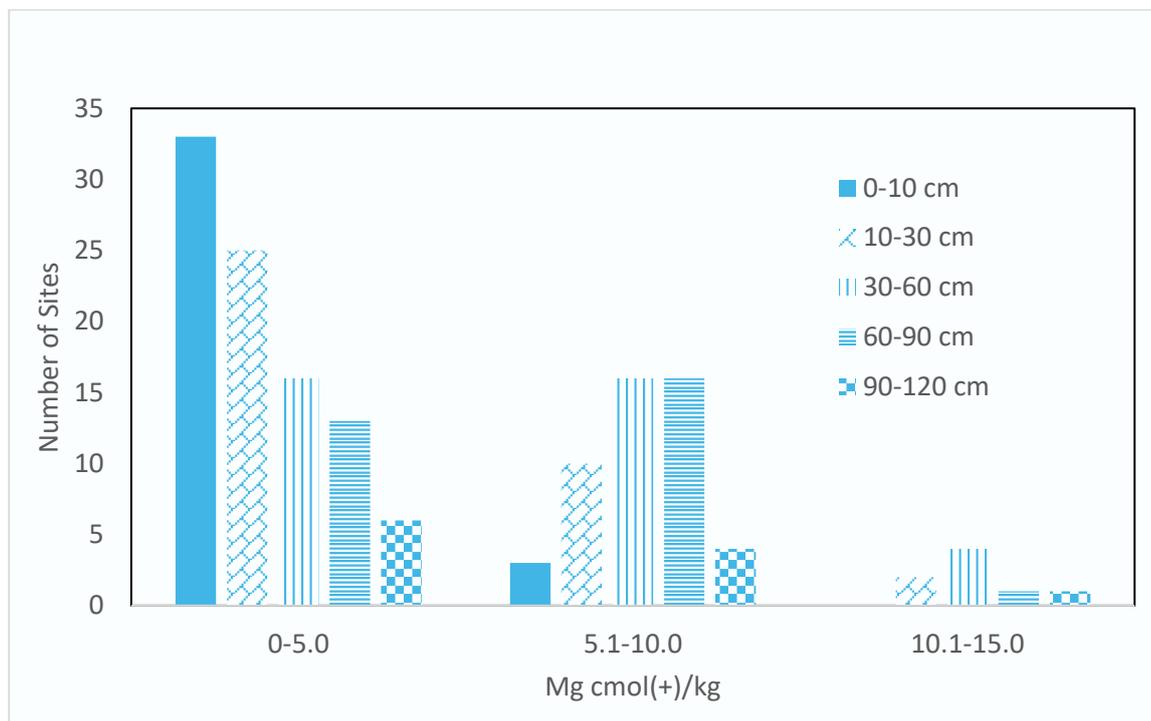
**Apx Figure 6. Distribution of total nitrogen (Total N, %) in soils at the specified depth for the sampling sites in the study area.**



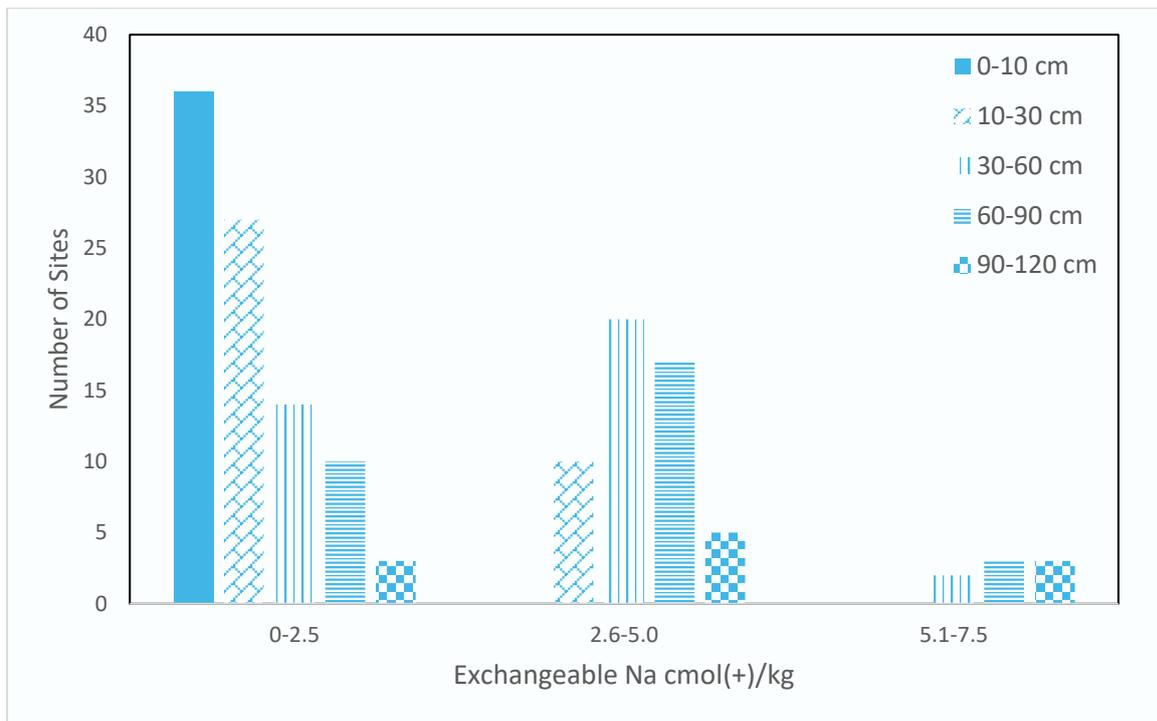
**Apx Figure 7. Distribution of ammonium nitrogen (NH<sub>4</sub>-N, mg/kg) in soils at the specified depth for the sampling sites in the study area.**



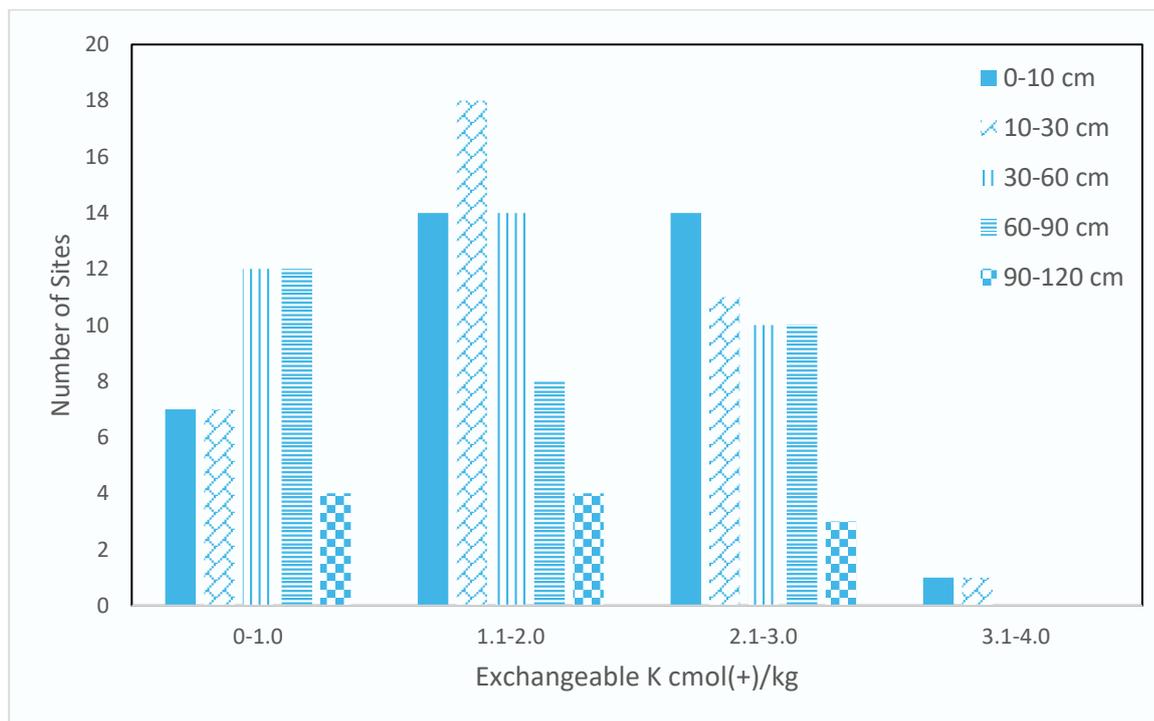
Apx Figure 8. Distribution of exchangeable calcium (Ca, cmol(+)/kg) in soils at the specified depth for the sampling sites in the study area.



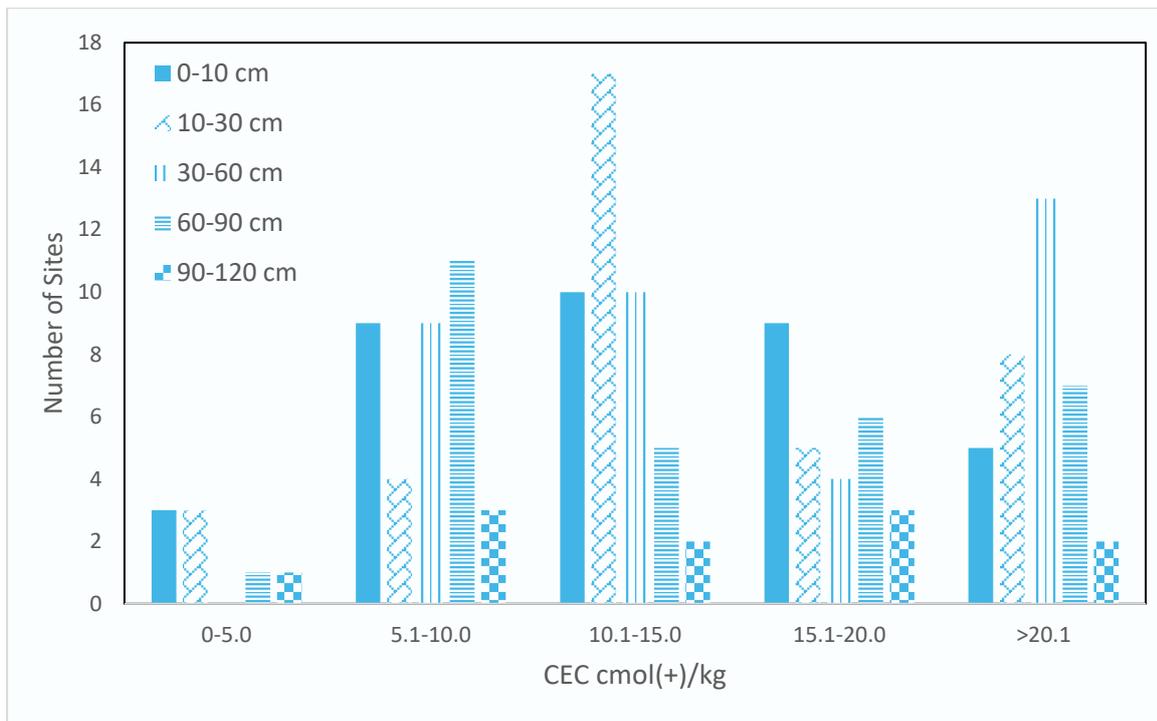
Apx Figure 9. Distribution of exchangeable magnesium (Mg, cmol(+)/kg) in soils at the specified depth for the sampling sites in the study area.



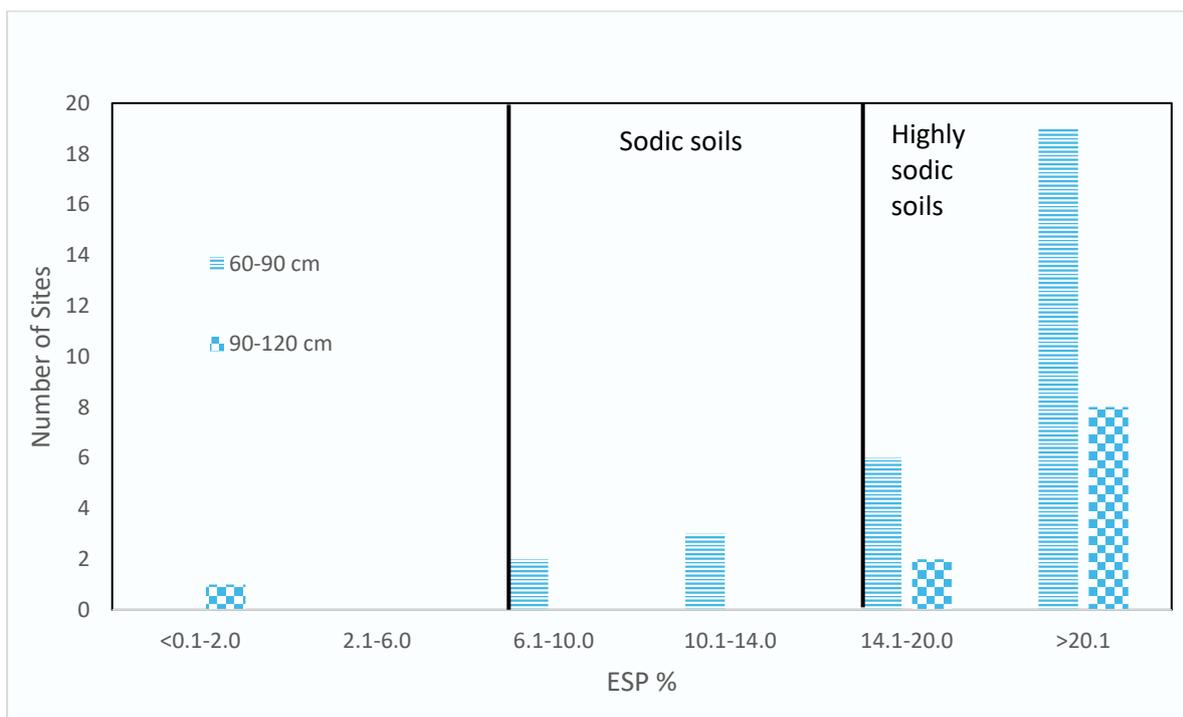
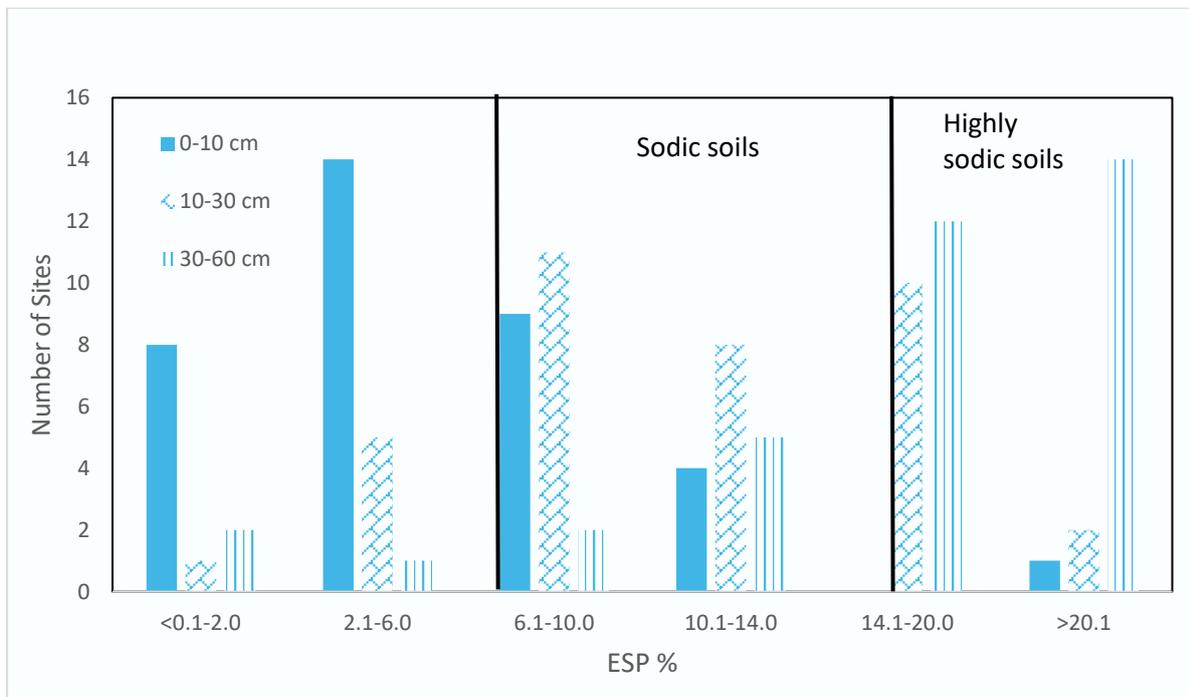
**Apx Figure 10. Distribution of exchangeable sodium (Na, cmol(+)/kg) in soils at the specified depth for the sampling sites in the study area.**



