ALCOA OF AUSTRALIA

No. 37

EVALUATING TECHNIQUES FOR REDUCING pH OF BAUXITE PROCESSING RESIDUE SAND AT DEPTH USING GYPSUM AND IRRIGATION

I. R. Phillips
August 2010

ISSN 1320-4807

SUMMARY

This report presents findings from a three year study that was established to identify the role of irrigation in residue rehabilitation, and whether depth of gypsum placement affects rehabilitation performance. Irrigation did not significantly improve rehabilitation performance nor did it significantly affect the movement of gypsum throughout the residue sand profile. This was because irrigation was not applied on a continuous basis, but when residue sand water storage decreased to a value considered low enough to induce drought stress in the vegetation cover. Although some movement of gypsum to depths below its zone of incorporation was detected, the rate of movement was relatively slow, and incomplete removal of carbonate was still evident two years after incorporation. It was suggested that restricted movement may be due to the low solubility of gypsum coupled with the poor water retention properties of residue sand. Changes in Na, CO_3 and HCO_3 proved to be more reliable indicators of gypsum interaction with residue sand than pH, Ca and SO_4. If shallow gypsum incorporation was to be recommended, additional studies would need to confirm that its rate of movement throughout the residue sand profile was faster than the rate of plant root growth. This would identify whether gypsum movement was a limiting factor to plant root growth, hence water and nutrient uptake.

Irrigation was found to significantly increase above-ground biomass (as measured by cover) but had no affect on species richness. Plant performance was found to be independent of gypsum incorporation depth. This was because both the shallow and deep treatments resulted in gypsum being distributed throughout much of the plant root zone. As such, neither the shallow or deep gypsum treatments should have limited plant root distributions in terms of their accessibility to moisture and nutrients. The higher bulk density, coupled with the hostile chemical characteristics, of residue sand below the zone of gypsum incorporation was considered to pose the greater restriction to depth of root penetration. Plant roots were also observed to be associated with high concentrations of gypsum, particularly in the shallow treatments. It is possible that plant roots in shallow gypsum treatments may preferentially remain closer to the surface, which may also render plants more susceptible to drought stress during summer.

It is recommended that:

- Irrigation be removed from the current prescription for residue rehabilitation because it (1) is not a sustainable practice in terms of long term management of residue disposal areas, (2) is

an inefficient use of a limited natural resource at a time when water management is essential, and (3) may restrict root distribution to shallow depths in the residue sand profile.

- Deep gypsum incorporation be retained as the preferred method due to its proven effectiveness in rapidly altering the characteristics of residue sand such that it is more conducive for plant growth, and it encourages deeper penetration of plant roots.
- Maintain botanical monitoring of the trials to test whether any of the treatments causes a reduction in rehabilitation performance in the longer term.
- Use the parameters Na, CO_3 and HCO_3 in conjunction with Ca, SO_4 and pH as a measure of gypsum interaction with residue sand.
- Prior to establishing any field trial, ensure that a complete history of past management is obtained and assess whether any previous activity will affect the primary objectives (or hypotheses to be tested) of the study.

INTRODUCTION

Developing and refining effective methods for improving the growth media for rehabilitating Alcoa of Australia (Alcoa) bauxite-processing storage areas (RSA) represent a primary objective of residue rehabilitation research. Maximising plant-root distribution throughout the residue sand profile is considered critical to establishing and maintaining a sustainable vegetation cover across RSA embankments. The incorporation of gypsum to reduce alkalinity and pH, and the use of irrigation to increase plant-water availability throughout the profile and to leach soluble salts from the plant-root zone, represent two key steps in residue rehabilitation to encourage root penetration to depth, and to increase the volume of residue sand utilised by the plant rhizosphere.

In 2003, Alcoa’s Western Australian Operations (WAO) altered the depth and rate of gypsum incorporation into residue sand from a shallow application of 50 t/ha (disced to a 300 mm depth) to 225 t/ha incorporated throughout a depth of 1500 mm. Gypsum incorporation to depth is expensive (increased from $10,000/ha to $14,500/ha in 2006), and alternative methods of distributing gypsum throughout the profile have been considered. These have included the use of a ripping tine (Phillips 2010b), and leaching surface-applied gypsum with irrigation and/or rainfall (Eastham and Mullins 2004b). The study by Eastham and Mullins (2004b) suggested that a shallow application of 225 t/ha resulted in rapid leaching of gypsum through the residue sand profile with a corresponding reduction in pH at depth (> 600 mm) 15 months after application.

Up until 2008, irrigation had routinely been installed at all new rehabilitated residue sand embankments to assist with plant establishment. It is impractical to maintain irrigation in the long-term; however, rehabilitation protocol currently does not include a strategy to gradually remove the vegetation's irrigation-dependency. Furthermore, there is concern that irrigated vegetation will not achieve the required root structure to survive without artificial water additions, particularly over summer, and the vegetation cover will be at a density which can only be sustained by continued watering. Eastham and Morald (2004a) found that root density in 1 and 2 year old residue rehabilitation tended to be highest in the surface 300 mm and decreased rapidly with depth. Furthermore, total root biomass was observed to decrease significantly with increasing compaction of residue sand. Recent work has found that the surface 300 mm of the residue sand profile dries out to very low water contents (<0.03 m^3/m^3) during summer, and that compaction increases markedly below the zone of gypsum incorporation (Dobrowolski *et al.* 2009). A better understanding of plant-water relations is therefore required to determine if (1) a sustainable vegetation cover can be established without irrigation, (2) the vegetation cover has a root structure and physiology capable of surviving under extreme water-stress conditions, and (3) the resulting cover density is acceptable from a visual amenity perspective.

To address the above concerns, a field trial was established at the Kwinana and Pinjarra RSAs in 2005 (Kiepert 2005) to (1) compare the performance of rehabilitation on residue sand embankments receiving shallow and deep incorporation of 225 t/ha of gypsum, (2) determine if irrigation is necessary for plant establishment and survival, (3) determine if irrigation assists in leaching of gypsum to depth as a means of reducing residue profile pH and creating an environment encouraging root growth to depth, (4) evaluate the effect of irrigation on the root architecture of selected plant species, and (5) compare the visual perspective of non-irrigated and irrigated rehabilitated embankments due to sustainable vegetation cover density. To date, chemical analysis of residue sand profiles and botanical monitoring of the established vegetation have been undertaken on three occasions since commencement of the trial. Additionally, root distribution and microbial "health status" of selected rehabilitated areas of RSA were measured in 2007 (Dobrowolski *et al.* 2009).

The primary objectives of this study are to present data on (1) the effect of leaching on gypsum distribution throughout the residue sand profile, and (2) the effect of irrigation on plant cover performance. Results from root distribution, chemical distributions within a residue sand profile to a depth of 3 m, and microbial "health status" at selected rehabilitated sites will also be provided to support conclusions based on the above two objectives.

MATERIALS AND METHODS

Field Trial Description

A detailed description of the trial can be found in Kiepert (2005) and Wilkinson (2005). A brief summary of this information is presented below.

Trial establishment - Pinjarra

The trial was established on RSA4 and RSA5 in 2005. The southern batter of RSA5 was mechanically placed in 1993 and 1996 where Block 1 treatments were created. Blocks 2 and 3 were created on the SW corner of RSA4, and residue sand in this area had been mechanically placed in 1994 and 1995. All three blocks were located on outer embankments that had previously received the standard shallow 50 t/ha of gypsum, fertiliser addition (poultry manure) and dust suppression crops. Thus, the effects of shallow gypsum addition as a treatment may not be evident. Each block comprised of a randomised plot design. Plots on RSA5 were 50 m wide by 60 m wide, and 50 m by 50 m on RSA4.

Trial establishment - Kwinana

Due to a lack of available space, the trial at Kwinana RSA was split across two areas. The irrigation component of the trial was established on Area F3, and the depth of gypsum incorporation was established on Areas F4 and F5. The irrigation trial (Area F3) was established on plots 70 m long by 17 m wide in an area that had been mechanically placed in 1996/1997, and had received fertilizers (poultry manure) and multiple gypsum applications to establish dust suppression crops. The gypsum trial (Area F4/5) comprised of a fully randomised treatment design incorporating plots 20 m long by 50 m wide. The trial was set-up on a residue sand outer embankment that had been hydraulically placed in 2004 (i.e. 6 months old). Prior to commencement of the trial, this area had only received surface bitumen and mulch for dust suppression. No gypsum or fertilizers had been applied prior to trial establishment.

Gypsum Treatments

Pinjarra

Prior to shallow gypsum incorporation, all weeds were scrapped off to a depth of about 100 mm and discarded. However, where deep incorporation of gypsum was studied, all weeds were buried at a depth of about 1500 mm. For shallow gypsum incorporation treatments, 225 t/ha of gypsum were spread on the residue sand surface and disc harrowed to a depth of 200 mm, after which the surface was covered with bitumen for dust control. Each plot received a basal dressing of 2.571 t/ha of DAP-based fertiliser (Appendix 1), which was incorporated by ripping to 600 mm. Since gypsum had been applied prior to fertiliser incorporation, it is highly likely that ripping re-distributed the gypsum throughout the 0 – 600 mm depth interval. This greater depth of incorporation will need to be accounted for when assessing the depth of gypsum leaching. Unfortunately, the shallow gypsum irrigated and non-irrigated plots received a higher rate of gypsum (300 t/ha) instead of 225 t/ha.

Each plot received 1.88 kg/ha of seed, followed by 60 mm of mulch (equivalent to a surface application of 600 m^3/ha), and planted out with about 3400 stems/ha. The seeded and planted species and quantities used are provided in Appendix 2 (Wilkinson 2005). Each planted seedling received a 50 grams fertiliser tablet (Appendix 1), and was marked with a bamboo cane to assist with differentiating between planted and seeded individuals. In each plot, 68 species were seeded and or planted; 18 species were planted only, 14 were seeded only and 36 were planted and seeded (Wilkinson 2005).