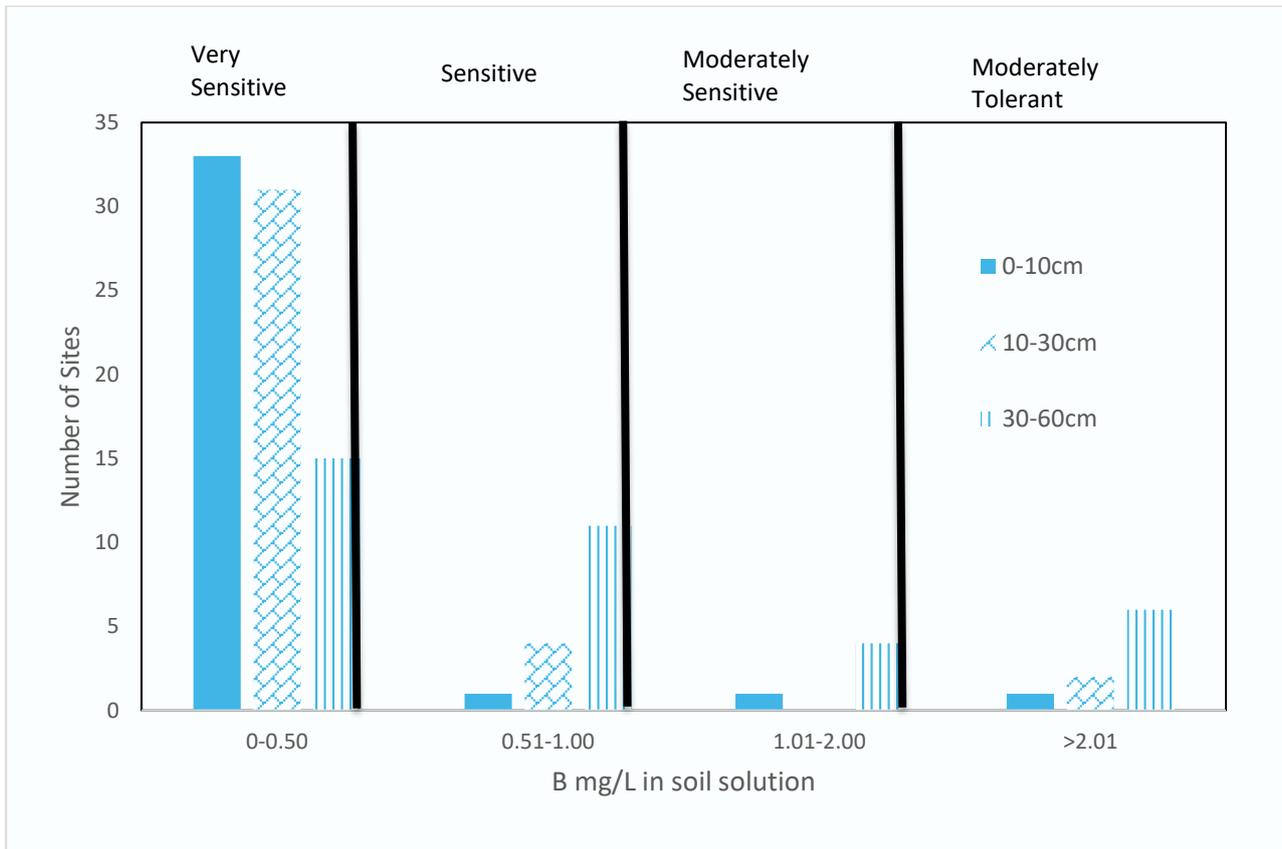
**Apx Figure 11. Distribution of exchangeable potassium (K, cmol(+)/kg) in soils at the specified depth for the sampling sites in the study area.**



**Apx Figure 12. Distribution of cation exchange capacity (CEC, cmol(+)/kg) in soils at the specified depth for the sampling sites in the study area.**



**Apx Figure 13. Distribution of exchangeable sodium percentage (ESP %) in soils at the specified depth for the sampling sites in the study area. ESP values > 6% are sodic and > 14% are highly sodic (Hazelton and Murphy, 2007).**



**Apx Figure 14. Distribution of boron (B, mg/L) in soil solution determined at field capacity using a high chloride solution (550 mg Cl<sup>-</sup>/L) in soils at the specified depth. These measurements were made only in soils at the following depths: 0-10 cm, 30-60 cm and 60-90 cm. Crop tolerance to soil solution B from Leyshon and Jame (1993) is indicated.**

## Raw data for hydraulic properties for soils collected in NAP focus area

Soils representing the 4 major soil groups (Hard red brown, deep uniform to gradational, Sand over clay and Calcareous) were sampled at the following depths (0-10 cm, 10-30 cm, 30-60 cm, 60-90 cm and 90-120 cm). There were occasions where it was not possible to sample to the lower depths due to limitations in the field.

All soils were dried and sieved <2 mm and scanned by infrared (IR). From the IR spectra the soil properties were predicted. A subset of soils was selected to cover the range of spectra and traditional chemical measurements were made on this subset to validate the IR predictions. All detection limits were based upon those for the traditional chemical methods (as performed by CSIRO Analytical Services Unit) and are presented in the first row of the data for the Deep uniform to gradational soils.

At some sites sampling below 60 cm was very difficult. At some sites soil was only collected from 60-70 cm or 60-80 cm and not through the whole 60-90 cm profile. Consequently, the chemical data is summarised i) over the depths sampled and ii) over 60-90 cm for consistency across all sites. For the latter, data for 60-90 cm will include data from some sites where soil could only be collected from a shallower depth profile (e.g. 60-70 cm).

Particle size categories are: clay (<0.002 mm); silt (0.002 – 0.02 mm) and sand (0.02- 2.0 mm).

Hydraulic properties were determined only on sites NAP8-NAP20 since NAP1-NAP7 were sampled from pits before the project had commenced. Generally, only 0-10 cm and 10-30 cm were sampled due to difficulties in obtaining suitable samples from augered holes. Note: Where there is no value for matric potential it was experimental error. The chemical data for each sampling site are given in Apx Table 3 and the physical data for each sampling site are given in Apx Table 4.

**Apx Table 3. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Deep Uniform to Gradational**

Soil depth (cm)		EC <sup>1</sup> (µS/cm)	pH <sub>w</sub> <sup>2</sup>	pH <sub>Ca</sub> <sup>3</sup>	Total C <sup>4</sup> (%)	Org. C <sup>5</sup> (%)	Total N <sup>6</sup> (%)	NH <sub>4</sub> -N <sup>7</sup> (mg/kg)	Clay <sup>8</sup> (%)	Silt <sup>8</sup> (%)	Sand <sup>8</sup> (%)	CaCO <sub>3</sub> <sup>9</sup> (%)
Detection limit					0.1	0.1	0.01	0.1				0.2
0-10	min	61	6.93	6.35	1.1	0.9	0.12	3.3	8	9	34	bdl <sup>10</sup>
	max	223	8.48	7.91	1.8	1.5	0.19	4.9	32	34	78	0.9
	mean	131	7.59	6.97	1.3	1.2	0.13	4.4	16	22	61	0.4
	median	124	7.34	6.86	1.1	1.1	0.12	4.6	12	21	67	bdl <sup>10</sup>
10-30	min	82	7.88	6.93	0.5	0.5	0.06	3.7	4	12	39	bdl <sup>10</sup>
	max	211	8.87	7.88	2.2	2.2	0.11	4.4	32	31	61	12.0
	mean	147	8.49	7.42	1.2	1.2	0.09	4.0	21	25	51	3.0
	median	131	8.59	7.35	1.0	1.0	0.10	4.0	26	26	51	bdl <sup>10</sup>
30-60	min	86	8.88	7.46	0.6	0.4	0.07	3.1	16	11	33	bdl <sup>10</sup>
	max	523	10.05	8.94	3.3	2.0	0.14	3.7	34	40	50	23.8
	mean	223	9.27	8.17	1.3	1.0	0.09	3.5	25	25	45	5.6
	median	152	9.04	7.92	0.8	0.8	0.08	3.5	27	26	49	1.2

<sup>1</sup> Electrical conductivity, <sup>2</sup> pH 1:5, soil:water, <sup>3</sup> pH 1:5 soil:0.01M CaCl<sub>2</sub>, <sup>4</sup> Total carbon, <sup>5</sup> Organic carbon, <sup>6</sup> Total nitrogen, <sup>7</sup> Ammonium-nitrogen, <sup>8</sup> particle size categories are: clay (<0.002 mm), silt (0.002 - 0.02 mm) and sand (0.02 -2.0 mm), <sup>9</sup> Calcium carbonate, <sup>10</sup> below detection limit

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Deep Uniform to Gradational**

Soil depth (cm)		EC <sup>1</sup> (µS/cm)	pH <sub>w</sub> <sup>2</sup>	pH <sub>Ca</sub> <sup>3</sup>	Total C <sup>4</sup> (%)	Org. C <sup>5</sup> (%)	Total N <sup>6</sup> (%)	NH <sub>4</sub> -N <sup>7</sup> (mg/kg)	Clay (%) <sup>8</sup>	Silt (%) <sup>8</sup>	Sand (%) <sup>8</sup>	CaCO <sub>3</sub> <sup>9</sup> (%)
60-90	min	182	9.05	7.62	0.4	0.1	0.04	2.3	19	17	16	0.3
	max	1253	9.54	8.75	4.4	0.9	0.12	3.9	60	28	55	35.8
	mean	624	9.34	8.28	1.5	0.5	0.07	3.1	31	23	40	8.1
	median	263	9.30	8.33	0.7	0.6	0.05	3.0	24	24	49	2.0
90-120	min	374	9.40	8.32	0.5	0.3	0.02	1.8	25	14	17	3.0
	max	429	9.80	8.54	1.6	1.1	0.05	2.4	52	28	54	11.0
	mean	408	9.63	8.41	0.9	0.7	0.03	2.1	35	22	41	5.7
	median	422	9.69	8.36	0.6	0.6	0.03	2.0	27	22	52	3.2

<sup>1</sup> Electrical conductivity, <sup>2</sup> pH 1:5, soil:water, <sup>3</sup> pH 1:5 soil:0.01M CaCl<sub>2</sub>, <sup>4</sup> Total carbon, <sup>5</sup> Organic carbon, <sup>6</sup> Total nitrogen, <sup>7</sup> Ammonium-nitrogen, <sup>8</sup> particle size categories are: clay (<0.002 mm), silt (0.002 - 0.02 mm) and sand (0.02 -2.0 mm), <sup>9</sup> Calcium carbonate

**ApX Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Deep Uniform to Gradational**

Exchangeable cations (cmol(+)/kg)								
Soil depth (cm)		Ca <sup>1</sup>	Mg <sup>2</sup>	Na <sup>3</sup>	K <sup>4</sup>	Total cations (Eff CEC) <sup>5</sup>	CEC <sup>6</sup> (cmol(+)/kg)	ESP <sup>7</sup> (%)
Detection limit		0.4	0.2	0.1	0.05		1.0	
0-10	min	3.3	bdl <sup>8</sup>	0.1	1.2	1.1	5.2	0.9
	max	9.0	5.1	2.0	2.1	18.3	18.8	10.4
	mean	5.7	1.3	0.5	1.6	7.7	9.8	3.2
	median	3.8	bdl <sup>8</sup>	0.1	1.6	5.1	8.8	1.6
10-30	min	2.2	bdl <sup>8</sup>	0.3	1.3	3.5	6.9	2.5
	max	10.2	5.2	3.9	2.0	16.8	16.4	23.5
	mean	5.7	2.4	1.7	1.6	11.5	12.6	11.9
	median	5.6	1.7	1.4	1.7	13.1	13.0	10.6
30-60	min	2.1	1.8	2.3	1.3	8.8	10.5	16.4
	max	6.6	6.1	3.5	2.1	18.4	17.8	25.5
	mean	4.4	3.4	2.9	1.7	12.6	13.6	21.7

<sup>1</sup> Calcium, <sup>2</sup> Magnesium, <sup>3</sup> Sodium, <sup>4</sup> Potassium, <sup>5</sup> Effective cation exchange capacity, <sup>6</sup> cation exchange capacity, <sup>7</sup> exchangeable sodium percentage, <sup>8</sup> below detection limit

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Deep Uniform to Gradational**

		Exchangeable cations (cmol(+)/kg)						
Soil depth (cm)		Ca <sup>1</sup>	Mg <sup>2</sup>	Na <sup>3</sup>	K <sup>4</sup>	Total cations (Eff CEC) <sup>5</sup>	CEC <sup>6</sup> (cmol(+)/kg)	ESP <sup>7</sup> (%)
60-90	min	1.0	2.3	1.8	0.3	8.5	7.6	12.1
	max	9.7	7.7	4.0	2.5	23.2	24.8	45.0
	mean	4.3	4.1	3.3	1.5	13.3	13.3	28.8
	median	4.4	3.6	3.6	1.5	10.0	10.0	23.8
90-120	min	1.4	3.9	3.4	0.7	9.2	6.2	24.6
	max	8.0	11.5	6.3	2.1	28.1	25.5	55.9
	mean	4.9	6.9	4.8	1.2	17.8	15.7	37.2
	median	5.3	5.1	4.8	0.9	16.2	15.4	31.2

<sup>1</sup> Calcium, <sup>2</sup> Magnesium, <sup>3</sup> Sodium, <sup>4</sup> Potassium, <sup>5</sup> Effective cation exchange capacity, <sup>6</sup> Cation exchange capacity, <sup>7</sup> Exchangeable sodium percentage

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Deep Uniform to Gradational**