Kwinana

Trials were set-up as described above for Pinjarra, and all plots received the correct amount of gypsum (i.e. 225 t/ha).

Irrigation Treatments

The method of irrigation was the same at both Kwinana and Pinjarra. Water was supplied along rows of aluminium pipes (12 m apart) with riser sprinklers every 9 m of length. Each sprinkler had an effective radius of about 9 m, resulting in some areas receiving 2 to 3 times more water than others. The sprinkler system was constructed such that there was 20 m distance between the irrigated and non-irrigated areas.

Irrigation commenced on 21st December 2005, the day before the botanical monitoring was completed. Thus, irrigation was not included as a treatment in data analysis for data collected before December 2005 as it would not have affected plant germination or growth, or gypsum leaching. Irrigation scheduling was based on a water balance approach (G. Mullins, personal communication). During the 2005/2006 summer, irrigated plots received 20.4 mm per day for seven irrigation events. During the 2006/2007 summer the irrigated plots received 42.7 mm per day for three irrigation events.

Sampling of Residue Sand Profiles

Pre-gypsum addition (April 2005)

Prior to gypsum incorporation, samples of residue sand at all plots (except the deep gypsum, no irrigation treatment at Pinjarra) were collected at depths of 100, 300, 500, 700, 900, 1100, 1300 and 1500 mm for chemical analyses. Samples were obtained by hand-augering, stored in sealable plastic bags, and transported to CSBP Ltd for chemical analysis. Prior to analysis, each sample was air-dried and passed through a 2 mm sieve. The < 2 mm fraction was retained for analysis. Each sample was analysed for available (2M KCl) nitrate (NO_3) and ammonium (NH_4), Colwell (0.5 M $NaHCO_3$ pH 8.5) phosphorus (P), Colwell (0.5 M $NaHCO_3$ pH 8.5) potassium (K), available (0.25 M KCl) sulphur (S), organic carbon (Org C, Walkley Black), amorphous iron (am-Fe, ammonium oxalate), electrical conductivity (EC, 1:5 residue sand to water ratio), pH (H_2O and 0.01 M $CaCl_2$, 1:5 residue sand to solution ratio), exchangeable (0.1M $BaCl_2$/0.1M NH_4Cl) calcium (Ca), magnesium (Mg), sodium (Na) and potassium (K) (Appendix 3 and 4).

Post-gypsum addition (November 2005)

Post-gypsum sampling of each plot was undertaken in November 2005. Each plot was sampled (n = 2) at three random locations at depths of 0 – 100, 500 – 700 and 1300 – 1500 mm. Samples were collected and analysed as outlined above. The non-consistent sampling depths between sampling events limits the extent of statistical analysis that can be undertaken (Appendix 3 and 4).

6-month sampling (May 2006)

Additional sampling of residue sand profiles was undertaken 6-months after gypsum incorporation (i.e. May 2006). Samples were collected only from those treatments receiving “a shallow application of 225 t/ha and no irrigation” for the following reasons. Firstly, this treatment provided the highest gypsum concentration in the smallest volume of residue sand, thereby providing the best opportunity to detect gypsum leaching throughout the profile. Secondly, this treatment provided the opportunity to monitor gypsum leaching via rainfall infiltration alone, which would reflect conditions should irrigation be removed from standard rehabilitation operations.

Samples were collected from the 0 – 800 mm depth interval as follows. Sampling locations (n = 2) in each plot were selected randomly; one from the upper section, the other from the lower section, of the embankment. A PVC pipe (50 mm *i.d.* × 900 mm long) was carefully hammered into the residue sand to a depth of 800 mm. The pipe was then dug out and both ends sealed with a PVC end cap. Each sealed pipe was retained in a vertical position prior to extruding the residue sand core in 100 mm increments. Each increment of residue sand was placed in a clearly identifiable, sealable plastic bag, and transported to CSBP Ltd for chemical analysis.

Each sample was analysed for the parameters listed above, with the addition of amorphous Al (am-Al, ammonium oxalate) and exchangeable Al (1M KCl). Amorphous Al represents a significant adsorption surface for P, and contributes significantly to the surface charge characteristics of residue sand (Phillips and Chen 2010). Exchangeable Al (which includes soluble and weakly-sorbed forms of Al) is known to vary with pH, and so may represent a major cation balancing the surface electrical charge carried by residue sand.

12-month sampling (December 2006)

Sampling of the "non-irrigated plots with a shallow gypsum incorporation of 225t/ha of gypsum" was repeated after winter to determine if infiltrating rainwater has caused leaching of gypsum to depths below the zone of incorporation (i.e. > 600 mm). Cores of residue sand to a depth of 800 mm were collected as outlined above. Previous sampling events highlighted the difficulty in detecting statistically significant differences between specific samples based on solid phase concentrations. Changes in solution phase concentrations are known to be more reliable measures of treatment effects on soil chemistry (Phillips and Bond 1989). Consequently, the water-soluble and solid phase concentrations of a range of parameters were measured for each sample as follows. A saturated paste was prepared by mixing a known mass of residue sand with Mill-Q deionised water until saturation characteristics were attained ($\theta_{sat} \approx 0.3$). The paste was left overnight to equilibrate, and a sample of the pore-water removed under vacuum. The pore-water was analysed for Ca, Mg, K, Na, Al, pH, EC, P, Cl, SO_4, NH_4, NO_3, HCO_3 and CO_3 using standard techniques (Rayment and Higginson 1992). The remaining solids were sub-sampled and analysed for the parameters listed above, and for EDTA-extractable copper (Cu), zinc (Zn), manganese (Mn) and Fe, exchangeable Fe, phosphorus buffering index (PBI), Total Fe and Total Al. All analyses were performed by CSBP Ltd.

Botanical Monitoring

Botanical monitoring has been undertaken on three occasions since trial establishment; December 2005 (Wilkinson 2005), July 2006 (Narducci 2006) and August 2007 (LeRoy 2007) as follows. Three botanical monitoring plots were set-up within each treatment plot (Figure 1); (a) two 36 m^2 (6 × 6 m) for density and cover of seeded and planted species, and (b) one 400 m^2 (20 × 20 m or 10 × 40 m) for density and survival of planted seedlings. At both RSAs, one of the 36 m^2 plots was placed on the upper slope and one was placed on the lower slope, thereby allowing position on the slope to be included in data analyses. For the KW irrigation trial, the treatment plots were not wide enough for upper and lower plots to be meaningful so the two monitoring plots were treated as replicates (pseudo replicates). An aluminium tag marked with a permanent plot number and a fence dropper was used to mark the north-west corner of each monitoring plot and wooden stakes were used to mark the remaining plot corners (Figure 1). A more detailed description of individual plot locations can be found in Wilkinson (2005).

Germination success

A quadrat (2 × 2 m) was laid within the 36 m^2 monitoring plots, and the number and percent cover (of the 4 m^2 area) of each species recorded. Planted seedlings were recorded separately from germinated seed. This process was repeated until the entire 36 m^2 plot had been monitored (i.e. 9 quadrats per 36 m^2 plot). A single plant within a 36 m^2 plot is equivalent to 278 plants/ha (10,000 $m^2 \div 36$ m^2), assuming even distribution of the plants. Therefore, the density of a species required in the field to ensure that it occurs within the monitoring plot is at least 278 plants/ha. However, given the way seed is applied during rehabilitation (hand-seeding with preferential segregation of seeds of different mass), an even distribution of seed is highly unlikely. In fact, groups of plants of the same species can often be observed in the field.

Planted success

The number of each planted species was recorded in a 400 m^2 area. As the density of many planted species was low, large monitoring plots were used to increase the reliability of the data. Each plant was identified, the bamboo cane moved as close as possible to the base of the plant, and fluorescent paint sprayed on the top of the cane to indicate it had been counted. If the plant was dead, the death was recorded and the cane was removed. For the Kwinana Irrigation Trial there were three monitoring plots (RD117, RD123 and RD129) which contained large pipes close to, or exposed at, the soil surface. As these areas may not have received gypsum and the pipe may affect plant growth, they were not included in the calculations for the plots. The approximate area affected by the pipes was measured and subtracted from the plot area, the bamboo stakes were removed and the reduced area was taken into account for species density calculations. A single plant within a 400 m^2 area is equivalent to 25 plants/ha (10,000 $m^2 \div 400$ m^2), assuming even distribution of the plants. Therefore, the density of a species required to ensure that it is monitored in our plots is at least 25 plants/ha.

Data Analyses

Residue sand

Statistical differences between residue sand characteristics were analysed at discrete depths using ANOVAs and LSD All-Pairwise Comparisons Tests. Data for the two sites was analysed separately due to the difference in past history of gypsum and fertiliser at Pinjarra but not at Kwinana (depth of gypsum incorporation site).

Botanical monitoring

Summary data for each site was determined by averaging the density and cover data for all monitoring plots regardless of treatment. Irrigation trial plots were analysed separately from gypsum trial plots. Density, cover and number of species (species richness) were summed across species for each 36 m^2 monitoring plot, and this number was used to compare treatments. Data was analysed using Statistix 8.0 using ANOVAs and LSD All-Pairwise Comparisons Tests. Data for the two sites, Kwinana and Pinjarra, was analysed separately to determine site differences.

RESULTS AND DISCUSSION – RESIDUE SAND

Effect of Time on Gypsum Leaching In Residue Sand Profiles

Water Inputs Over The Period Of Study

The amounts of rainfall ± irrigation added over the four sampling events are presented in Figure 2. Irrigated treatments received significantly more water ($p < 0.05$) than unirrigated treatments, and this was most obvious over the December 2005 to June 2006 period (Event 2). Both the non-irrigated and irrigated treatments received the same amount of water over events 1 and 3 since irrigation was not applied over the winter period. Over the monitoring period (August 2005 to December 2007), Kwinana received significantly more water ($p < 0.05$) than Pinjarra (i.e. 1869 mm versus 1808 mm).