		Metals in soil solution (mg/L) extracted in a high Cl <sup>-</sup> solution <sup>1</sup>					Metals in soil solution (mg/L) extracted in a low Cl <sup>-</sup> solution <sup>2</sup>								
Depth (cm)		B	Mn	P	S	Si	Sr	Al	B	Fe	Mn	P	S	Si	Sr
Detection		0.10	0.05	0.2	0.1	0.1	0.05	0.05	0.10	0.1	0.05	0.2	0.1	0.1	0.05
Limit (dl)															
0-10	min	0.12	0.06	0.4	13	12	1.4								
	max	0.35	2.09	0.7	83	43	2.4								
	mean	0.25	1.08	0.6	48	28	1.9								
	median	0.29	1.08	0.6	48	28	1.9								
10-30	min	0.05	0.03	bdl <sup>3</sup>	9.5	7.3	0.93								
	max	0.60	0.05	0.2	13	18	1.3								
	mean	0.28	0.03	bdl <sup>3</sup>	10	11	1.1								
	median	0.27	0.03	bdl <sup>3</sup>	10	8.6	1.1								
30-60	min	0.23	0.03	bdl <sup>3</sup>	8.2	3.1	0.90	bdl <sup>3</sup>	0.74	bdl <sup>3</sup>	bdl <sup>3</sup>	0.3	30	4.2	0.27
	max	1.21	0.03	0.4	214	23	2.9	bdl <sup>3</sup>	1.24	bdl <sup>3</sup>	bdl <sup>3</sup>	0.7	226	18.9	2.71
	mean	0.63	0.03	0.2	65	9.2	1.6	bdl <sup>3</sup>	0.95	bdl <sup>3</sup>	bdl <sup>3</sup>	0.4	109	9.7	1.38
	median	0.65	0.03	bdl <sup>3</sup>	30	6.8	1.5	bdl <sup>3</sup>	0.87	bdl <sup>3</sup>	bdl <sup>3</sup>	0.3	72	6.1	1.16

Metal concentrations in soil solution after soils extracted at maximum water holding capacity using <sup>1</sup> a high chloride solution (550 mg Cl<sup>-</sup>/L) or <sup>2</sup> a low chloride solution (4 mg Cl<sup>-</sup>/L), <sup>3</sup> below detection limit

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Hard Red Brown Soils.**

Depth (cm)		EC ( $\mu\text{S/cm}$ )	pH <sub>w</sub>	pH <sub>Ca</sub>	Total C (%)	Org. C (%)	Total N (%)	NH <sub>4</sub> -N (mg/kg)	Clay (%)	Silt (%)	Sand (%)
0-10	min	64	5.86	4.88	1.0	0.7	0.10	3.6	9	7	31
	max	233	8.65	8.17	3.7	3.7	0.35	7.5	40	34	79
	mean	152	7.70	7.05	2.0	2.0	0.18	4.6	20	24	52
	median	157	7.90	7.43	2.1	2.1	0.19	4.4	19	25	52
10-30	min	69	6.30	5.51	0.1	0.1	0.01	2.2	8	1	7
	max	321	8.89	7.90	2.1	2.1	0.18	4.3	69	33	80
	mean	145	8.28	7.35	1.1	0.9	0.11	3.4	35	23	41
	median	127	8.46	7.54	1.0	1.0	0.12	3.3	31	24	45
30-60	min	823	7.92	6.38	0.3	0.1	0.02	1.5	23	2	18
	max	730	9.41	8.50	3.7	2.3	0.12	3.5	57	29	55
	mean	345	8.83	7.93	1.5	1.2	0.07	2.4	41	19	33
	median	221	8.76	7.97	1.4	1.4	0.07	2.5	44	21	34
60-70	min	78	8.59	7.80	0.9	0.9	0.03	1.7	30	9	29
	max	299	9.94	8.37	4.2	3.6	0.10	3.5	36	21	41
	mean	194	9.07	8.05	2.9	1.8	0.05	2.5	32	14	33
	median	206	8.69	7.98	3.6	0.9	0.03	2.2	31	11	29

Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Hard Red Brown Soils.

Sol depth (cm)		EC (μS/cm)	pH <sub>w</sub>	pH <sub>Ca</sub>	Total C (%)	Org. C (%)	Total N (%)	NH <sub>4</sub> -N (mg/kg)	Clay (%)	Silt (%)	Sand (%)
60-80	min	129	7.96	7.97	1.1	1.1	0.04	1.1	32	14	29
	max	3712	9.87	8.63	2.8	2.2	0.11	3.0	47	31	42
	mean	998	9.00	8.31	1.7	1.6	0.09	2.0	39	24	33
	median	231	8.99	8.34	1.5	1.5	0.10	1.9	37	25	32
60-90	min	292	8.95	7.81	0.5	0.5	0.02	1.3	26	12	23
	max	1080	9.54	8.58	1.8	1.8	0.05	2.5	49	27	61
	mean	754	9.32	8.32	1.0	1.0	0.04	1.8	35	19	44
	median	823	9.39	8.44	0.8	0.8	0.04	1.6	33	19	46
60-90	min	78	7.96	7.80	0.5	0.5	0.02	1.1	26	9	23
	max	3712	9.94	8.63	4.2	3.6	0.11	3.5	49	31	61
	mean	738	9.11	8.25	1.7	1.4	0.06	2.0	36	20	36
	median	292	9.24	8.37	1.3	1.3	0.05	1.8	36	21	32
90-120	min	328	9.21	8.09	0.3	0.3	0.04	2.8	21	11	34
	max	1182	9.55	8.71	1.1	1.1	0.07	3.6	36	34	63
	mean	875	9.36	8.44	0.7	0.7	0.05	3.1	27	22	48
	median	996	9.33	8.47	0.7	0.7	0.05	3.0	25	21	47

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Hard Red Brown Soils.**

		Exchangeable cations (cmol(+)/kg)								
Soil (cm)	depth	CaCO <sub>3</sub> <sup>1</sup> (%)	Ca <sup>2</sup>	Mg <sup>3</sup>	Na <sup>4</sup>	K <sup>5</sup>	Total cations (Eff CEC) <sup>6</sup>	CEC <sup>7</sup> (cmol(+)/kg)	ESP <sup>8</sup> (%)	
0-10	min	bdl <sup>9</sup>	1.2	0.4	0.1	0.5	3.3	6.1	0.4	
	max	6.4	11.8	6.2	1.7	3.6	22.2	24.0	10.7	
	mean	2.5	7.6	2.4	0.8	2.1	13.2	15.2	5.6	
	median	2.1	7.9	1.9	0.8	2.3	12.9	14.9	5.4	
10-30	min	bdl <sup>9</sup>	1.0	0.3	0.5	0.6	2.4	4.5	4.4	
	max	4.5	18.8	10.4	4.0	3.4	32.4	31.5	19.7	
	mean	1.5	8.7	5.3	2.2	1.9	18.6	19.4	11.3	
	median	0.5	7.8	6.0	2.1	2.1	19.7	18.2	10.4	
30-60	min	bdl <sup>9</sup>	5.6	4.7	2.5	1.0	15.1	13.2	11.8	
	max	26.6	12.8	12.5	6.9	2.4	30.0	27.5	27.7	
	mean	7.1	8.1	7.6	4.0	1.9	21.9	21.1	18.9	
	median	4.9	7.8	6.8	3.8	2.0	20.5	21.4	18.7	

<sup>1</sup> Calcium carbonate, <sup>2</sup> Calcium, <sup>3</sup> Magnesium, <sup>4</sup> Sodium, <sup>5</sup> Potassium, <sup>6</sup> Effective cation exchange capacity, <sup>7</sup> Cation exchange capacity, <sup>8</sup> Exchangeable sodium percentage, <sup>9</sup> below detection limit

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Hard Red Brown Soils.**

Soil depth (cm)	Exchangeable cations (cmol(+)/kg)							Total cations (Eff CEC) <sup>6</sup>	CEC <sup>7</sup> (cmol(+)/kg)	ESP <sup>8</sup> (%)
	CaCO <sub>3</sub> <sup>1</sup> (%)	Ca <sup>2</sup>	Mg <sup>3</sup>	Na <sup>4</sup>	K <sup>5</sup>					
60-70	min	1.2	4.6	5.7	2.9	1.0	15.5	12.5	14.0	
	max	35.2	8.5	8.0	5.6	2.2	20.3	21.0	34.3	
	mean	21.4	6.2	6.6	3.8	1.8	18.6	16.6	23.9	
	median	27.7	5.4	6.0	2.9	2.1	20.0	16.3	23.5	
60-80	min	1.1	2.7	5.1	3.4	1.7	15.3	18.1	17.2	
	max	20.7	7.8	8.2	5.0	2.6	22.3	23.0	27.7	
	mean	7.0	5.9	6.5	4.5	2.3	19.5	20.5	22.2	
	median	5.1	6.5	6.6	4.8	2.4	19.8	20.2	22.3	
60-90	min	2.4	2.2	4.4	4.6	1.2	12.5	9.7	26.7	
	max	11.4	6.7	10.3	6.4	2.2	25.7	23.8	47.9	
	mean	6.5	4.0	6.7	5.2	1.7	17.6	15.3	37.4	
	median	6.1	3.6	6.0	5.0	1.6	16.0	13.8	37.6	

<sup>1</sup> Calcium carbonate, <sup>2</sup> Calcium, <sup>3</sup> Magnesium, <sup>4</sup> Sodium, <sup>5</sup> Potassium, <sup>6</sup> Effective cation exchange capacity, <sup>7</sup> cation exchange capacity, <sup>8</sup> exchangeable sodium percentage

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Hard Red Brown Soils.**

Soil depth (cm)	Exchangeable cations (cmol(+)/kg)						Total cations (Eff CEC) <sup>6</sup>	CEC <sup>7</sup> (cmol(+)/kg)	ESP <sup>8</sup> (%)
	CaCO <sub>3</sub> <sup>1</sup> (%)	Ca <sup>2</sup>	Mg <sup>3</sup>	Na <sup>4</sup>	K <sup>5</sup>				
60-90	min	1.1	2.2	4.4	2.9	1.0	12.5	9.7	14.0
	max	35.2	8.5	10.3	6.4	2.6	25.7	23.8	47.9
	mean	10.1	5.4	6.6	4.6	2.0	18.7	18.0	27.3
	median	6.4	5.4	6.2	4.7	2.2	18.9	19.5	25.8
90-120	min	0.9	3.5	0.1	0.1	1.3	1.9	5.8	0.9
	max	9.8	6.2	8.3	6.2	2.2	23.0	21.0	33.8
	mean	4.7	4.6	4.7	3.9	1.8	14.2	14.3	23.2
	median	4.0	4.4	5.1	4.6	1.8	15.9	15.3	29.0

<sup>1</sup> Calcium carbonate, <sup>2</sup> Calcium, <sup>3</sup> Magnesium, <sup>4</sup> Sodium, <sup>5</sup> Potassium, <sup>6</sup> Effective cation exchange capacity, <sup>7</sup> cation exchange capacity, <sup>8</sup> exchangeable sodium percentage

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Hard Red Brown Soils.**

		Metals in soil solution (mg/L) extracted in a high Cl <sup>-</sup> solution <sup>1</sup>					
Soil depth (cm)		B	Mn	P	S	Si	Sr
0-10	min	0.12	0.03	0.6	12	14	0.6
	max	5.36	11.86	4.8	40	76	3.6
	mean	0.63	1.71	1.8	23	30	1.7
	median	0.25	0.25	1.1	25	18	1.8
10-30	min	0.12	0.03	0.1	4	5	1.2
	max	9.13	4.81	1.5	52	102	3.1
	mean	1.03	0.45	0.3	21	18	1.7
	median	0.37	0.03	0.1	14	11	1.4
30-60	min	0.06	0.03	0.1	2	4	0.7
	max	10.53	0.03	0.1	302	13	2.8
	mean	1.96	0.03	0.1	75	6.9	1.6
	median	0.80	0.03	0.1	24	6.0	1.5

<sup>1</sup>Metal concentrations in soil solution after soils extracted at maximum water holding capacity using a high chloride solution (550 mg Cl<sup>-</sup>/L)

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Hard Red Brown Soils.**

		Metals in soil solution (mg/L) extracted in a low Cl <sup>-</sup> solution <sup>1</sup>							
Soil	depth (cm)	Al	B	Fe	Mn	P	S	Si	Sr
0-10	min	0.68	0.51	0.37	0.52	1.4	21	24	0.3
	max	0.91	0.76	0.69	5.40	2.7	32	45	0.5
	mean	0.79	0.64	0.53	2.96	2.0	27	34	0.4
	median	0.79	0.64	0.53	2.96	2.0	27	34	0.4
10-30	min	0.03	0.97	0.05	0.13	0.3	6	18	0.1
	max	39.47	2.55	22.07	5.82	4.9	54	81	1.0
	mean	13.24	1.62	7.39	2.88	1.8	25	51	0.6
	median	0.22	1.34	0.05	2.70	0.3	15	54	0.8
30-60	min	0.03	0.63	0.05	0.03	0.1	4	3	0.1
	max	45.36	12.72	27.20	0.11	1.2	297	102	3.4
	mean	3.81	2.72	2.34	0.03	0.3	115	14	1.2
	median	0.03	1.95	0.05	0.03	0.2	73	5	1.0

<sup>1</sup>Metal concentrations in soil solution after soils extracted at maximum water holding capacity using a low chloride solution (4 mg Cl<sup>-</sup>/L)

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Sand over clay soils.**

Soil depth (cm)		EC ( $\mu\text{S}/\text{cm}$ )	pH <sub>w</sub>	pH <sub>Ca</sub>	Total C (%)	Org. C (%)	Total N (%)	NH <sub>4</sub> -N (mg/kg)	Clay (%)	Silt (%)	Sand (%)
0-10	min	14	7.00	6.25	0.3	0.3	0.03	2.1	0	0	81
	max	108	8.82	8.29	1.3	1.3	0.11	10.4	14	2	100
	mean	74	8.09	7.34	0.8	0.8	0.07	4.1	5	0	94
	median	97	8.55	7.77	0.9	0.9	0.07	3.2	4	0	96
10-30	min	17	7.37	7.33	0.1	0.1	0.02	1.9	0	0	62
	max	128	8.80	8.04	3.3	2.8	0.14	4.3	29	4	100
	mean	78	8.23	7.65	1.3	1.1	0.06	3.0	12	1	81
	median	100	8.63	7.68	1.3	1.1	0.05	2.5	11	0	75
30-60	min	18	7.58	7.34	0.1	0.1	0.02	1.5	0	0	41
	max	124	9.00	8.32	5.6	2.2	0.11	3.7	28	2	100
	mean	82	8.56	7.91	2.4	1.1	0.06	2.6	11	1	71
	median	106	8.96	8.13	2.0	1.2	0.05	2.5	10	1	66

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Sand over clay soils.**

Soil depth (cm)		EC ( $\mu\text{S}/\text{cm}$ )	pH <sub>w</sub>	pH <sub>Ca</sub>	Total C (%)	Org. C (%)	Total N (%)	NH <sub>4</sub> -N (mg/kg)	Clay (%)	Silt (%)	Sand (%)
60-90	min	25	8.03	7.37	0.1	0.1	0.02	1.1	0	0	18
	max	188	9.65	8.49	6.2	1.4	0.06	2.5	37	11	100
	mean	127	9.05	8.13	2.6	0.5	0.04	2.1	18	3	67
	median	161	9.37	8.29	1.9	0.1	0.05	2.3	20	0	77
90-120	min	32	8.51	7.93	0.1	0.1	0.05	1.4	0	0	100
	max	36	8.74	8.04	0.1	0.1	0.05	2.1	0	0	100
	mean	34	8.63	7.99	0.1	0.1	0.05	1.7	0	0	100
	median	34	8.63	7.99	0.1	0.1	0.05	1.7	0	0	100

<sup>1</sup> Electrical conductivity, <sup>2</sup> pH 1:5, soil:water, <sup>3</sup> pH 1:5 soil:0.01M CaCl<sub>2</sub>, <sup>4</sup> Total carbon, <sup>5</sup> Organic carbon, <sup>6</sup> Total nitrogen, <sup>7</sup> ammonium-nitrogen, <sup>8</sup> particle size categories are: clay (<0.002 mm), silt (0.002 - 0.02 mm) and sand (0.02 -2.0 mm), <sup>9</sup> Calcium carbonate

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Sand over clay soils.**

Soil depth (cm)		CaCO <sub>3</sub> (%)	Exch Ca <sup>1</sup>	Exch Mg <sup>1</sup>	Exch Na <sup>1</sup>	Exch K <sup>1</sup>	Total cations (Eff CEC)	CEC (cmol(+)/kg)	ESP (%)
0-10	min	bdl <sup>2</sup>	bdl <sup>2</sup>	0.3	0.1	0.1	0.7	1.8	0.1
	max	5.3	9.1	2.0	0.5	1.4	12.2	10.2	27.0
	mean	1.0	5.0	1.0	0.2	0.7	6.7	5.9	7.3
	median	bdl <sup>2</sup>	5.3	1.0	0.3	0.7	7.3	5.1	3.4
10-30	min	bdl <sup>2</sup>	0.8	0.4	0.1	bdl <sup>2</sup>	1.6	2.3	0.1
	max	16.3	10.8	5.3	1.4	1.1	18.4	13.7	17.7
	mean	6.6	7.0	2.2	0.6	0.6	10.4	8.3	8.3
	median	4.7	8.8	1.8	0.4	0.6	12.0	8.7	9.2
30-60	min	bdl <sup>2</sup>	3.2	0.9	0.1	0.1	5.5	5.3	0.1
	max	43.4	10.0	4.5	0.9	0.9	16.2	11.5	15.8
	mean	17.4	6.8	2.6	0.6	0.5	10.6	8.2	7.5
	median	12.1	7.4	2.6	0.7	0.4	11.2	8.0	6.9
60-90	min	bdl <sup>2</sup>	1.6	0.3	0.7	0.1	3.7	3.8	6.4
	max	51.4	10.0	7.1	2.0	0.9	15.6	11.5	29.4
	mean	20.1	5.1	3.6	1.1	0.5	10.7	8.3	15.3
	median	10.9	3.1	3.5	0.9	0.5	11.9	8.8	14.4

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Sand over clay soils.**

Soil depth (cm)		CaCO <sub>3</sub> (%)	Exch Ca <sup>1</sup>	Exch Mg <sup>1</sup>	Exch Na <sup>1</sup>	Exch K <sup>1</sup>	Total cations (Eff CEC)	CEC (cmol(+)/kg)	ESP (%)
90-120	min	bdl <sup>2</sup>	1.6	0.8	0.5	0.1	3.1	3.2	14.4
	max	0.4	3.0	1.4	1.1	0.2	5.9	5.4	19.9
	mean	0.2	2.3	1.1	0.8	0.1	4.5	4.3	17.2
	median	0.2	2.3	1.1	0.8	0.1	4.5	4.3	17.2

<sup>1</sup>Exchangeable cations (cmol(+)/kg), <sup>2</sup> below detection limit

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Sand over clay soils.**

		Metals in soil solution (mg/L) extracted in a high Cl <sup>-</sup> solution <sup>1</sup>					
Soil depth (cm)		B	Mn	P	S	Si	Sr
0-10	min	0.09	0.03	0.4	3	11	1.6
	max	0.15	0.43	0.8	15	16	2.6
	mean	0.11	0.11	0.6	10	13	2.1
	median	0.11	0.03	0.6	12	13	2.1
10-30	min	0.09	0.03	0.1	9	10	2.2
	max	0.26	0.03	0.4	18	23	3.2
	mean	0.16	0.03	0.3	12	14	2.6
	median	0.16	0.03	0.2	11	12	2.5
30-60	min	0.10	0.03	0.1	6	9	2.6
	max	0.56	0.03	0.1	14	12	5.3
	mean	0.33	0.03	0.1	10	10	4.0
	median	0.33	0.03	0.1	11	10	4.1

<sup>1</sup>Metal concentrations in soil solution after soils extracted at maximum water holding capacity using <sup>1</sup>a high chloride solution (550 mg Cl<sup>-</sup>/L)

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Sand over clay soils.**

		Metals in soil solution (mg/L) extracted in a low Cl <sup>-</sup> solution <sup>1,2</sup>							
Soil depth (cm)		Al	B	Fe	Mn	P	S	Si	Sr
30-60	min	0.03	0.58	0.05	0.03	0.1	18	11	1.4
	max	0.03	0.59	0.05	0.03	0.1	21	13	1.8
	mean	0.03	0.58	0.05	0.03	0.1	19	12	1.6
	median	0.03	0.58	0.05	0.03	0.1	19	12	1.6

<sup>1</sup>Metal concentrations in soil solution after soils extracted at maximum water holding capacity using <sup>1</sup>a low chloride solution (4 mg Cl<sup>-</sup>/L), <sup>2</sup> Depths 0-10 and 10-30 cm were not extracted with the low chloride solution

Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Calcareous soils.

Soil depth (cm)		EC (µS/cm)	pH <sub>w</sub>	pH <sub>Ca</sub>	Total C (%)	Org. C (%)	Total N (%)	NH <sub>4</sub> -N (mg/kg)	Clay (%)	Silt (%)	Sand (%)	CaCO <sub>3</sub> (%)
0-10	min	151	8.29	7.72	2.1	2.1	0.17	2.9	12	14	42	2.6
	max	176	8.76	8.11	4.5	3.5	0.21	4.3	30	25	56	26.4
	mean	167	8.49	7.91	3.3	3.0	0.19	3.7	17	18	50	12.5
	median	171	8.44	7.94	3.1	3.1	0.19	3.7	13	17	51	10.0
10-30	min	149	8.49	7.82	3.2	2.5	0.08	1.7	9	8	33	17.5
	max	195	8.98	8.33	5.7	5.7	0.12	2.9	25	22	47	43.3
	mean	166	8.69	7.99	4.5	3.3	0.10	2.5	15	13	39	31.4
	median	157	8.59	7.92	4.4	3.0	0.10	2.6	15	12	37	31.8
30-60	min	170	8.65	7.89	4.7	0.9	0.03	1.6	14	5	17	38.1
	max	300	9.57	8.42	6.5	2.0	0.06	2.1	20	13	32	57.3
	mean	218	9.07	8.10	5.8	1.6	0.05	1.8	17	9	27	48.2
	median	210	8.91	7.99	5.9	1.7	0.05	1.8	18	10	29	47.9
60-90	min	335	9.32	8.09	4.6	0.1	0.03	1.6	12	5	18	39.2
	max	738	9.82	8.65	7.0	1.8	0.05	1.9	18	13	33	65.1
	mean	514	9.56	8.37	5.8	0.9	0.04	1.7	15	8	27	50.8
	median	492	9.55	8.36	5.9	0.8	0.03	1.7	14	6	29	49.5

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Calcareous soils.**

Soil depth (cm)		Exch Ca	Exch Mg	Exch Na	Exch K	Total cations (Eff CEC)	CEC (cmol(+)/kg)	ESP (%)
0-10	min	8.5	1.1	0.5	1.6	12.7	13.5	2.4
	max	10.8	3.6	1.1	2.8	17.6	20.8	8.2
	mean	9.5	2.4	0.9	2.2	14.8	17.0	5.5
	median	9.6	2.5	1.0	2.2	14.7	16.7	5.8
10-30	min	5.3	1.5	0.4	1.4	9.1	9.7	4.5
	max	7.4	4.8	3.3	2.1	17.1	17.8	23.1
	mean	6.3	3.2	2.1	1.6	13.0	12.6	15.8
	median	6.2	2.9	1.9	1.5	12.9	11.9	16.9
approx 30-60	min	3.7	3.5	1.2	0.8	10.8	9.1	12.9
	max	5.4	5.4	2.9	1.2	13.3	11.6	28.8
	mean	4.4	4.2	2.2	0.9	11.6	10.0	21.3
	median	4.1	3.9	2.3	0.9	11.3	9.9	23.0

Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Calcareous soils.

Soil depth (cm)			Exch Ca	Exch Mg	Exch Na	Exch K	Total cations (Eff CEC)	CEC (cmol(+)/kg)	ESP (%)
approx	60-90	min	1.5	3.1	1.3	0.7	9.1	7.9	15.3
		max	4.5	3.9	3.7	1.1	10.8	9.3	46.9
		mean	3.3	3.5	2.5	0.9	10.2	8.5	29.7
		median	3.6	3.6	2.5	0.9	10.3	8.5	28.3

<sup>1</sup>Exchangeable cations (cmol+)/kg)

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Calcareous soils.**

		Metals in soil solution (mg/L) extracted in a high Cl <sup>-</sup> solution <sup>1</sup>					
Soil depth (cm)		B	Mn	P	S	Si	Sr
0-10	min	0.11	0.03	0.4	14	15	1.5
	max	0.31	0.15	0.8	69	23	2.4
	mean	0.22	0.06	0.5	31	19	2.0
	median	0.22	0.03	0.5	24	19	2.1
10-30	min	0.21	0.03	0.1	11	14	2.0
	max	0.38	0.03	0.5	50	25	2.7
	mean	0.30	0.03	0.2	23	20	2.4
	median	0.30	0.03	0.2	15	22	2.4
30-60	min	0.26	0.03	0.1	14	8	1.3
	max	2.86	0.03	0.1	228	18	3.3
	mean	1.24	0.03	0.1	78	12	2.4
	median	0.75	0.03	0.1	46	13	2.5

<sup>1</sup>Metal concentrations in soil solution after soils extracted at maximum water holding capacity using <sup>1</sup>a high chloride solution (550 mg Cl<sup>-</sup>/L)

**Apx Table 3 cont. Chemical data (minimum, maximum, mean and median) separated into the major soil groups. Calcareous soils.**

		Metals in soil solution (mg/L) extracted in a low Cl <sup>-</sup> solution <sup>1,2</sup>							
Soil depth (cm)		Al	B	Fe	Mn	P	S	Si	Sr
30-60	min	0.03	0.68	0.05	0.03	0.1	18	10	0.7
	max	0.03	3.46	0.05	0.03	0.5	77	13	1.2
	mean	0.03	1.95	0.05	0.03	0.3	43	12	1.0
	median	0.03	1.83	0.05	0.03	0.3	38	13	1.0

<sup>1</sup>Metal concentrations in soil solution after soils extracted at maximum water holding capacity using a low chloride solution (4 mg Cl<sup>-</sup>/L),

<sup>2</sup> Depths 0-10 and 10-30 cm were not extracted with the low chloride solution

**Apx Table 4. Summary of hydraulic properties in NAP soils divided into the main soil groups in the region and the depths sampled. Hard red brown earths 0-10 cm.**

Depth 0-10 cm	Ksat	Water retention at matric potential, kPa						
		0.01	4	8	33	60	100	1500
Field site	m/s	0.01	4	8	33	60	100	1500
NAP-10, Rep1	2.84E-06	0.456	0.380	0.372	0.321	0.274	0.258	0.122
NAP-10, Rep2	4.14E-06	0.438	0.401	0.389	0.341	0.293	0.281	0.146
NAP-10, mean	3.5E-06	0.447	0.391	0.380	0.331	0.283	0.269	0.134
St dev	9.2E-07	0.009	0.015	0.012	0.014	0.013	0.016	0.017
NAP-12, Rep1	8.93E-07	0.543	0.463	0.431	0.340	0.317	0.307	0.114
NAP-12, Rep2	5.67E-07	0.481	0.459	0.423	0.377	0.336	0.294	0.152
NAP-12, mean	7.3E-07	0.512	0.461	0.427	0.358	0.327	0.301	0.133
St dev	2.3E-07	0.044	0.003	0.005	0.026	0.014	0.009	0.026
NAP-13, Rep1	2.42E-05	0.426	0.373	0.349	0.312	0.279	0.246	0.123
NAP-13, Rep2	8.95E-07	0.417	0.391	0.366	0.326	0.289	0.263	0.117
NAP-13, mean	1.3E-05	0.422	0.382	0.358	0.319	0.284	0.255	0.120
St dev	1.6E-05	0.007	0.013	0.012	0.010	0.007	0.012	0.004

**Apx Table 4 contd. Summary of hydraulic properties in NAP soils divided into the main soil groups in the region and the depths sampled. Hard red brown earths 0-10 cm.**

Depth 0-10 cm	Ksat m/S	0.01 kPa	4 kPa	8 kPa	33 kPa	60 kPa	100 kPa	1500 kPa
NAP-15, Rep1	3.20E-06	0.539	0.463	0.439	0.399	0.353	0.354	0.208
NAP-15 Rep2	3.23E-07	0.522	0.467	0.452	0.408	0.370	0.372	0.283
NAP-15, mean	1.8E-06	0.530	0.465	0.446	0.404	0.362	0.363	0.246
St dev	2.0E-06	0.012	0.003	0.009	0.006	0.012	0.013	0.053
NAP-16, Rep1	8.97E-06	0.465	0.392	0.364	0.290	0.255	0.252	0.125
NAP-16, Rep2	2.53E-05	0.506	0.402	0.355	0.274	0.242	0.237	0.084
NAP-16, mean	1.7E-05	0.485	0.397	0.360	0.282	0.249	0.244	0.105
St dev	1.2E-05	0.029	0.007	0.007	0.012	0.010	0.011	0.029
NAP-18, Rep1	3.19E-05	0.438	0.386	0.377	0.336	0.289	0.283	0.178
NAP-18 Rep2	8.07E-07	0.409	0.381	0.376	0.329	0.283	0.280	0.187
NAP-18, mean	1.6E-05	0.424	0.383	0.377	0.333	0.286	0.281	0.182
St dev	2.2E-05	0.020	0.004	0.001	0.005	0.004	0.003	0.006
NAP-20, Rep1	2.39E-07	0.464	0.405	0.395	0.358	0.326	0.322	0.224
NAP-20, Rep2	2.04E-07	0.466	0.396	0.384	0.353	0.326	0.322	0.227
NAP-20, mean	2.2E-07	0.465	0.400	0.390	0.356	0.326	0.322	0.226
St dev	2.5E-08	0.001	0.006	0.008	0.003	0.001	0.000	0.002

**Apx Table 4 contd. Summary of hydraulic properties in NAP soils divided into the main soil groups in the region and the depths sampled. Hard red brown earths 10-30 cm.**