2005 Sampling: Pre- and Post- Gypsum Incorporation - Pinjarra

Gypsum addition, either via shallow or deep incorporation, generally increased exchangeable Ca, available-S, and EC, and decreased pH, relative to residue sand characteristics prior to gypsum addition (Figure 3). The magnitude of these changes was more pronounced in the shallow gypsum treatments. Changes in exchangeable Na, bicarbonate-K and bicarbonate-P concentrations were less obvious, which may be due to previous fertiliser and gypsum additions as part of RSA5's rehabilitation management history. Generally, nutrient concentrations, pH and EC for irrigated treatments were found to be similar in magnitude to those for non-irrigated treatments. However, this finding was not consistent throughout the trial.

A primary objective of this trial was to determine if shallow incorporation (0 – 300 mm) of high rates of gypsum and subsequent leaching, could improve subsoil characteristics that promote root growth to depth. The parameters initially considered to demonstrate this effect best are pH, EC, exchangeable Ca, exchangeable Na and available-S (Figure 3). Prior to gypsum incorporation, (Figure 3), values of pH, EC, exchangeable Ca, exchangeable Na and available-S in the 0 – 100, 500 – 700 and 1300 – 1500 mm depth intervals was 7.8, 9.0 and 9.2; 57, 7 and 9 mS/m; 5.5, 4.3 and 4.1 cmol/kg; 0.1, 0.1 and 0.6 cmol/kg; and 602, 10 and 9 mg/kg, respectively. For post-gypsum incorporation, values of pH, EC, exchangeable Ca, exchangeable Na and available-S in the 0 – 100, 500 – 700 and 1300 – 1500 mm depth intervals was 7.4, 8.3 and 8.4; 138, 26 and 32 mS/m; 10.5, 4.6 and 4.4 cmol/kg; 0.1, 0.3 and 0.8 cmol/kg; and 3043, 200 and 233 mg/kg, respectively. These data suggest that in the shallow gypsum incorporation treatment, much of the gypsum still remains in the surface layer (0 - 100 mm), although some penetration to depth (up to 1500 mm) may have occurred.

2005 Sampling: Pre- and Post- Gypsum Incorporation - Kwinana

Gypsum addition, either via shallow or deep incorporation, generally increased exchangeable Ca, available-S, and EC, and decreased pH and exchangeable Na, relative to residue sand characteristics prior to gypsum addition (Figure 4). The magnitudes of these changes were more pronounced in the shallow gypsum treatments. Changes in bicarbonate-K and bicarbonate-P were less obvious, particularly in the deep gypsum treatments.

Prior to gypsum incorporation (Figure 4), values of pH, EC, exchangeable Ca, exchangeable Na and available-S in the 0 – 100, 500 – 700 and 1300 – 1500 mm depth intervals were 9.8, 10.1 and 10.1; 48, 94 and 104 mS/m; 3.0, 2.6 and 2.4 cmol/kg; 3.7, 5.9 and 5.7 cmol/kg; and 10, 21 and 25 mg/kg, respectively. Following gypsum incorporation, values of pH, EC, exchangeable Ca, exchangeable Na and available-S in the 0 – 100, 500 – 700 and 1300 – 1500 mm depth intervals were 8.0, 9.0 and 9.0; 163, 50 and 103 mS/m; 9.9, 4.0 and 5.6 cmol/kg; 0.6, 2.4 and 3.5; and 2965, 357 and 594 mg/kg, respectively. These data are consistent with that from the Pinjarra trial, and suggest that following shallow gypsum incorporation, the majority of gypsum still remains in the surface layer (0 - 100 mm), although some penetration to depth (up to 1500 mm) may have occurred.

2006 Sampling: 6-Month and 12-Month - Pinjarra

Additional sampling at times of 6-months and 12-months following gypsum incorporation were undertaken to better understand if gypsum leaching to depth within the residue sand profile has occurred. Sampling was restricted to only those shallow gypsum plots receiving no irrigation for reasons outlined earlier. For clarity, only the data for those ions (i.e. Ca, Na and SO_4) and parameters (i.e. pH and EC) indicative of the presence of gypsum will be discussed in this report. Data for all other analyses undertaken are provided in Appendix 5.

The distribution of pH within the residue sand profile tended towards lower values with increasing time (Figure 5). For example, the pH of the 0 – 100 mm depth for the pre-gypsum, post-gypsum, 6-month and 12 month samplings was 7.8, 7.4, 7.1 and 6.9 respectively, while the pH of the 600 – 700 mm depth for the pre-, post- gypsum, 6-month and 12 month samplings was 9.0, 8.3, 8.7 and 6.8 respectively. After 12 months, the pH remained relatively constant at pH 7 over the 0 – 800 mm interval. A similar trend was observed for the EC. Exchangeable Ca and Na tended to demonstrate relatively small non-significant changes throughout the profile. Available SO_4 did not display any significant variation throughout the profile with time.

Distributions of water-soluble Ca, Na, SO_4, CO_3 and HCO_3 are presented in Figure 6. Very little Ca and SO_4 were found in the soil solution below a gypsum incorporation depth of 600 mm. There appeared to be a good relationship between the distribution of soluble and exchangeable Na with depth and pH at the 12-month sampling event. This relationship suggests that Na and its accompanying anion may be largely responsible for controlling the pH of residue sand.

2006 Sampling: 6-Month and 12-Month - Kwinana

The pH of residue sand over the 0 – 800 mm depth decreased with time, although the changes over the 12-month period were small relative to values immediately following gypsum incorporation (Figure 5). For example, the pH of the 0 – 100 mm depth for the pre-gypsum, post-gypsum, 6-month and 12 month samplings was 9.8, 8.0, 8.3 and 7.6 respectively, while the pH of the 600 – 700 mm depth for the pre-gypsum, post-gypsum, 6-month and 12 month samplings was 10.1, 9.0, 9.8 and 8.7 respectively. In contrast to Pinjarra, however, the pH was observed to increase steadily over the 0 – 800 mm depth, and mimicked values observed immediately post-gypsum incorporation. The EC decreased significantly ($p < 0.05$) between the 6-month and 12-month sampling events in the 0 – 300 mm zone, and remained relatively constant at 10 mS/m below this depth. Exchangeable Ca and available SO_4 tended to demonstrate relatively small non-significant changes throughout the profile. In contrast, exchangeable Na concentrations tended to decrease with increasing time within the 0 – 800 mm depth.

Water-soluble Ca and SO_4 concentrations within the 0 – 800 mm depth were typically low relative to that in the adsorbed phase (Figure 6). The distribution of water-soluble Na concentrations displayed a similar pattern to that observed for pH.

General Discussion

Of the two sites at which the study was conducted, Kwinana provided the best opportunity to assess the effects of gypsum incorporation depth and subsequent leaching. This is because the depth of gypsum incorporation study was established at the only area which had not received previous gypsum and/or fertiliser additions. Although data interpretation for both sites was complicated by the absence of sampling immediately following gypsum and fertiliser addition (which may have highlighted the effect of gypsum on various chemical properties), previous fertiliser additions at the Pinjarra study area appear to have already resulted in a build-up of plant nutrients in the residue sand profiles. Therefore, gypsum and/or fertiliser from past additions could not be separated from that applied at the commencement of the trial, which limited an assessment of whether the non-irrigated and irrigated treatments have had a positive or otherwise impact on gypsum and nutrient availability and movement in residue sand profiles.

The effects of gypsum on plant nutrient (N, P, K, Mg, Ca and S) concentrations and pH observed at Kwinana were not unexpected based on the known behaviour of gypsum in residue sand (Phillips 2010a). In general, these can be summarised as follows. The movement of gypsum throughout the residue sand profile will primarily be governed by its rate of dissolution, hence solubility in the pore-water. The dissolution of gypsum is described as:

$$CaSO_4.2H_2O \leftrightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \qquad (CaSO_4 \log K_{sp} = -4.58) \qquad (1)$$

The solubility product (K_{sp}) of gypsum used in residue rehabilitation is about 0.22 g/100 mL (Phillips 2010a). This implies that when the concentration of gypsum in the pore-water is less than 0.22 g/100 mL, Eqn (1) will proceed to the right and dissolution of gypsum should occur. Whereas if pore-water gypsum concentrations exceed 0.22 g/100 mL, then Eqn (1) proceeds to the left and gypsum precipitation would occur. Due to the high application rates (particularly in the shallow incorporation treatment) and low solubility of gypsum, coupled with poor water retention properties of residue sand, considerable amounts of applied gypsum could persist in the residue sand for extended periods of time. In fact, excavations in the shallow incorporation trial found exceedingly high amounts of undissolved gypsum within the 0 – 200 mm depth, with some locations exhibiting nearly 100%

gypsum (i.e. no residue sand) in the 0 – 150 mm zone (Figure 7). The impacts of this dominance of gypsum on plant establishment and nutrient availability are currently unknown, although preliminary root distribution studies (see below) suggest this may in fact restrict root penetration depths. The ability of gypsum to alter the chemical properties of residue sand below the zone of gypsum incorporation must be considered limited, at least in the short term.

Prior to gypsum amendment, residue sand typically contains very high concentrations of carbonate (about 18000 mg CO_3 /L), with lower concentrations of bicarbonate (about 600 mg HCO_3 /L), anions (Appendix 6). Following gypsum amendment, the concentration of these anions are considerably reduced (through formation of $CaCO_3$ and conversion of CO_3 to HCO_3 as a function of pH (Stumm and Morgan 1981), with HCO_3 becoming the dominant inorganic carbon-based ion (about 590 mg HCO_3 /L; Appendix 6).The reduction in pH following gypsum addition arises from the reaction of Ca^{2+} with carbonate (CO_3^{2-}) to form weakly-soluble $CaCO_3$ (Barrow 1982):

$$CaSO_4 + Na_2CO_3 \leftrightarrow CaCO_3 + Na_2SO_4 \qquad (CaCO_3 \log K_{sp} = -8.48;\ Na_2SO_4 \log K_{sp} = 0.7) \qquad (2)$$

The smaller K_{sp} for $CaCO_3$ compared to Na_2SO_4 results in $CaCO_3$ being precipitated within the residue sand, with the more soluble Na_2SO_4 being leached from the material with drainage water. However, as soluble Ca moves with the leaching water, the opportunity for Na:Ca cation exchange reactions can also occur. Residue sand has a cation exchange capacity (CEC) of about 5 cmol/kg, and this is initially dominated by exchangeable Na. The dissolution of gypsum (Eqn 1) provides Ca in the water phase which can subsequently displace Na from the exchange sites according to:

$$2X\text{-}Na^{+} + Sol\text{-}Ca^{2+} \leftrightarrow X\text{-}Ca + 2Sol\text{-}Na^{2+} \qquad (3)$$

where X refers to exchangeable cation and Sol refers to solution cation.