Depth 10-30 cm	Ksat	Water retention at matric potential, kPa						
		0.01	4	8	33	60	100	1500
Field site	m/s	0.01	4	8	33	60	100	1500
NAP-10, Rep1	3.46E-05	0.378	0.332	0.318	0.285	0.262	0.245	0.126
NAP-10, Rep2	3.54E-07	0.369	0.341	0.329	0.304	0.284	0.270	0.132
NAP-10, mean	1.7E-05	0.374	0.337	0.323	0.295	0.273	0.258	0.129
St dev	2.4E-05	0.023	0.006	0.007	0.013	0.015	0.018	0.004
NAP-12, Rep1	6.31E-07	0.357	0.352	0.332	0.299	0.281	0.242	-
NAP-12, Rep2	4.71E-07	0.378	0.347	0.328	0.301	0.282	0.257	0.145
NAP-12, mean	5.5E-07	0.367	0.350	0.330	0.300	0.282	0.249	0.145
St dev	1.1E-07	0.015	0.003	0.003	0.001	0.001	0.011	-
NAP-13, Rep1	1.47E-06	0.357	0.317	0.300	0.254	0.235	0.226	0.174
NAP-13, Rep2	1.59E-05	0.362	0.316	0.305	0.255	0.234	0.230	0.107
NAP-13, mean	8.7E-06	0.360	0.317	0.303	0.254	0.235	0.228	0.141
St dev	1.0E-05	0.003	0.001	0.004	0.001	0.001	0.003	0.048

**Apx Table 4 contd. Summary of hydraulic properties in NAP soils divided into the main soil groups in the region and the depths sampled. Hard red brown earths 10-30 cm.**

Depth 10-30 cm	Ksat	Water retention at matric potential, kPa						
		0.01	4	8	33	60	100	1500
Field site	m/s	0.01	4	8	33	60	100	1500
NAP-15, Rep1	3.30E-07	0.561	0.550	0.527	0.462	0.437	0.428	0.331
NAP-15, Rep2	3.76E-07	0.573	0.549	0.516	0.449	0.420	0.415	0.312
NAP-15, mean	3.5E-07	0.567	0.549	0.521	0.456	0.429	0.421	0.322
St dev	3.2E-08	0.008	0.000	0.008	0.009	0.012	0.009	0.014
NAP-16, Rep1	5.20E-05	0.506	0.403	0.351	0.280	0.244	0.226	0.141
NAP-16, Rep2	1.88E-05	0.446	0.328	0.292	0.243	0.212	0.205	0.158
NAP-16, mean	3.5E-05	0.476	0.366	0.321	0.261	0.228	0.215	0.150
St dev	2.3E-05	0.042	0.053	0.041	0.026	0.023	0.015	0.012
NAP-18, Rep1	2.07E-07	0.436	0.404	0.389	0.348	0.324	0.319	0.263
NAP-20, Rep1	1.33E-06	0.531	0.432	0.410	0.370	0.352	0.347	0.270
NAP-20, Rep2	1.92E-07	0.556	0.497	0.473	0.449	0.428	0.423	0.375
NAP-20, mean	7.6E-07	0.543	0.464	0.442	0.409	0.390	0.385	0.322
St dev	8.1E-07	0.018	0.047	0.044	0.056	0.054	0.054	0.074

**Apx Table 4 contd. Summary of hydraulic properties in NAP soils divided into the main soil groups in the region and the depths sampled. Hard red brown earths 30-60 cm.**

Depth 30-60 cm	Ksat	Water retention at matric potential, kPa						
		0.01	4	8	33	60	100	1500
Field site	m/s	0.01	4	8	33	60	100	1500
NAP-13, Rep1	9.98E-07	0.473	0.358	0.324	0.301	0.286	0.284	0.222
NAP-13, Rep2	9.84E-05	0.456	0.382	0.340	0.312	0.296	0.292	0.216
NAP-13, mean	5.0E-05	0.465	0.370	0.332	0.307	0.291	0.288	0.219
St dev	6.9E-05	0.012	0.017	0.011	0.008	0.007	0.006	0.004

**Apx Table 4 contd. Summary of hydraulic properties in NAP soils divided into the main soil groups in the region and the depths sampled. Sand over clay soils. 0-10 cm.**

Depth 0-10 cm	Ksat	Water retention at matric potential, kPa						
		0.01	4	8	33	60	100	1500
Field site	m/s	0.01	4	8	33	60	100	1500
NAP-9, Rep1	2.19E-05	0.400	0.398	0.334	0.131	0.107	0.098	0.088
NAP-9, Rep2	3.08E-05	0.471	0.418	0.346	0.162	0.122	0.107	0.048
NAP-9, mean	2.6E-05	0.436	0.408	0.340	0.147	0.114	0.103	0.068
St dev	6.3E-06	0.051	0.014	0.008	0.022	0.011	0.006	0.028
NAP-11, Rep1	1.11E-05	0.404	0.364	0.313	0.179	0.151	0.138	0.107
NAP-11, Rep2	1.04E-05	0.393	0.350	0.321	0.197	0.159	0.152	0.100
NAP-11, mean	1.1E-05	0.399	0.357	0.317	0.188	0.155	0.145	0.104
St dev	5.5E-07	0.008	0.010	0.006	0.013	0.005	0.010	0.005
NAP-14, Rep1	7.40E-05	0.399	0.348	0.185	0.089	0.065	0.057	0.016
NAP-14, Rep2	6.74E-05	0.403	0.345	0.164	0.100	0.061	0.050	0.015
NAP-14, mean	7.1E-05	0.401	0.347	0.175	0.095	0.063	0.053	0.015
St dev	4.6E-06	0.003	0.002	0.015	0.008	0.003	0.005	0.001

**Apx Table 4 contd. Summary of hydraulic properties in NAP soils divided into the main soil groups in the region and the depths sampled. Sand over clay soils. 10-30 cm.**

Depth 10-30 cm	Ksat	Water retention at matric potential, kPa						
		0.01	4	8	33	60	100	1500
Field site	m/s	0.01	4	8	33	60	100	1500
NAP-9, Rep1	1.68E-05	0.483	0.410	0.350	0.249	0.215	0.198	0.106
NAP-9, Rep2	7.94E-06	0.479	0.407	0.361	0.267	0.219	0.206	0.118
NAP-9, mean	1.2E-05	0.481	0.408	0.355	0.258	0.217	0.202	0.112
St dev	6.3E-06	0.003	0.002	0.007	0.013	0.003	0.006	0.009
NAP-11, Rep1	1.08E-05	0.445	0.369	0.309	0.260	0.234	0.226	0.156
NAP-11, Rep2	9.96E-06	0.425	0.365	0.321	0.294	0.255	0.250	0.175
NAP-11, mean	1.0E-05	0.435	0.367	0.315	0.277	0.245	0.238	0.165
St dev	6.3E-07	0.014	0.003	0.009	0.025	0.015	0.017	0.013
NAP-14, Rep1	1.34E-05	0.416	0.340	0.137	0.075	0.068	0.045	0.026
NAP-14, Rep2	1.12E-05	0.376	0.328	0.132	0.062	0.064	0.049	0.025
NAP-14, mean	1.2E-05	0.396	0.334	0.135	0.069	0.066	0.047	0.025
St dev	1.5E-06	0.028	0.009	0.004	0.009	0.003	0.003	0.001

**Apx Table 4 contd. Summary of hydraulic properties in NAP soils divided into the main soil groups in the region and the depths sampled. Sand over clay soils. 30-60 cm.**

Depth 30-60 cm	Ksat	Water retention at matric potential, kPa						
Field site	m/s	0.01	4	8	33	60	100	1500
NAP-11, Rep1	1.16E-06	0.402	0.386	0.333	0.289	0.261	0.256	0.172
NAP-14, Rep1	1.80E-05	0.373	0.308	0.209	0.091	0.077	0.067	0.049
NAP-14, Rep2	1.16E-05	0.369	0.316	0.220	0.134	0.120	0.106	0.080
NAP-14, mean	1.5E-05	0.371	0.312	0.215	0.113	0.098	0.087	0.064
St dev	4.5E-06	0.003	0.006	0.008	0.031	0.030	0.027	0.022

**Apx Table 4 contd. Summary of hydraulic properties in NAP soils divided into the main soil groups in the region and the depths sampled. Sand over clay soils. 60-90 cm.**

Depth 60-90 cm	Ksat	Water retention at matric potential, kPa						
Field site	m/s	0.01	4	8	33	60	100	1500
NAP-11, Rep1	2.19E-05	0.462	0.408	0.320	0.255	0.226	0.218	0.162
NAP-14, Rep1	5.57E-06	0.372	0.364	0.129	0.044	0.083	0.075	0.091
NAP-14, Rep2	4.02E-05	0.352	0.324	0.119	0.085	0.060	0.054	0.032
NAP-14, mean	2.3E-05	0.362	0.344	0.124	0.065	0.071	0.065	0.061
St dev	2.4E-05	0.014	0.028	0.008	0.029	0.017	0.015	0.042

**Apx Table 4 contd. Summary of hydraulic properties in NAP soils divided into the main soil groups in the region and the depths sampled. Calcareous soils. 0-10 cm.**

Depth 0-10 cm	Ksat	Water retention at matric potential, kPa						
Field site	m/s	0.01	4	8	33	60	100	1500
NAP-17, Rep1	1.38E-06	0.441	0.403	0.394	0.358	0.319	0.314	0.191
NAP-17, Rep2	5.35E-05	0.463	0.401	0.384	0.341	0.305	0.301	0.201
NAP-17, mean	2.7E-05	0.452	0.402	0.389	0.349	0.312	0.307	0.196
St dev	3.7E-05	0.016	0.001	0.007	0.012	0.010	0.010	0.007
NAP-19, Rep1	1.95E-05	0.505	0.412	0.375	0.295	0.250	0.237	0.163
NAP-19, Rep2	3.37E-05	0.502	0.413	0.379	0.290	0.247	0.240	0.167
NAP-19, mean	2.7E-05	0.504	0.412	0.377	0.293	0.248	0.239	0.165
St dev	1.0E-05	0.002	0.000	0.003	0.004	0.002	0.002	0.002

**Apx Table 4 contd. Summary of hydraulic properties in NAP soils divided into the main soil groups in the region and the depths sampled. Calcareous soils. 10-30 cm.**

Depth 10-30 cm	Ksat	Water retention at matric potential, kPa						
Field site	m/s	0.01	4	8	33	60	100	1500
NAP-17, Rep1	1.16E-06	0.484	0.393	0.368	0.314	0.290	0.280	0.215
NAP-19, Rep1	2.54E-05	0.487	0.411	0.378	0.293	0.269	0.257	0.213

**Apx Table 4 contd. Summary of hydraulic properties in NAP soils divided into the main soil groups in the region and the depths sampled. Deep uniform to gradational soils. 0-10 cm.**

Depth 0-10 cm	Ksat	Water retention at matric potential, kPa						
Field site	m/s	0.01	4	8	33	60	100	1500
NAP-8, Rep1	1.59E-06	0.401	0.377	0.368	0.353	0.275	0.281	0.082
NAP-8, Rep2	7.45E-06	0.387	0.370	0.361	0.357	0.292	0.287	-
NAP-8, mean	4.5E-06	0.394	0.373	0.365	0.355	0.284	0.284	0.082
St dev	4.1E-06	0.010	0.005	0.005	0.003	0.012	0.005	-

**Apx Table 4 contd. Summary of hydraulic properties in NAP soils divided into the main soil groups in the region and the depths sampled. Deep uniform to gradational soils. 10-30 cm.**

Depth 10-30 cm	Ksat	Water retention at matric potential, kPa						
Field site	m/s	0.01	4	8	33	60	100	1500
NAP-8, Rep1	6.22E-06	0.483	0.470	0.465	0.453	0.435	0.394	0.238
NAP-8, Rep2	1.77E-07	0.463	0.451	0.445	0.446	0.430	0.393	0.265
NAP-8, mean	3.2E-06	0.473	0.460	0.455	0.449	0.433	0.394	0.252
St dev	4.3E-06	0.014	0.014	0.014	0.005	0.003	0.000	0.020

# Appendix E – Causes and distributions of pH categories and possible amelioration strategies

**Apx Table 5. Causes and distribution of six diagnostic pH ranges found in Australian soils and possible amelioration strategies for maintaining production on these soils. Reproduced from Slattery et al. (1999).**

DIAGNOSTIC RANGE	CAUSES AND DISTRIBUTION	AMELIORATION
Soil pH <sub>Ca</sub> < 4 (pH <sub>w</sub> < 4.5)	Occur in extremely weathered mineral soils of low fertility, in soils subjected to very acidifying agricultural practices and where the buffering capacity is low. Soil pH values markedly less than 4 will also be encountered in peat soils and acid sulfate soils. Acid sulfate conditions are most commonly found in coastal (mangrove swamp), sub-coastal low-lying areas and some inland situations where oxidisable sulphide is present in groundwater and in mine sites where sulfidic ores are mined.	These soils are difficult to ameliorate since they are usually associated with acidic sub-soils and will require large amount of lime to return them to a productive state.
Soil pH <sub>Ca</sub> 4-4.5 (pH <sub>w</sub> 4.5-5.3)	Caused by significant soil acidification. This can be as a result of natural processes or from the long term use of intensive agricultural practices (associated with nitrate leaching from improved pastures, fertiliser effects due to ammonium nitrogen transformation and the removal of alkali in produce). In this soil pH range the process of mineral weathering is dominant and exchangeable cations such as Al and Mn may exhibit a toxicity to plants, increasing in concentration with decreasing soil pH. In addition, at these low soil pH values deficiencies of nutrients such as Mo (decreased availability) and Ca, Mg, Na and K (due to leaching loss) can occur and populations or activity of some soil micro-organisms (especially nitrifiers) are significantly altered.	Clay mineral and organic matter content, that together usually control the buffering capacity of the soil, will determine at what rate a soil is likely to acidify and decrease in pH. A sandy soil of low organic matter content (<1.0%) will acidify much more rapidly than a clay loam soil of high organic matter content (>2.0%). Amelioration of soils in this pH range is usually economically viable and necessary if productive yields are to be maintained.
Soil pH <sub>Ca</sub> 4.5-5.0 (pH <sub>w</sub> 5.3-5.8)	Soil is in a critical range where optimum growth can be obtained for many acid-tolerant cultivar, providing the adequate amounts of N and P are available. The effects of toxicities of exchangeable Mn may still limit optimum yield potential for the more acid-sensitive cultivars (e.g. French beans (Siman et al. 1971) particularly in soils with high reducible Mn contents, while below pH <sub>Ca</sub> 4.8 (pH <sub>w</sub> 5.5) Al toxicities will begin to limit production.	Amelioration of these soils is economically viable, and liming strategies should be determined according to the farming system in use to obtain optimum yields and prevent sub-soil acidification.

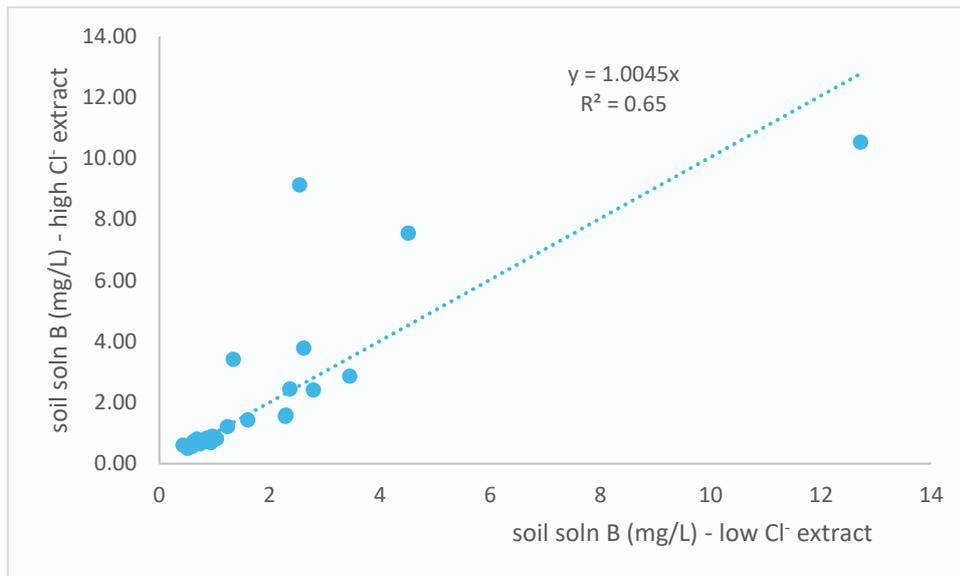
**Apx Table 5 cont. Causes and distribution of six diagnostic pH ranges found in Australian soils and possible amelioration strategies for maintaining production on these soils. Reproduced from Slattery et al. (1999).)**

Diagnostic range	Causes and distribution	Amelioration
Soil pH <sub>Ca</sub> 5.0-6.5 (pH <sub>w</sub> 5.8-7.0)	This pH range is optimal for the growth of most plant species. There will be no effect of soil acidity although below pH <sub>Ca</sub> 5.8 (pH <sub>w</sub> 6.5) there may be an effect of Mn toxicity for those mineral soils that contain Mn.	Soils are likely to be most productive, providing there are no nutrient deficiencies (e.g. P, N, Zn, Mo) or salinity effects.
Soil pH <sub>Ca</sub> 6.5-7.5 (pH <sub>w</sub> 7.0-8.0)	This pH range is regarded as neutral to slightly alkaline. Elements such as Zn and Mn that are strongly pH dependent become increasingly unavailable as the pH increases, whereas other nutrients such as Ca and Mo become more available. These soils generally contain high amounts of magnesium and calcium carbonate.	Micronutrient deficiencies may occur and plants should be monitored.
Soil pH <sub>Ca</sub> > 7.6 (pH <sub>w</sub> > 8.0)	Soils are alkaline and dominated by Na, Ca, and Mg carbonates. In these alkaline soils nutrient deficiencies (e.g. micronutrient) can occur. In addition, toxicities of B can exist which limit the production of sensitive cultivars. At extremely high soil pH values (greater than pH <sub>w</sub> 8.5) where exchangeable Na dominates and free NaHCO <sub>3</sub> and carbonates are present, the soil is likely to have a very poor nutritional and structural status. In some cases, a soil may become more alkaline with time because of large additions of Na (e.g. in irrigation water) causing a decline in soil structure.	Only alkaline-tolerant plants will survive, trace elements may be required and plants should be monitored for deficiencies. If soil EC > 1.4 dS/cm then the soil may be saline and groundwater will need to be lowered. If EC < 0.7 dS/cm then the soil is likely to be sodic and will require acidifying; legumes and gypsum may be effective at reducing exchangeable Na.

## Appendix F – Boron

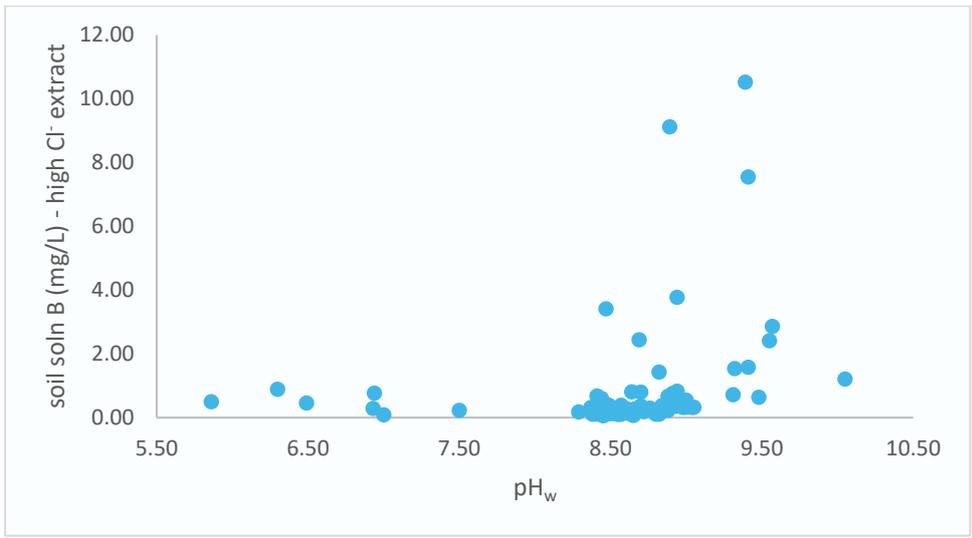
The B in soil solution was determined for a subset of soils sampled (i.e. surface soils 0-10 cm, 10-30 cm and 30-60 cm and within the pH range  $\text{pH}_w < 7$  and  $\text{pH}_w > 8.4$ ) was determined using a high  $\text{Cl}^-$  solution (550 mg  $\text{Cl}^-/\text{L}$ ) based on the maximum  $\text{Cl}^-$  content of the recycled waste water. Then B was determined in a smaller group of this subset using a low  $\text{Cl}^-$  solution (4 mg  $\text{Cl}^-/\text{L}$ ) based on rainwater.

Generally, there was a 1:1 relationship between the soil solutions using the two extractions and the concentration of  $\text{Cl}^-$  in the soil solution made no difference to the B extracted (Apx Figure 15).

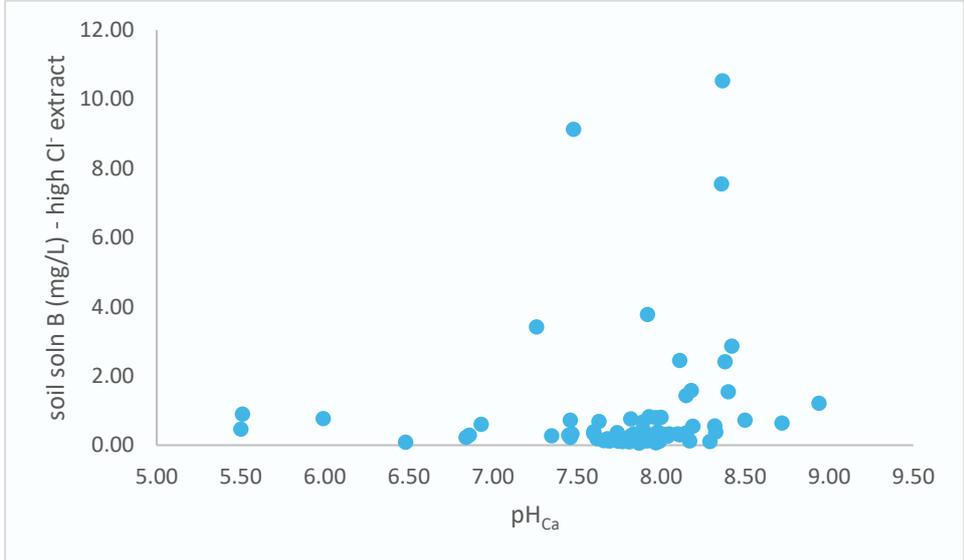


**Apx Figure 15. Relationship between soil solution B extracted using a high (550 mg/L)  $\text{Cl}^-$  solution and soil solution B extracted using a low (4 mg/L)  $\text{Cl}^-$  solution.**

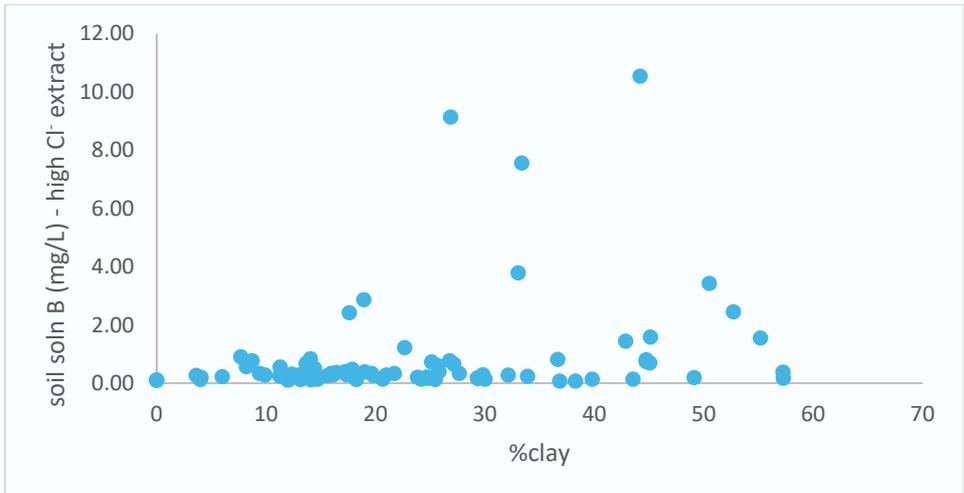
The B in soil solution extracted using the high (550 mg/L)  $\text{Cl}^-$  solution was then plotted against other soil properties to assess whether other properties could be used as a surrogate to predict high native readily available soil B (Apx Figs. 16 – 24). This was done to determine whether a more easily measured soil property could act as a surrogate or indicator of soil solution B.



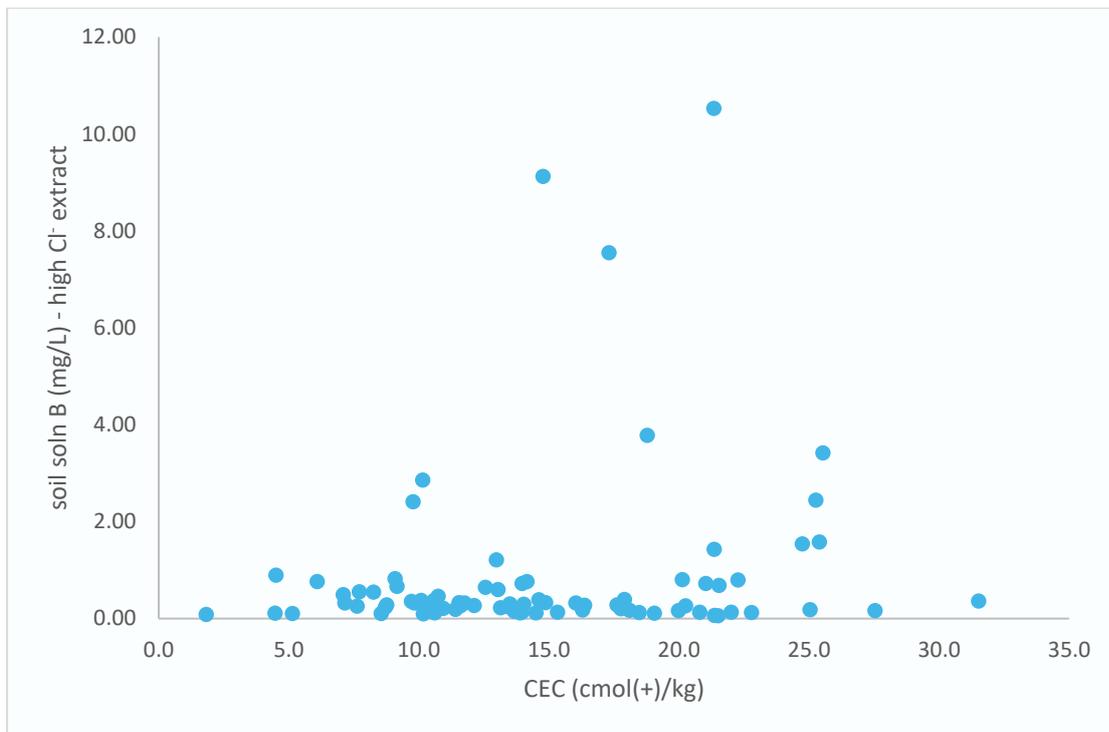
**Apx Figure 16.** Relationship between soil solution B extracted using a high Cl<sup>-</sup> solution and pH (1:5, soil:water).



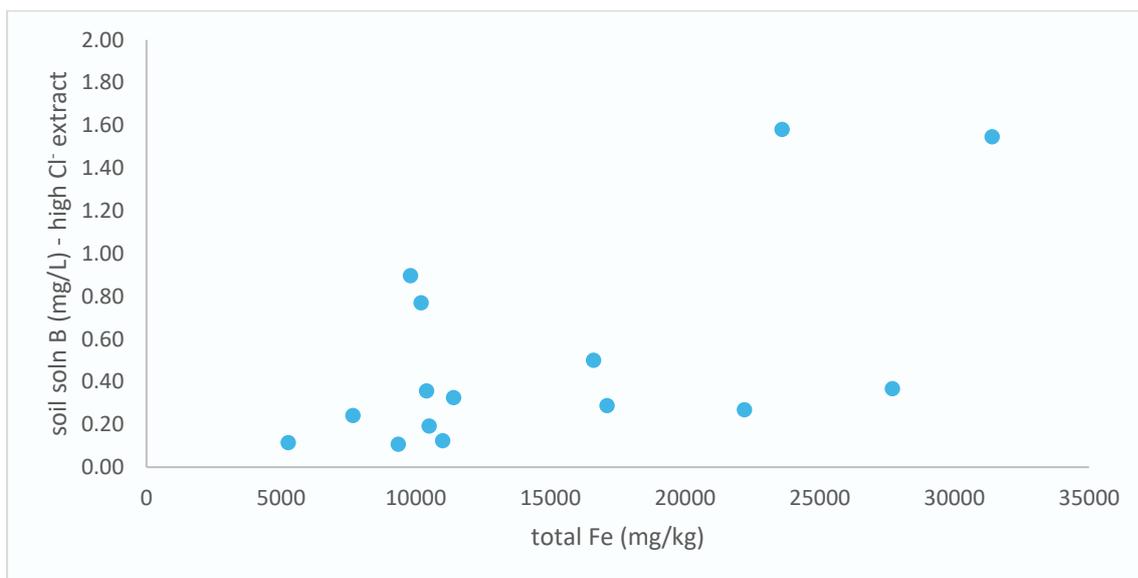
**Apx Figure 17.** Relationship between soil solution B extracted using a high Cl<sup>-</sup> solution and pH (1:5, soil:0.01 M CaCl<sub>2</sub>).