As solution Ca concentrations decrease due to precipitation (Eqn 2) and cation exchange (Eqn 3), this would stimulate further dissolution of gypsum until the saturation index became zero, after which the Ca, SO_4, Na, pH and EC of the solution phase would remain relatively constant.

Over the period August to November 2005, the cumulative rainfall plus irrigation was ≈ 300 mm for both sites (Figure 2). If it is assumed that field capacity of residue sand is 0.2 cm^3/cm^3, then the depth of water movement can be conservatively estimated to be about $300 \div 0.2 = 1500$ mm. Since the depth of shallow gypsum incorporation was up to 600 mm, sufficient water appears to have been applied to the treatment plots to cause movement of gypsum to depths of up to 1500 mm. In fact, the depth of penetration of the wetting front from an individual irrigation event of 20 mm can potentially exceed 1200 mm (Figure 8). Changes in exchangeable Ca, exchangeable Na, available-S, EC and pH profiles were consistent with gypsum interaction with residue sand. For example, exchangeable Na concentrations in the 0 – 100, 500 – 700 and 1300 – 1500 mm depth intervals pre- and post- gypsum incorporation were 3.7, 5.9 and 5.7, and 0.6, 2.4 and 3.5, respectively. These changes may be a result of Ca:Na exchange as soluble Ca moves through the residue sand profile with drainage water (particularly in the surface layer) and leaching of readily-soluble Na. This suggests that shallow gypsum incorporation may be capable of altering the chemical composition of residue sand profiles, albeit at a much slower rate relative to deep incorporation.

Based on the chemical composition of gypsum ($CaSO_4$), the presence of Ca and/or SO_4 below the zone of gypsum incorporation should be a good indicator of gypsum leaching. Typically, the sorption characteristics of these two ions in the presence of hydrous Fe and Al oxides can limit their availability and mobility (Theng 1980; Cichota *et al.* 2007). Consequently, the combined effects of low gypsum solubility and strong sorption of the dissolution products (coupled with the formation of low solubility $CaCO_3$), may be a major cause for only small (and possibly non-significant) changes in the concentration of Ca and/or SO_4 in both the soluble and adsorbed phases.

As mentioned above, non-gypsum amended residue sand is dominated by Na_2CO_3 and $NaHCO_3$ (Appendix 6), whereas after gypsum amendment, the concentration of these anions are considerably reduced through formation of $CaCO_3$ and conversion of CO_3 to HCO_3 as a function of pH. Thus, the relative proportion of water-soluble CO_3 to HCO_3 may provide a more reliable indicator of gypsum interaction with residue sand and mobility. For the Pinjarra study, no CO_3 was present within the 0 – 800 mm depth, although HCO_3 was present at a relatively constant concentration of 300 – 400 mg/L (Figure 6). Although this suggests gypsum leaching has occurred below the depth of incorporation (about 600 mm), there is a strong possibility this movement may be a consequence of previous gypsum additions (i.e. prior to trial establishment). In contrast, the Kwinana study demonstrated water-soluble CO_3 concentrations about 1% of that found in unamended residue sand (about 200 mg/L) were present at depths below 400 mm (Figure 6). Since the Kwinana trial was established on an embankment which had not previously received gypsum and fertilizer additions, this finding suggests some gypsum leaching below the depth of incorporation (about 600 mm) may have occurred. Unfortunately, the limited sampling depth of 0 – 800 mm does not provide information on how the CO_3 to HCO_3 ratio varies at greater depths which may have indicated the depth of gypsum penetration since trial commencement. Alternately, CO_3 concentrations may have decreased naturally over time due to leaching and/or carbonation by infiltrating water (Phillips 2010a).

In 2008, samples of residue sand were collected from a 4-year old rehabilitated residue sand embankment to a depth of 3 m, and were analysed for a range of chemical and physical parameters (Phillips, unpublished data). Parameters relevant to gypsum leaching are provided in Appendix 6b. Gypsum was incorporated to a depth of up to 1.5 m, and key indicators such as pH, Ca, Na (in both the solid and soluble fractions), and soluble SO_4, CO_3 and HCO_3, indicate that the effects of gypsum were primarily confined to its depth of incorporation (1 – 1.5 m). These data provide strong evidence that little movement below the zone of incorporation has occurred within a 4 year period. Thus, leaching of surface-applied gypsum would not appear to be suitable for ameliorating the pH of residue sand at depth.

Previous studies (Phillips 2010a) suggested that Ca preferentially reacts with CO_3 (Eqn 1) prior to undergoing cation exchange. Calcium sorption involves both adsorption and precipitation reactions but the relative importance of these two mechanisms in removing solution Ca was not studied in this experiment. Wong and Ho (1995) reported that Na was preferentially adsorbed by residue mud relative to Ca at solution cation fractions > 10%, and that Ca rarely exceeded 20% of the exchange phase. This cation exchange behaviour can be attributed to the presence of zeolitic-type minerals grouped as desilication product (DSP; Wong and Ho 1995). Desilication product (DSP) is formed by the reaction of soda and alumina with reactive silica during the Bayer process. Residue mud contains about 11% DSP, whereas residue sand contains about 1% DSP. Phillips (2010a) estimated that DSP may account for up to 3 cmol/kg of charge, or ≈ 40% of the overall CEC. This implies that a significant proportion of the CEC of residue sand may exhibit a relatively low affinity for Ca (particularly at high solution Ca fractions) and this would encourage Ca to remain in solution and be preferentially lost via precipitation as $CaCO_3$.

Additional Information

Plant root distribution

Field studies on root distribution for three plant species, *Hardenbergia comptoniana*, *Acacia cochlearis* and *Eucalyptus gomphocephala* were selected to represent examples of ground cover, shrub and tree species, respectively (Dobrowolski *et al.* 2009). It was generally found that irrespective of plant species, the roots were primarily confined to the zone of gypsum incorporation. Also, compaction within the residue sand profile increased dramatically below the zone of gypsum incorporation. This appeared to restrict root penetration below the gypsum zone, which was particularly evident for the shallow gypsum treatment. This restriction would severely limit the volume of residue sand available to the plant for extracting water and nutrients, which may markedly affect the long term sustainability of the plant cover system. The apparent dependency of depth of root penetration on depth of gypsum incorporation provides strong support for not recommending shallow gypsum incorporation for residue rehabilitation.

Health criteria

The soil microbial biomass is mainly composed of fungi and bacteria, and provides an indication of short-term changes in soil fertility. The fungi and bacteria present in residue sand would be largely responsible for the decomposition of plant residues, and they can release plant nutrients via mineralisation, or can accumulate nutrients through immobilisation within the microbial biomass. To assess the fertility status of the residue sand at the Pinjarra site, residue sand from the 300 (within root zone), 1000 (below root zone) and 1800 (compaction zone) mm depths were analysed for microbial biomass. All samples recorded negligible microbial biomass and would be regarded as exhibiting low fertility (Dobrowolski *et al.* 2009). Although these findings are not directly related to the objectives of this study, they do highlight the need to improve the fertility status and nutrient-supplying capacity of the overall residue sand profile as a means of encouraging greater plant root distribution. Without this ability to supply nutrients, plant roots may be restricted to zones of artificial nutrient sources such as that created by gypsum incorporation and/or fertiliser addition.

Conclusions and Recommendations

Shallow and deep gypsum incorporation improved the chemical characteristics of residue sand for plant growth, although these effects were less obvious in profiles which had a previous history of gypsum and/or fertiliser additions. Gypsum addition typically reduced pH and Na concentrations, and increased Ca and SO_4 concentrations within the zone of incorporation. Some gypsum leaching below the zone of incorporation was evident, but shallow incorporation may limit amelioration of unfavourable chemical conditions at depth due to the limited solubility of gypsum in residue sand. The extent of leaching was however better described using water-soluble CO_3 to HCO_3 ratios.

Shallow gypsum incorporation represents a significant cost-saving in operational residue rehabilitation. However, based on (1) issues associated with solubility and *in-situ* movement within the residue sand profile, and (2) possible limitations on plant root distribution, this method of incorporation is not recommended as part of the operational prescription of residue rehabilitation. It is recommended that the current method of deep incorporation be maintained.

RESULTS AND DISCUSSION – BOTANICAL MONITORING

A detailed description of the botanical monitoring component of this study was prepared by LeRoy (2007). A summary of those findings are provided in this report.

Irrigation Trial - Pinjarra

Irrigation did not affect cover or species richness of natives and exotics ($p > 0.05$). However, density was significantly greater in non-irrigated plots than irrigated plots ($p < 0.05$), which was largely due to the contribution from exotics (Figures 9, 10 and 11). Native species contributed to a significantly greater amount of cover and species richness relative to the exotic species ($p < 0.001$) despite exotics having a significantly greater density measurement than natives ($p<0.001$).

Over the 2005 – 2007 monitoring period, the proportion of cover increased significantly with each consecutive year ($p<0.001$). Plant density in 2006 and 2007 was significantly greater than in 2005 ($p < 0.001$), whereas species richness was significantly greater in 2005 and 2006 than in 2007 ($p < 0.05$). Visually, rehabilitation in Block 1 appeared to be out-performing that in Blocks 2 and 3. Block 1 contained less exotic species and therefore looked healthier (Figures 12 and 13). Analyses of results showed Block 1 had significantly less density than Blocks 2 and 3 ($p < 0.05$), as well as significantly less species richness ($p < 0.05$). This may be due to the exotic plants in Blocks 2 and 3 contributing to the higher density and species richness.