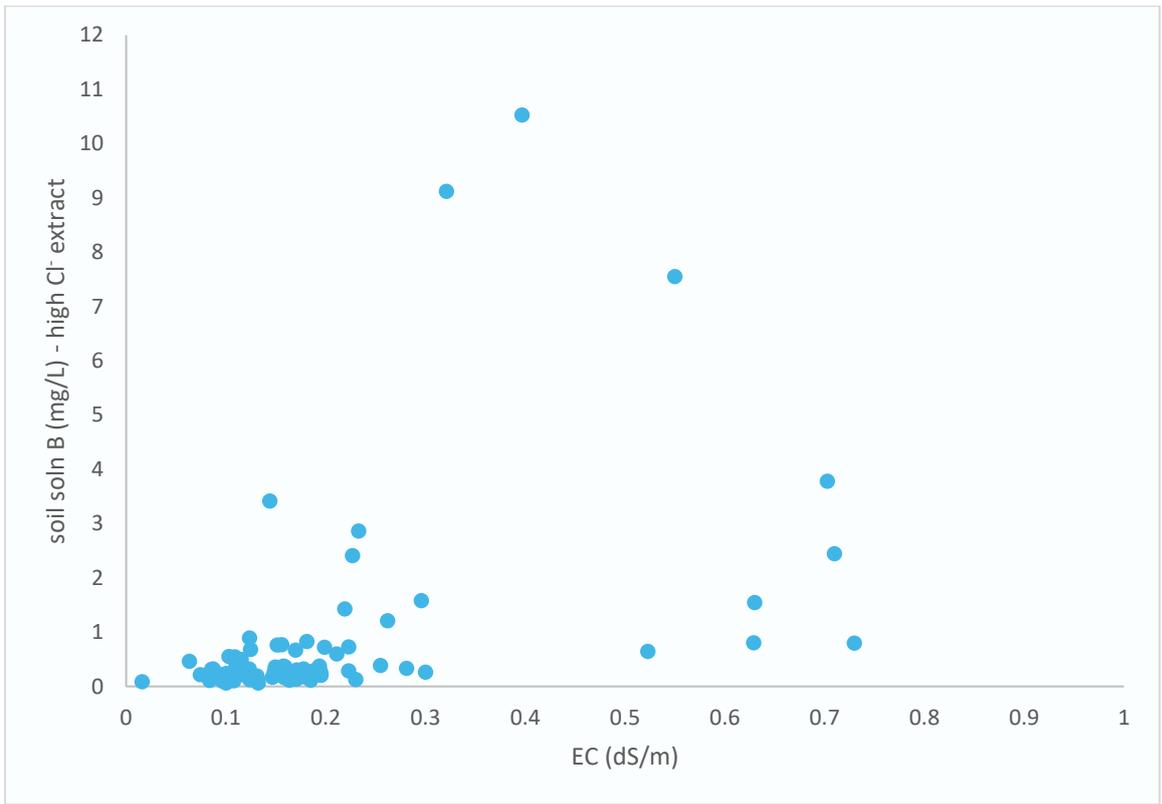
**Apx Figure 18.** Relationship between soil solution B extracted using a high Cl<sup>-</sup> solution and clay content.



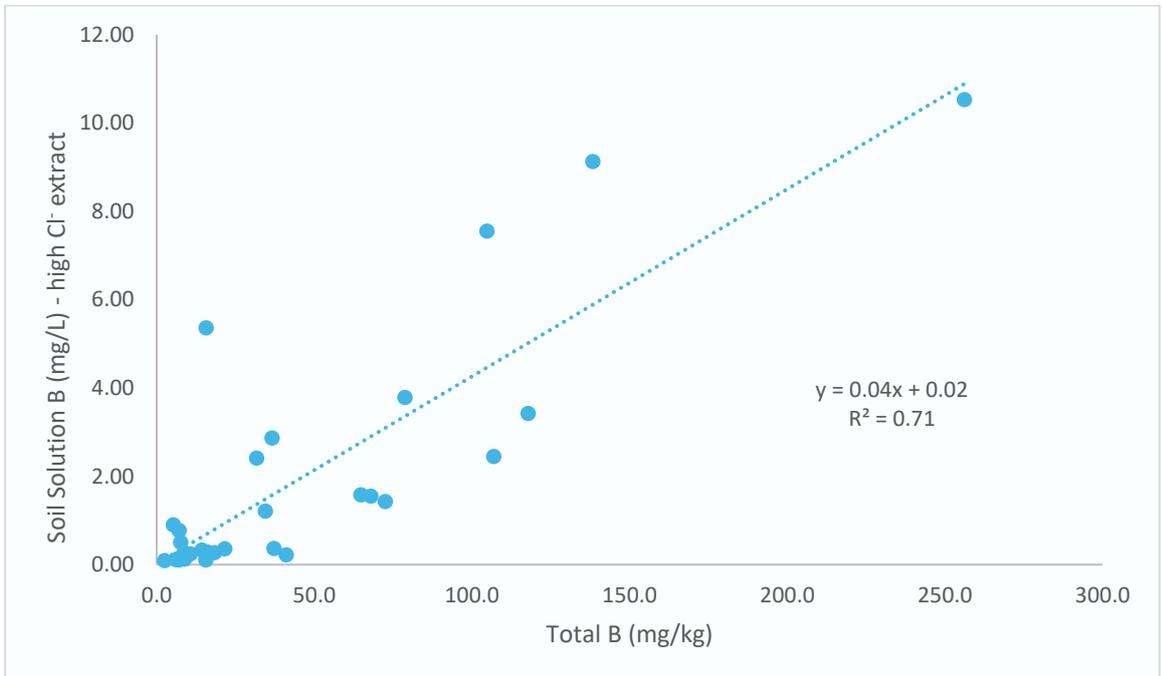
**Apx Figure 19. Relationship between soil solution B extracted using a high Cl<sup>-</sup> solution and cation exchange capacity (CEC).**



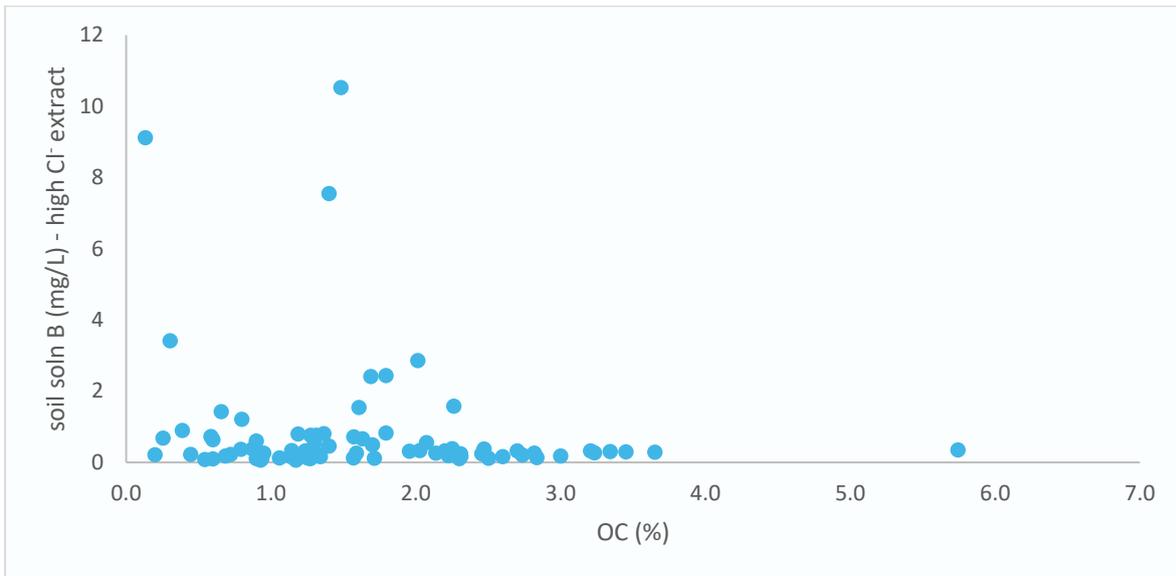
**Apx Figure 20. Relationship between soil solution B extracted using a high Cl<sup>-</sup> solution and total Fe.**



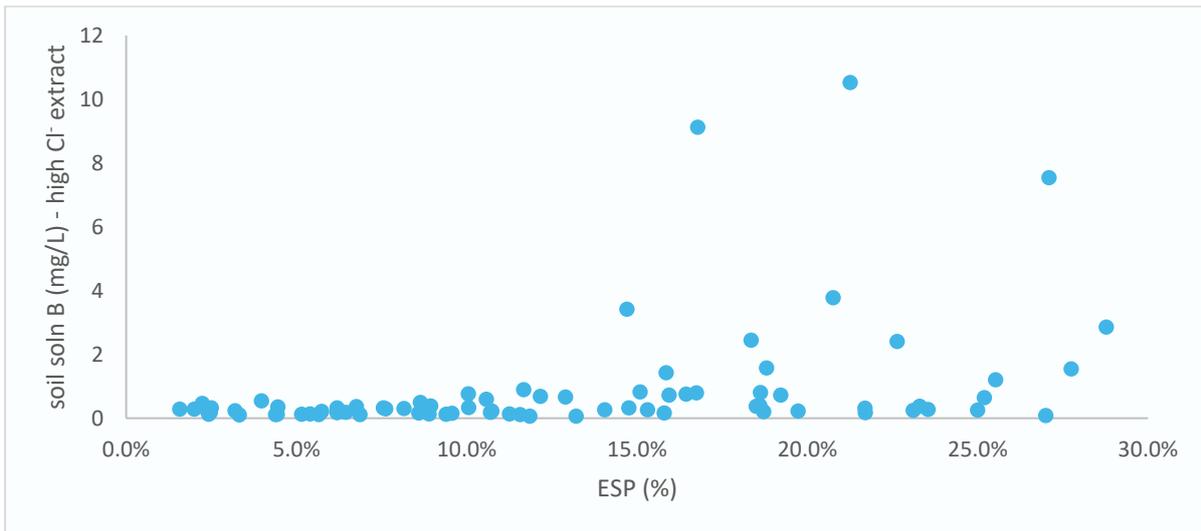
**Apx Figure 21.** Relationship between soil solution B extracted using a high Cl<sup>-</sup> solution and EC (1:5, water).



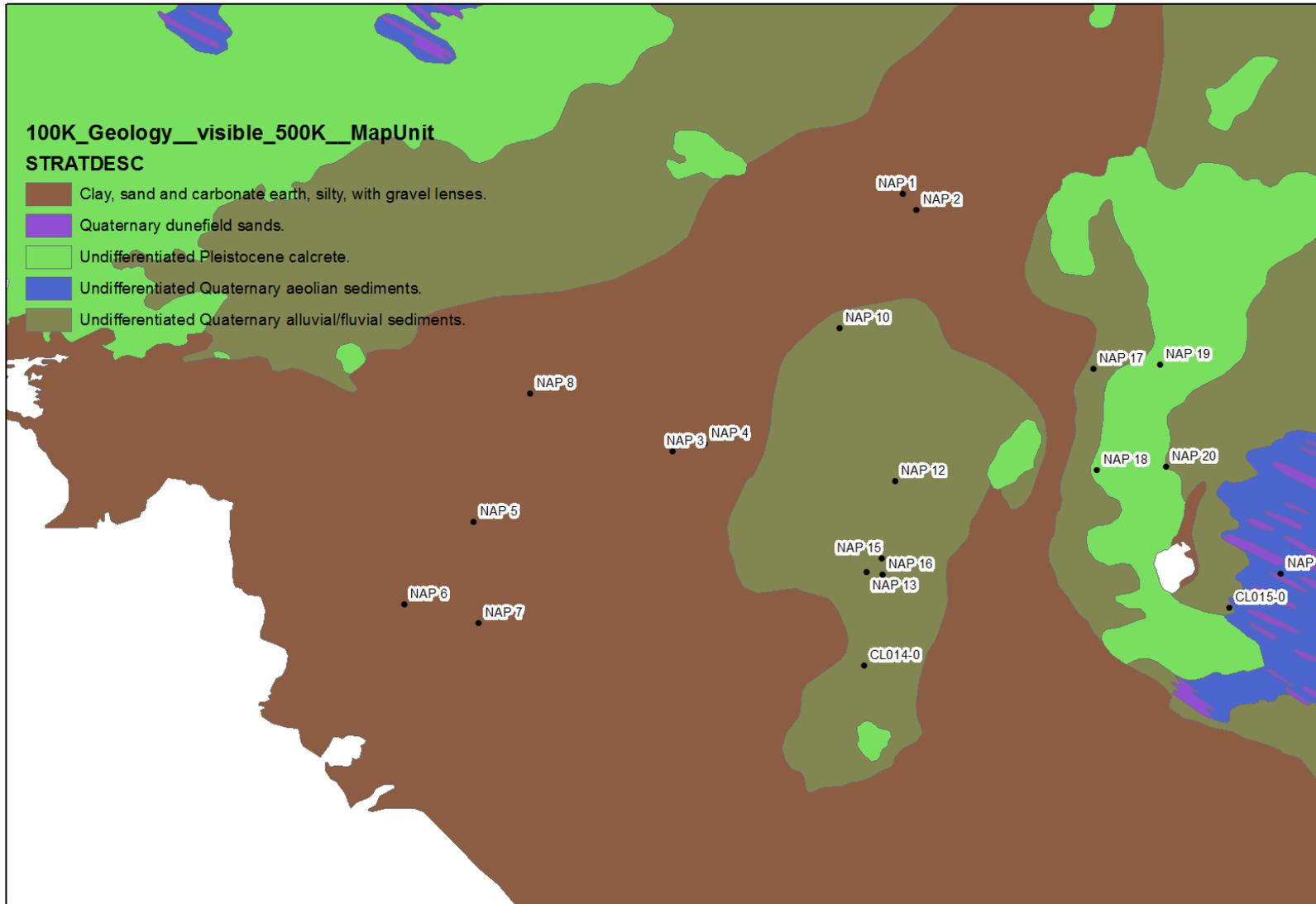
**Apx Figure 22.** Relationship between soil solution B extracted using a high Cl<sup>-</sup> solution and total soil B.



**Apx Figure 23. Relationship between soil solution B extracted using a high Cl<sup>-</sup> solution and organic carbon (OC, %).**



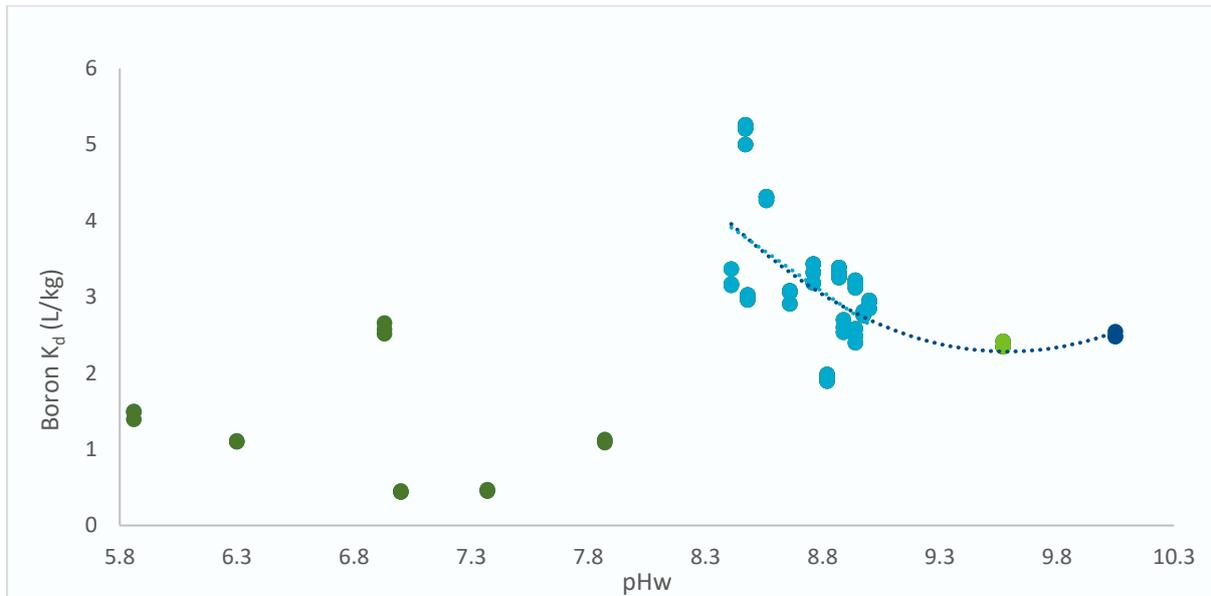
**Apx Figure 24. Relationship between soil solution B extracted using a high Cl<sup>-</sup> solution and exchangeable sodium percentage (ESP, %).**



Apx Figure 25. Soil sampling locations and major geological classes (SA Government, 2018).

## Sorption coefficients ( $K_d$ values) for boron (B)

Sorption behaviour of B was assessed in soils covering a range of pH values. At  $pH_w < \text{approx. } 8$  and  $> 8.4$  the sorption declined significantly. There were only a limited number of soils in the  $pH_w < 8$  region due to most soils in the region being highly alkaline. A decreasing exponential relationship was found for the  $K_d$  values plotted against  $pH_w$  using the data for soils  $pH_w > 8.4$  ( $y = -0.96x + 11.58$ ;  $R^2 = 0.27$ ) (Apx Figure 26). The average  $K_d$  values are given in Apx Table 6.



Apx Figure 26. Relationship between  $K_d$  values for boron and  $pH_w$  for Northern Adelaide Plains (NAP) soils.

**Apx Table 6. Average (+/- standard deviation) of sorption coefficients ( $K_d$  values) for B in different soils representative of the four major soil groups in the focus area of the NAP.**

NAP code	Major soil group	Depth (cm)	Average B $K_d$ (L/kg)	Std dev	%CV
NAP 17	Calcareous	0-10	5.16	0.14	3%
NAP 01	Deep uniform to gradational	0-10	2.58	0.07	3%
NAP 02	Deep uniform to gradational	0-10	3.01	0.04	1%
NAP 04	Hard red brown	0-10	1.46	0.06	4%
NAP 16	Calcareous	0-10	3.31	0.13	4%
NAP 14	Sand over clay	0-10	0.44	0.01	2%
NAP 09	Sand over clay	0-10	1.94	0.04	2%
NAP 17	Calcareous	10-30	4.30	0.03	1%
NAP 05	Deep uniform to gradational	10-30	3.32	0.07	2%
NAP 07	Hard red brown	10-30	1.10	0.01	1%
NAP 16	Calcareous	10-30	2.78	0.03	1%
NAP 06	Hard red brown	10-30	2.61	0.08	3%
NAP 09	Sand over clay	10-30	3.02	0.09	3%
NAP 14	Sand over clay	10-30	0.46	0.01	3%
NAP 19	Calcareous	30-60	3.17	0.05	2%
NAP 08	Deep uniform to gradational	30-60	2.50	0.04	1%
NAP 13	Hard red brown	30-60	3.23	0.12	4%
NAP 16	Calcareous	30-60	2.37	0.04	2%
NAP 14	Sand over clay	30-60	1.11	0.02	2%
NAP 11	Sand over clay	30-60	2.91	0.06	2%
NAP 07	Hard red brown	30-60	2.49	0.09	4%

# Appendix G – Electrical conductivity (EC)

**Apx Table 7. Soil salinity criteria  $EC_{se}$ , corresponding to a 10% yield reduction for the plant salt tolerance groupings of Maas and Hoffman (1977) and the equivalent  $EC_{1:5}$  for four ranges of clay content determined using equation 1 below. Reproduced from Shaw (1999).**

Plant salt tolerance grouping <sup>A</sup>	$EC_{se}$ range <sup>B</sup> (dS/m)	Corresponding $EC_{1:5}$ (dS/m), based on soil clay content				Soil salinity rating
		10-20% clay	20-40% clay	40-60% clay	60-80% clay	
Sensitive crops	<0.95	<0.07	<0.09	<0.12	<0.15	Very low
Moderately sensitive crops	0.95-1.9	0.07-0.15	0.09-0.19	0.12-0.24	0.15-0.3	Low
Moderately tolerant crops	1.9-4.5	0.15-0.34	0.19-0.45	0.24-0.56	0.3-0.7	Medium
Tolerant crops	4.5-7.7	0.34-0.63	0.45-0.76	0.56-0.96	0.7-1.18	High
Very tolerant crops	7.7-12.2	0.63-0.93	0.76-1.21	0.96-1.53	1.18-1.87	Very high
Generally too saline for crops	>12.2	>0.93	>1.21	>1.53	>1.87	Extreme

<sup>A</sup> These groupings are statistically derived divisions based on families of linear curves representing the salt tolerance ratings of the majority of crops reported by Maas & Hoffman (1977). The terminology of Maas & Hoffman (1977) has been modified and an additional group of sensitive crops incorporated.

<sup>B</sup>  $EC_{se}$  is the boundary  $EC_{se}$  at which 10% yield reduction occurs for these plant salt tolerance groups. The  $EC_{1:5}$  ranges have been determined from these  $EC_{se}$  ranges using equation (4) with all anions as chloride (Shaw, 1999).

$$\frac{EC_{se}}{EC_{1:5}} = \left[ \frac{500 + 6(0.59 + 0.016clay)^{1.5}}{25.57 + 0.74clay} \right] \left[ \frac{1}{1.024 + 0.232 \ln \left[ \frac{EC_{1:5}}{6.64Cl\%} \right]} \right] \quad (1)$$

## Appendix H – Salt tolerance among crops

Apx Table 8. Guideline to relative salt tolerances among crops based on the concept of Maas & Hoffman (1977), within broad plant groups from SalCon (1997) (Reproduced from Shaw, 1999).

Common name	Scientific name	Tolerance based on <sup>1</sup> :	Salinity threshold (EC <sub>se</sub> ) (dS/m)	Reference
<b>Grains</b>				
Barley, grain	<i>Hordeum vulgare</i>	Grain yield	8.0	Maas & Hoffman (1977)
Corn, grain	<i>Zea mays</i>	Ear fresh weight	1.7	Maas & Hoffman (1977)
Oats	<i>Avena satvia</i>	Grain yield	5.0	Shaw et al. (1987)
Wheat	<i>Triticum aestivum</i>	Grain yield	6.0	Maas & Hoffman (1977)
<b>Fruits</b>				
Almond	<i>Prunus dulcis</i>		1.5	Maas & Hoffman (1977)
Date	<i>Phoenix dactylifera</i>		4.0	Maas & Hoffman (1977)
Fig	<i>Ficus carica</i>		4.2	Bresler et al. (1982)
Grape	<i>Vitis spp.</i>		1.5	Maas & Hoffman (1977)
Olive	<i>Olea europaea</i>		4.0	Bresler et al. (1982)
<b>Heavy vegetables</b>				
Onion	<i>Allium cepa</i>	Bulb yield	1.2	Maas & Hoffman (1977)
Potato	<i>Solanum tuberosum</i>	Tuber yield	1.7	Maas & Hoffman (1977)

Apx Table 8 contd. Guideline to relative salt tolerances among crops based on the concept of Maas & Hoffman (1977), within broad plant groups from SalCon (1997) (Reproduced from Shaw, 1999).

Common name	Scientific name	Tolerance based on <sup>1</sup> :	Salinity threshold (EC <sub>se</sub> ) (dS/m)	Reference
<b>Vegetables</b>				
Bean	<i>Phaseolus vulgaris</i>	Seed yield	1.0	Maas & Hoffman (1977)
Broadbean	<i>Vicia faba</i>		1.6	Maas & Hoffman (1977)
Broccoli	<i>Brassica oleracea</i>		2.8	Maas & Hoffman (1977)
Cabbage	<i>Brassica oleracea</i>	Head fresh weight	1.8	Maas & Hoffman (1977)
Carrot	<i>Daucus carota</i>	Storage root	1.0	Maas & Hoffman (1977)
Cauliflower	<i>Brassica oleracea</i>		2.5	Bresler et al. (1982)
Celery	<i>Apium graveolens</i>	Petiole fresh weight	1.8	Maas (1986)
Cucumber	<i>Cucumis sativus</i>		2.5	Maas & Hoffman (1977)
Eggplant	<i>Solanum melongena</i>	Fruit yield	1.1	Heuer et al. (1986)
Kale	<i>Brassica campestris</i>	Fruit yield	6.5	Bresler et al. (1982)
Lettuce	<i>Lactuca sativa</i>		1.3	Maas & Hoffman (1977)
Pea	<i>Pisum sativum L.</i>	Top fresh weight	2.5	Bresler et al. (1982)
Pepper	<i>Capsicum annum</i>	Seed fresh weight	1.5	Shaw et al. (1987)
Rosemary	<i>Rosmarinus lockwoodii</i>	Fruit yield	4.5	Bresler et al. (1982)
Spinach	<i>Spinacia oleracea</i>		2.0	Maas & Hoffman (1977)
Squash	<i>Cucurbita maxima</i>	Top fresh weight	2.5	Bresler et al. (1982)
Tomato	<i>Lycopersicon esculentum</i>		2.3	Maas & Hoffman (1977)
Turnip	<i>Brassica rapa</i>	Fruit yield	0.9	Maas (1986)
Zucchini	<i>Cucurbita pepo melopepo</i>	Storage root	4.7	Maas (1986)
		Fruit yield		

<sup>1</sup> From Qadir et al. (2000)

# Appendix I – Sodicity and exchangeable sodium percentage (ESP)

Apx Table 9. Percentage of soils within each soil group/depth category sampled across the NAP focus area that are within each exchangeable sodium percentage (ESP%) or ESP and electrical conductivity (EC) threshold range. Data are presented for each of the major soil groups and for all the soils combined.

## i) Hard Red Brown

ESP or ESP and EC threshold range	0-10 cm	10-30 cm	30-60 cm	60-90 cm	90-120 cm
Total number of soils	18	18	18	17	4
ESP < 6	61.1%	5.6%	0.0%	0.0%	25.0%
ESP 6-14	38.9%	66.7%	16.7%	5.9%	0.0%
ESP > 14	0.0%	27.8%	83.3%	94.1%	75.0%
ESP > 7.7 & EC 0-0.2 dS/m	22.2%	72.2%	44.4%	11.8%	0.0%
ESP > 7.7 & EC > 0.2 dS/m	11.1%	16.7%	55.6%	88.2%	75.0%
EC > 0.7 dS/m	0.0%	0.0%	16.7%	35.3%	50.0%

## ii) Calcareous

ESP or ESP and EC threshold range	0-10 cm	10-30 cm	30-60 cm	60-90 cm	90-120 cm
Total number of soils	6	6	6	4	1
ESP < 6	50.0%	16.7%	0.0%	0.0%	0.0%
ESP 6-14	50.0%	0.0%	16.7%	0.0%	0.0%
ESP > 14	0.0%	83.3%	83.3%	100.0%	100.0%
ESP > 7.7 & EC 0-0.2 dS/m	16.7%	83.3%	50.0%	0.0%	0.0%
ESP > 7.7 & EC > 0.2 dS/m	0.0%	0.0%	50.0%	100.0%	100.0%
EC > 0.7 dS/m	0.0%	0.0%	0.0%	25.0%	100.0%

iii) Deep uniform

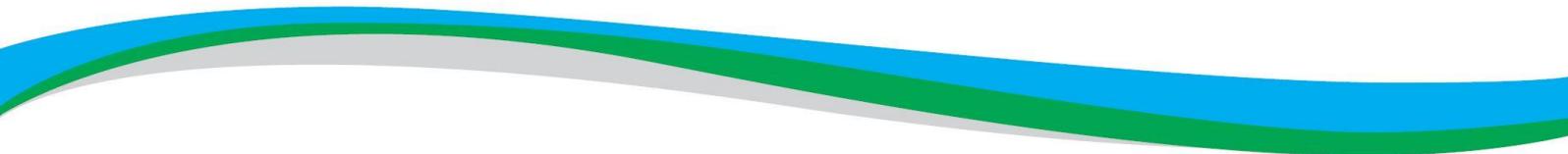
ESP or ESP and EC threshold range	0-10 cm	10-30 cm	30-60 cm	60-90 cm	90-120 cm
Total number of soils	5	5	5	5	3
ESP < 6	80.0%	20.0%	0.0%	0.0%	0.0%
ESP 6-14	20.0%	40.0%	0.0%	20.0%	0.0%
ESP > 14	0.0%	40.0%	100.0%	80.0%	100.0%
ESP > 7.7 & EC 0-0.2 dS/m	20.0%	60.0%	60.0%	20.0%	0.0%
ESP > 7.7 & EC > 0.2 dS/m	0.0%	20.0%	40.0%	80.0%	100.0%
EC > 0.7 dS/m	0.0%	0.0%	0.0%	40.0%	0.0%

iv) Sand over clay

ESP or ESP and EC threshold range	0-10 cm	10-30 cm	30-60 cm	60-90 cm	90-120 cm
Total number of soils	7	8	7	6	3
ESP < 6	57.1%	37.5%	42.9%	0.0%	0.0%
ESP 6-14	28.6%	50.0%	42.9%	50.0%	33.3%
ESP > 14	14.3%	12.5%	14.3%	50.0%	66.7%
ESP > 7.7 & EC 0-0.2 dS/m	28.6%	50.0%	28.6%	66.7%	66.7%
ESP > 7.7 & EC > 0.2 dS/m	0.0%	0.0%	0.0%	0.0%	0.0%
EC > 0.7 dS/m	0.0%	0.0%	0.0%	0.0%	0.0%

v) All data combined across all soil groups

ESP or ESP and EC threshold range	0-10 cm	10-30 cm	30-60 cm	60-90 cm	90-120 cm
Total number of soils	36	37	36	32	11
ESP < 6	61.1%	16.2%	8.3%	0.0%	9.1%
ESP 6-14	36.1%	48.6%	19.4%	15.6%	9.1%
ESP > 14	2.8%	35.1%	72.2%	84.4%	81.8%
ESP > 7.7 & EC 0-0.2 dS/m	22.2%	67.6%	44.4%	21.9%	18.2%
ESP > 7.7 & EC > 0.2 dS/m	5.6%	10.8%	41.7%	71.9%	63.6%
EC > 0.7 dS/m	0.0%	0.0%	8.3%	28.1%	27.3%



The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department for Environment and Water, CSIRO, Flinders University, the University of Adelaide, the University of South Australia, and the International Centre of Excellence in Water Resource Management.