Vegetation on the upper slope appeared to be less healthy than vegetation at the bottom of the slope. Although the upper slope of the plots exhibited a higher cover, density and species richness than the lower slope, these differences were not statistically significant ($p > 0.05$). The history of RSA5 embankment construction revealed that the upper section was hydraulically poured whilst the lower section was mechanically constructed. It is possible that this difference in embankment construction may have contributed to differences in plant performance (mechanically constructed tend to be compacted); however, any compaction should have been relieved during trial establishment and gypsum incorporation. Moisture profiles within the plant root zone (<2 m) did not exhibit major differences in between upper slope and lower slope locations, particularly during the late-summer period (Phillips unpublished data). However, plant water use (based on plant transpiration data over 2009; Phillips unpublished data) appeared to be greater on the lower than upper slopes. Other factors contributing to the performance of vegetation located on the upper part of the embankment may also involve operational activities at the adjacent mudlake (e.g. exposed to alkaline spray from mud/sand pipe discharge and/or alkaline dust).

Irrigation Trial - Kwinana

Irrigated plots displayed a significantly greater cover by natives and exotics ($p < 0.05$) yet significantly less density than non-irrigated plots ($p < 0.05$). Species richness was not significantly affected by irrigation ($p > 0.05$) (Figure 14, 15 and 16). There was no significant difference in proportion of cover between native and exotic species ($p > 0.05$). The density of exotic species was significantly greater ($p < 0.001$) than that of natives, irrespective of irrigation treatment. In contrast, exotic plants exhibited significantly less species richness compared with native species ($p < 0.001$). Over the three monitoring periods, species richness of natives numbered 21 compared to 7 for exotic species.

Over the three-year monitoring period, cover increased significantly with each consecutive year ($p < 0.001$) (Figure 14). The density of plants was significantly greater in 2007 than in 2005 and 2006 ($p < 0.001$). Species richness was greatest in 2005, but this number decreased significantly in 2006 and 2007 (Figure 16).

Gypsum Trial - Pinjarra

There were no significant differences ($p > 0.05$) in cover, density and species richness for natives and exotics growing in shallow and deep gypsum treatments (Figures 17, 18, 19). Also, there were no significant differences ($p > 0.05$) in vegetation cover and density between position on the embankment (i.e. upper or lower). However, species richness was significantly greater on the upper slope than the lower slope ($p < 0.001$).

Block 1 exhibited significantly less cover than Blocks 2 and 3 ($p < 0.05$) and significantly less density than Block 3 ($p < 0.05$). Blocks 1, 2 and 3 were all significantly different from each other with respect to species richness, with Block 1 having the least number of species and Block 3 the most ($p < 0.001$). Native plants displayed significantly greater species richness than exotic plants ($p < 0.001$), but significantly less density ($p < 0.001$). There was no significant difference between the proportion of cover for exotic and native species ($p > 0.05$) (Figure 17, 18 and 19).

Over the three-year monitoring period, cover was found to significantly increase on an annual basis (*p* <0.001). Plant density increased significantly from 2005 to 2006, but species richness declined significantly in 2007 relative to that in 2006 (*p* <0.001).

Gypsum Trial - Kwinana

There was no significant difference between shallow and deep gypsum treatments with respect to vegetation density, cover and species richness of natives and exotics (*p* >0.05). There was however a significant difference between the density, cover and species richness of native and exotic species. Native species displayed significantly greater cover and species richness (*p* <0.001), yet significantly less density (*p* <0.05) than exotic species (Figures 20, 21 and 22).

Vegetation cover and density significantly increased over the 2006 – 2007 period relative to that observed in 2005 (*p* <0.001 and *p* <0.05 respectively). In contrast, species richness significantly declined in 2007 compared to that in 2005 and 2006 (*p* <0.001). Position of vegetation on the embankment (upper or lower slope) had no significant effect on cover, density or species richness of native and exotic species (*p* >0.05).

Discussion and Conclusions

Irrigation trial

Plant density was found to be significantly lower in irrigated plots compared with non-irrigated plots. This was associated with a lower density of exotic species in irrigated plots than non-irrigated plots. It is possible that the additional water provided by irrigation may have accelerated growth of the native vegetation, thereby crowding out exotic species. This is supported from the finding that exotics have proliferated in non-irrigated plots. Furthermore, irrigation did not improve species richness at either site.

From the monitoring data, amounts of irrigation based on soil-water deficits have not been found to provide any significant benefit to residue rehabilitation. To achieve any significant benefits, much greater and more frequent irrigation applications may be required. However, this is not practical from a water resource perspective, and if a sustainable vegetation cover is to be achieved.

During the summer of 2006/2007 many species became stressed and some senesced (LeRoy 2007). Despite this, many species recovered after early winter rain periods, with many plants producing new growth. This provides additional support for removing irrigation from operational residue rehabilitation prescription; however, continued monitoring of species performance will be undertaken to ensure that rehabilitation failure will not occur in future years.

An additional finding from this study has been identification of those species that cannot survive under non-irrigated conditions (LeRoy 2007). These data are being used to refine the current rehabilitation seed mix.

Gypsum trial

Depth of gypsum incorporation in residue rehabilitation did not affect the measurement indices cover, species richness or density. Based on plant performance alone, it could be concluded that plant performance is independent of gypsum incorporation depth. But it must be remembered that the majority of plant roots resided in the surface 0 – 300 mm which was well within the depth of gypsum incorporation for both gypsum treatments.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This report presents findings from a three year study to identify the role of irrigation in residue rehabilitation, and whether depth of gypsum placement affects rehabilitation performance. The chemical analysis of residue sand profiles at varying times after gypsum incorporation suggested some movement of gypsum to depths below its zone of incorporation, and that the rate of movement was relatively slow. This rate of movement may be related to the low solubility of gypsum and the poor water retention properties of residue sand. Importantly, changes in Na, CO_3 and HCO_3 proved to be more reliable indicators of gypsum interaction with residue sand than pH, Ca and SO_4. This was because the strong sorption (adsorption and/or precipitation) of Ca and SO_4 tended to reduce their concentrations in solution to very low concentrations. If shallow gypsum incorporation were to be recommended, studies would need to confirm that its rate of movement throughout the residue sand profile was faster than the rate of plant root growth. This study would need to ensure that gypsum movement was not a limiting factor to plant root growth, hence water and nutrient uptake.

Irrigation did not significantly improve rehabilitation performance. These findings are not unexpected because irrigation was not applied on a continuous basis, rather when plant-stress from water-deficit in residue sand storage was estimated. Although irrigated plots received significantly more water than non-irrigated plots, the additional water probably was of little benefit to the plant cover due to the rapid hydraulic conductivity of residue sand (≈ 20 m/d).

Botanical monitoring found that a major response to irrigation was higher above-ground biomass (as measured by cover) but no difference in species richness. Plant performance was also found to be independent of gypsum incorporation depth. The combined effect of this would be that operational prescription for residue rehabilitation would involve the removal of irrigation and inclusion of shallow incorporation of gypsum. Although the removal of irrigation would not be expected to significantly hinder plant performance, shallow gypsum incorporation is not recommended for the following reasons.

Firstly, shallow incorporation should have been restricted to a depth of 0 – 300 mm; however, the actual depth was most likely 0 – 600 mm. Secondly, independent root distribution studies showed that a very high proportion of roots reside in the 0 – 300 mm with only a few roots penetrating to greater depths (Dobrowolski *et al.* 2009). Therefore, both the shallow and deep gypsum treatments resulted in gypsum being distributed throughout the root zone. As such, neither the shallow or deep gypsum treatments would have hindered plant root distributions and their accessibility to moisture and nutrients due to hostile chemical characteristics of the residue sand. Also, plant roots were observed to be associated with high concentrations of gypsum, particularly in the shallow treatments. Gypsum may provide a less-hostile environment for plant roots due to its lower pH, high nutritional value and potentially higher water content by virtue of its finer texture, compared to residue sand. It is possible therefore that plant roots in shallow gypsum treatments may preferentially remain closer to the surface with gypsum. Unfortunately this may also render plants more susceptible to drought stress during summer.

Recommendations

Although this study has provided good information on the reaction of gypsum with residue sand, factors such as past gypsum and fertiliser additions, incorporation of gypsum throughout the root zone irrespective of gypsum treatment, and irrigation applications which did not markedly affect plant available water, may not have truly tested the effect of gypsum placement and irrigation on plant performance. Despite this, it is recommended that:

- Irrigation be removed from the current prescription for residue rehabilitation because (1) it is not a sustainable practice in terms of long term management of residue disposal areas, (2) is an inefficient use of a limited natural resource at a time when water management is essential, and (3) may restrict root distribution to shallow depths in the residue sand profile.

- Deep gypsum incorporation be retained as the preferred method because (1) its proven effectiveness in rapidly altering the characteristics of residue sand such that it is more conducive for plant growth, and (2) it encourages deeper penetration of plant roots.
- Maintain botanical monitoring of the trials to test whether any of the treatments causes a reduction in rehabilitation performance in the longer term.
- Use the parameters Na, CO_3 and HCO_3 in conjunction with Ca, SO_4 and pH as a measure of gypsum interaction with residue sand.
- Prior to establishing any field trial, ensure that a complete history of past management is obtained and assess whether any previous activity will affect the primary objectives (or hypotheses to be tested) of the study.

REFERENCES

Barrow NJ (1982) Possibility of using caustic residue from bauxite for improving the chemical and physical properties of sandy soils. *Australian Journal of Agricultural Research* **33,** 275-285

Cichota R, Vogeler I, Bolan N, Clothier B (2007) Simultaneous adsorption of calcium and sulfate and its effect on their movement. *Soil Science Society of America Journal* **71,** 703 – 710

Dobrowolski MP, Mullins RG, Phillips IR (2009) Factors affecting plant root distribution in sand embankments of bauxite residue disposal areas. (Environmental Department Research Note No. 29 Alcoa of Australia: Perth)

Eastham J, Morald T (2004a) Improving root penetration and vegetation growth on bauxite residue embankments. (Unpublished Report Alcoa Western Australia Engineering Operations Alcoa of Australia: Perth)

Eastham J, Mullins G (2004b) Evaluating techniques for reducing pH of bauxite residue at depth using gypsum. (Unpublished Report Alcoa Western Australia Engineering Operations Alcoa of Australia: Perth)

Keipert N (2005) Chemical properties of residue prior to application of gypsum and irrigation treatments. (Unpublished Report Environmental Department Alcoa of Australia: Perth)

LeRoy M (2007) The effect of gypsum depth and irrigation on plant growth in residue sand. (Unpublished Report Environmental Department Alcoa of Australia: Perth)

Narducci M (2006) Effect of irrigation on survival and growth of rehabilitation on residue embankments. (Unpublished Report Environmental Department Alcoa of Australia: Perth)

Phillips IR (2010a) Characteristics of gypsum and fertiliser used in residue rehabilitation. (Environmental Department Research Note No. 35 Alcoa of Australia: Perth)

Phillips IR (2010b) Comparing techniques for incorporating gypsum into residue sand embankments at Alcoa's residue disposal areas. (Environmental Department Research Note No. 32 Alcoa of Australia: Perth)

Phillips IR, Bond WJ (1989) An extraction procedure for determining solution and exchangeable ions on the same soil sample. *Soil Science Society of America Journal* **53,** 1294 – 1297

Phillips IR, Chen C (2010) Surface charge properties and sorption properties of bauxite-processing residue sand. *Australian Journal of Soil Research* **48,** 77-87

Rayment GE, Higginson FR (1992) "Australian laboratory handbook of soil and water chemical methods". (Inkata Press: Melbourne)

Stumm W, Morgan JJ (1981) "Aquatic chemistry. 2nd edition". (John Wiley & Sons: Brisbane)

Theng BKG (1980) "Soils with variable charge". (New Zealand Society of Soil Science: Lower Hutt New Zealand)

Wilkinson C (2005) Botanical monitoring of gypsum/irrigation trials on bauxite residue – December 2005. (Unpublished Report Environmental Department Alcoa of Australia: Perth)

Wong JWC, Ho GE (1995) Cation exchange behaviour of bauxite refining residues from Western Australia. *Journal of Environmental Quality* **24,** 461- 466

Figure 1. A diagram (not to scale) of the botanical monitoring plots set up within each treatment plot. Distances for the different plots and compass bearings are shown. The dark square (■) is the North-west corner of the plot and is marked in the field by a fence dropper and a permanent plot number

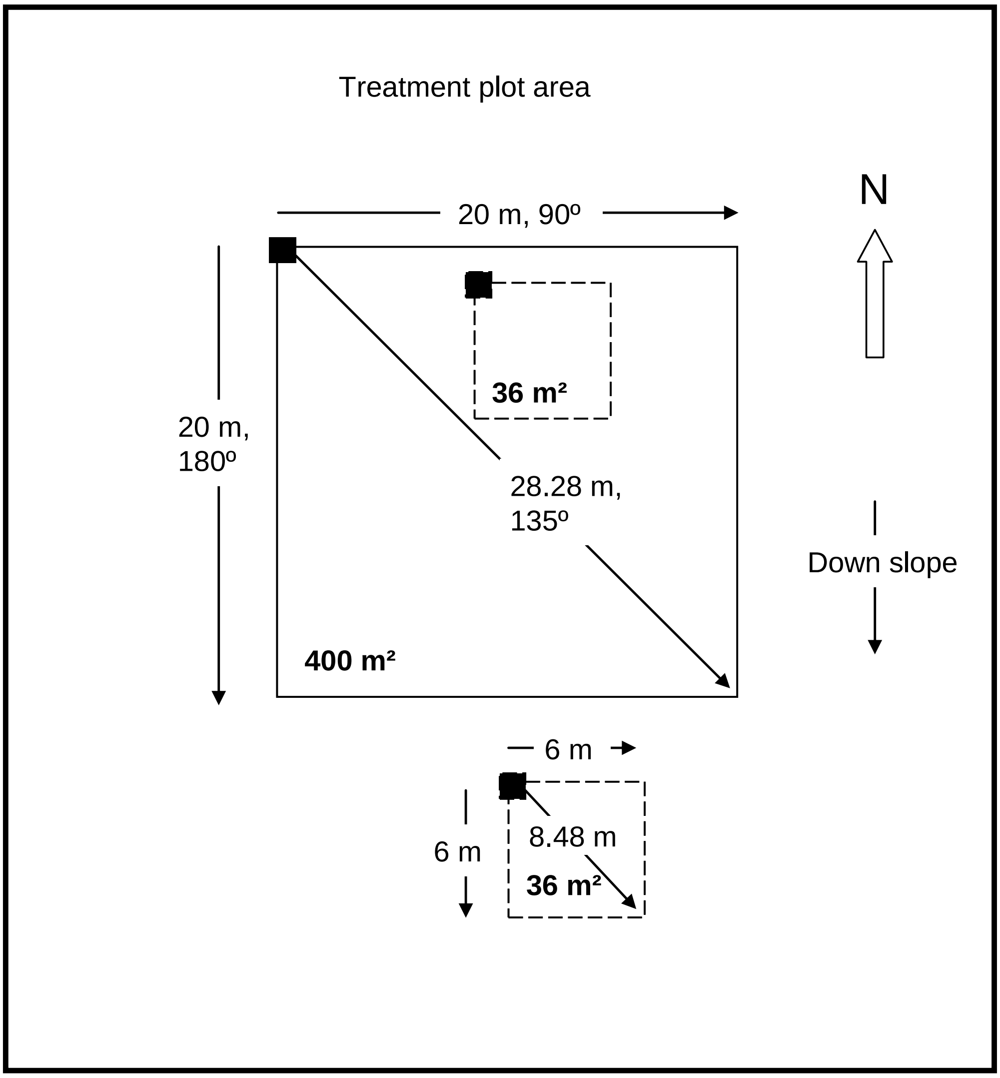
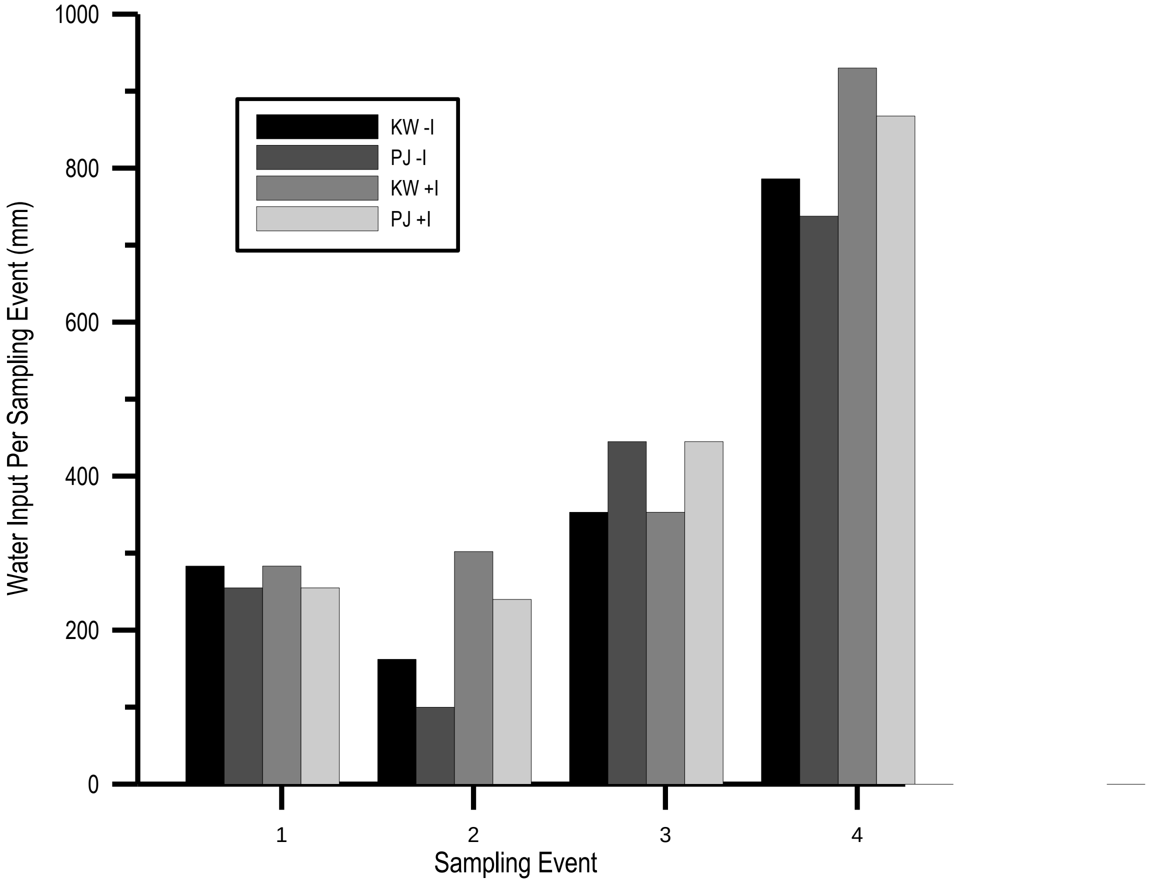
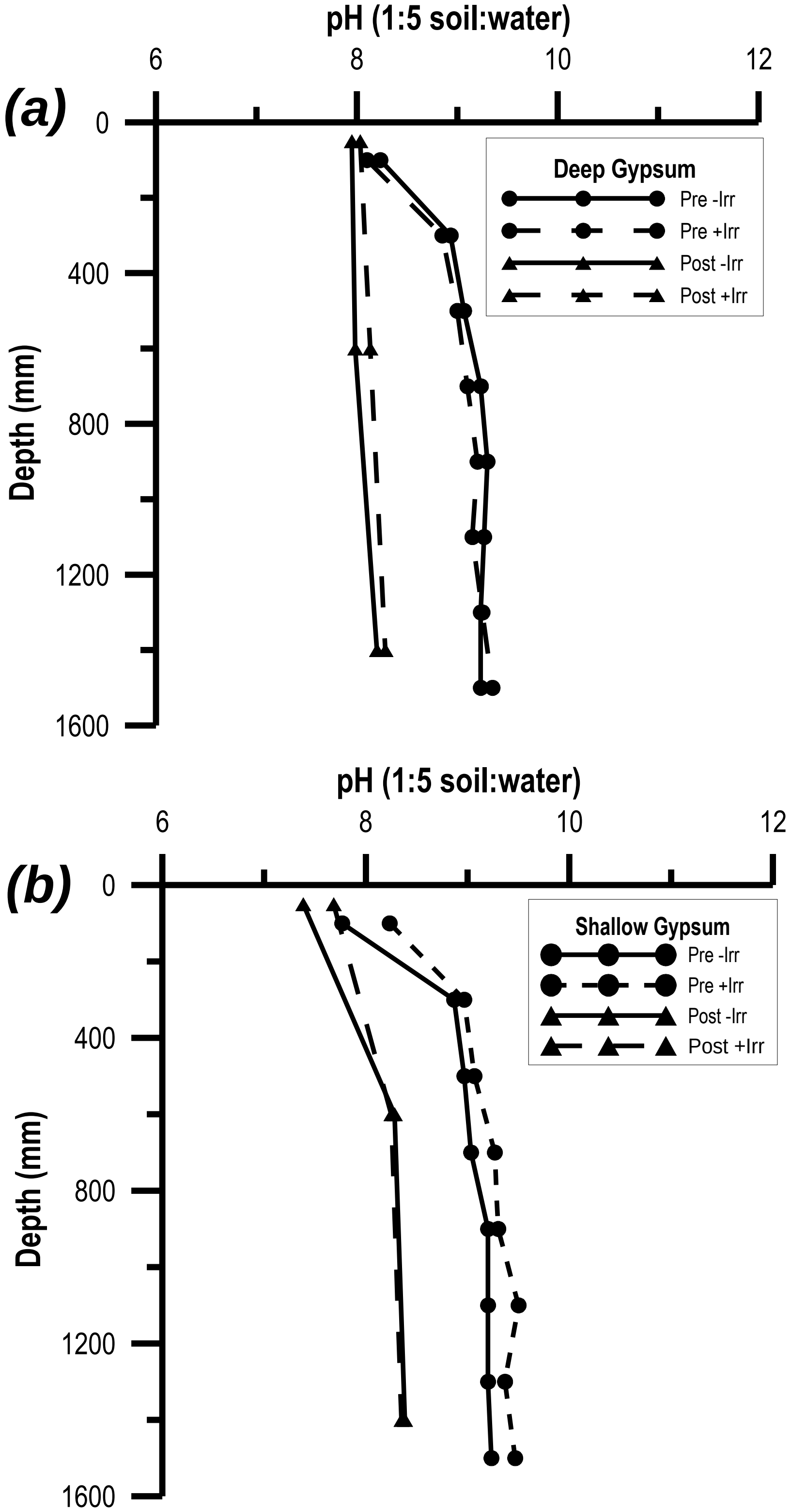
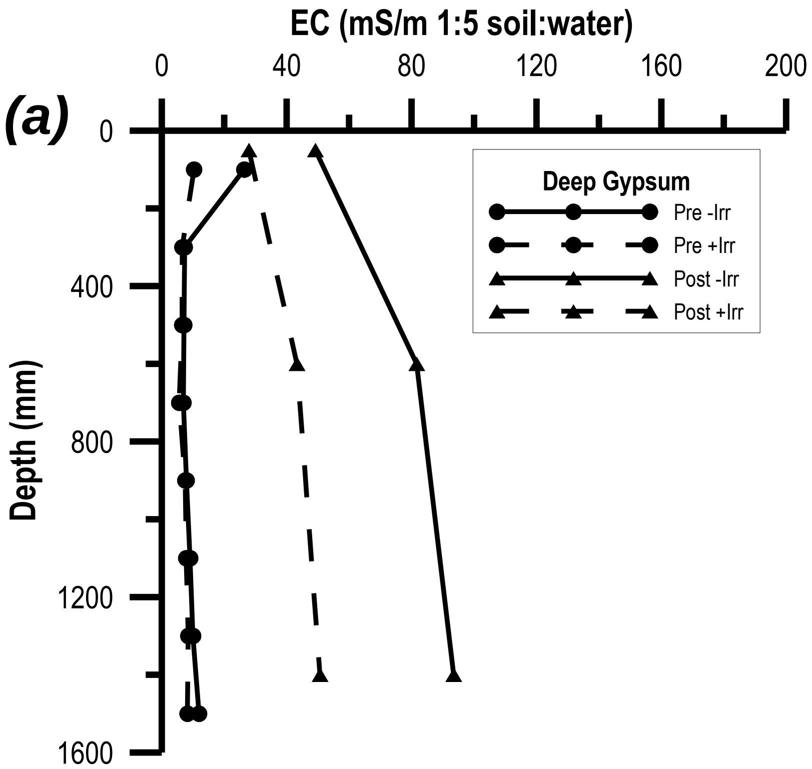
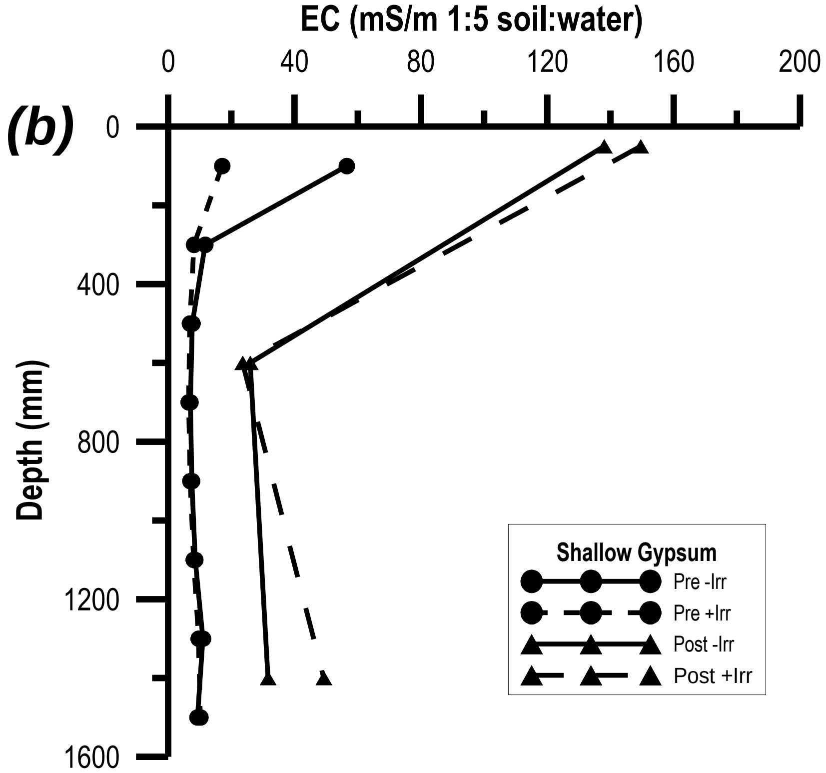


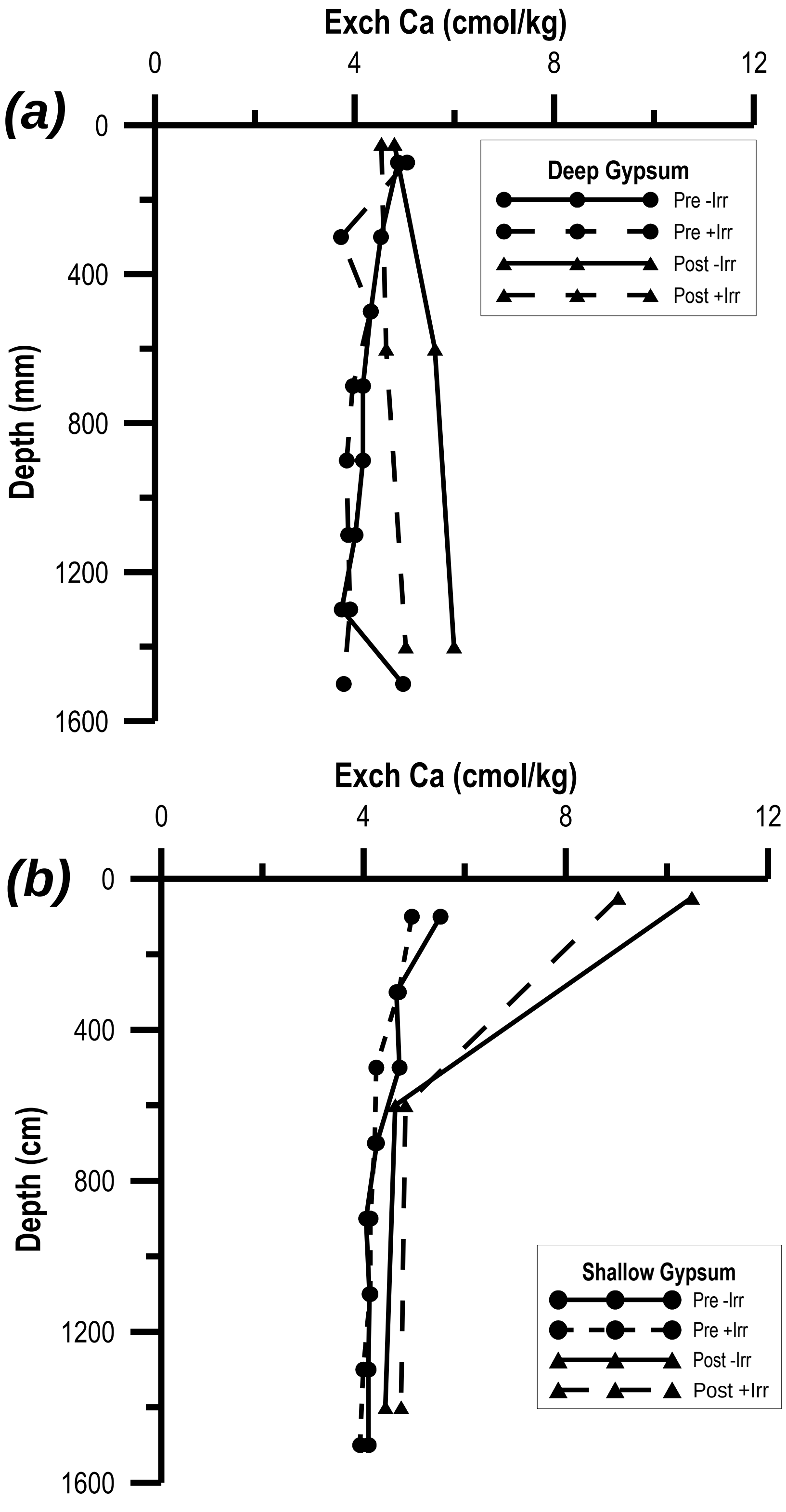
Figure 2. Rainfall ± irrigation received over each residue sand sampling event (1 = August 2005 to November 2005; 2 = December 2005 to June 2006; 3 = July 2006 to December 2006; 4 = January 2007 to December 2007)

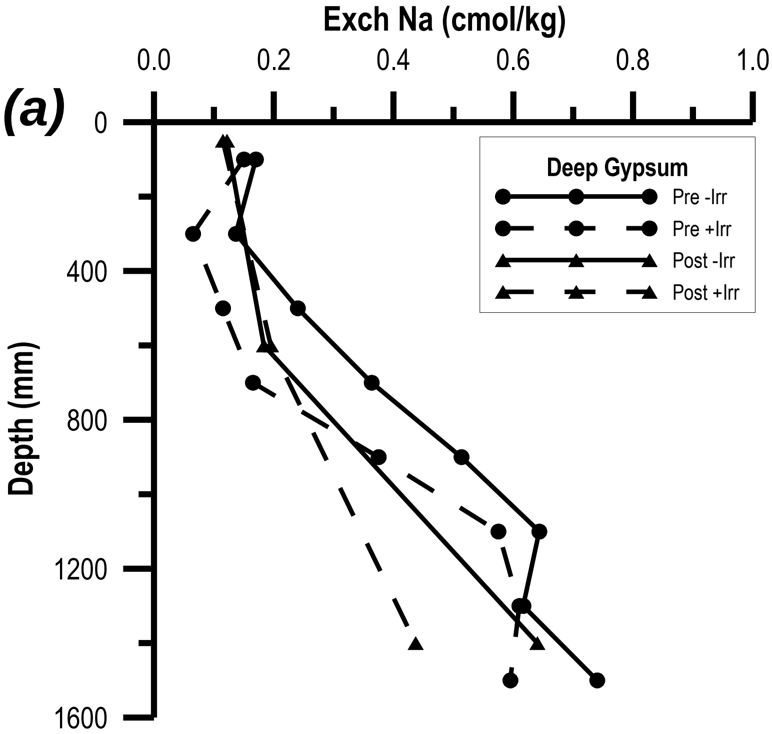


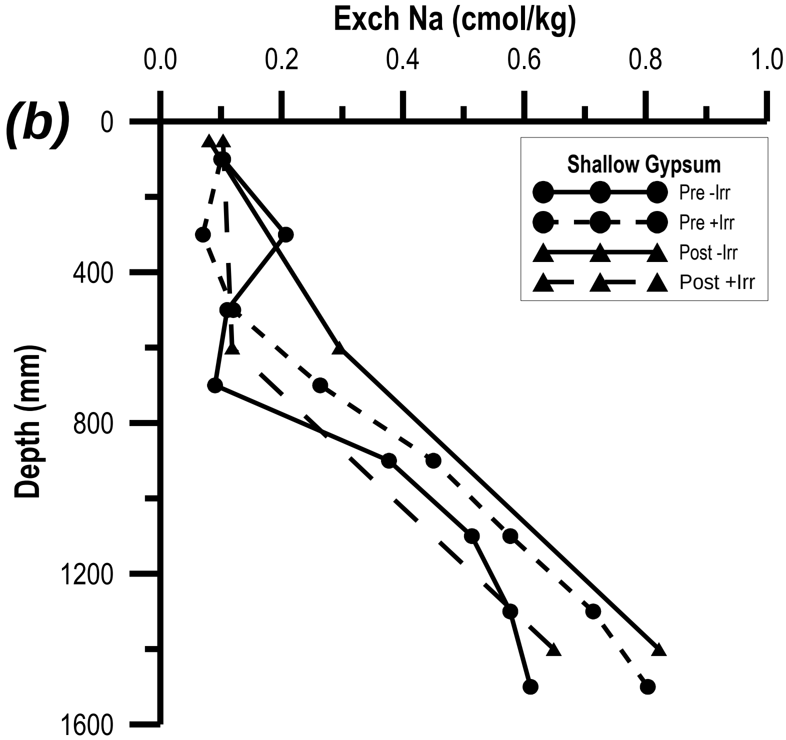

(a)
pH (1:5 soil:water)
6
8
10
12
0
400
800
1200
1600
Depth (mm)
Deep Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr
(b)
pH (1:5 soil:water)
6
8
10
12
0
400
800
1200
1600
Depth (mm)
Shallow Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr

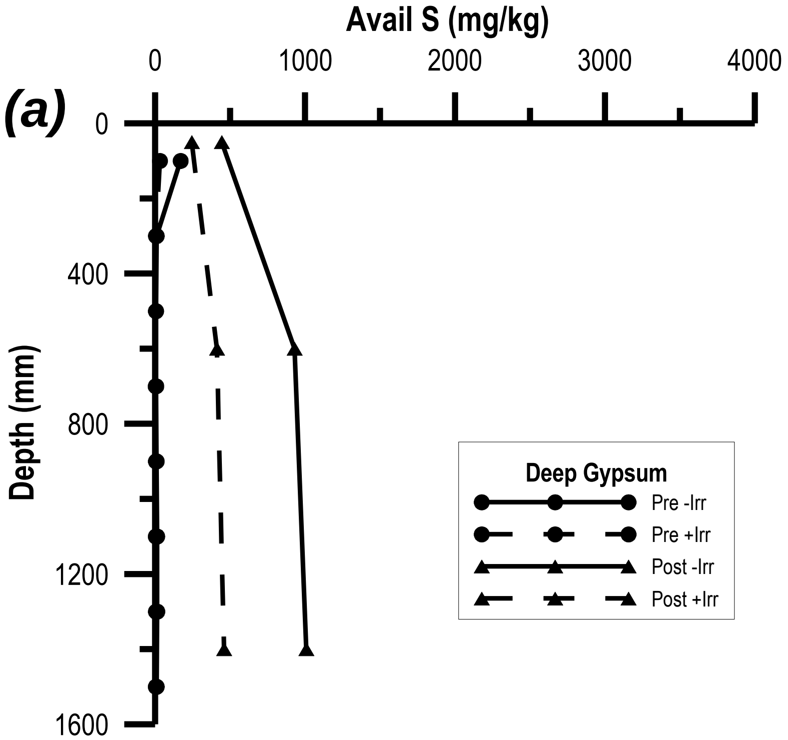

(a)
EC (mS/m 1:5 soil:water)
0
40
80
120
160
200
Depth (mm)
0
400
800
1200
1600
Deep Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr

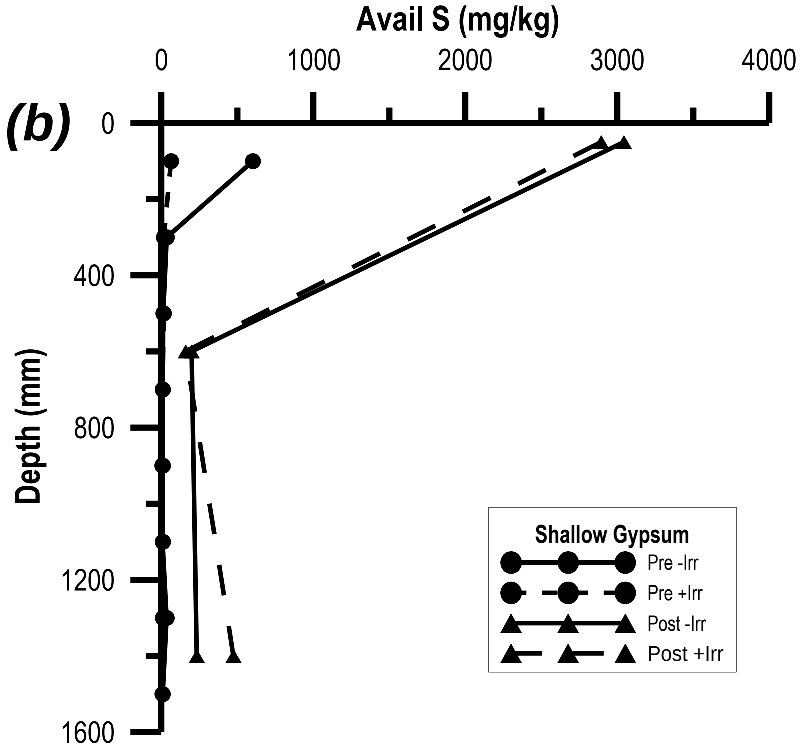

(b)
EC (mS/m 1:5 soil:water)
0
40
80
120
160
200
Depth (mm)
0
400
800
1200
1600
Shallow Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr

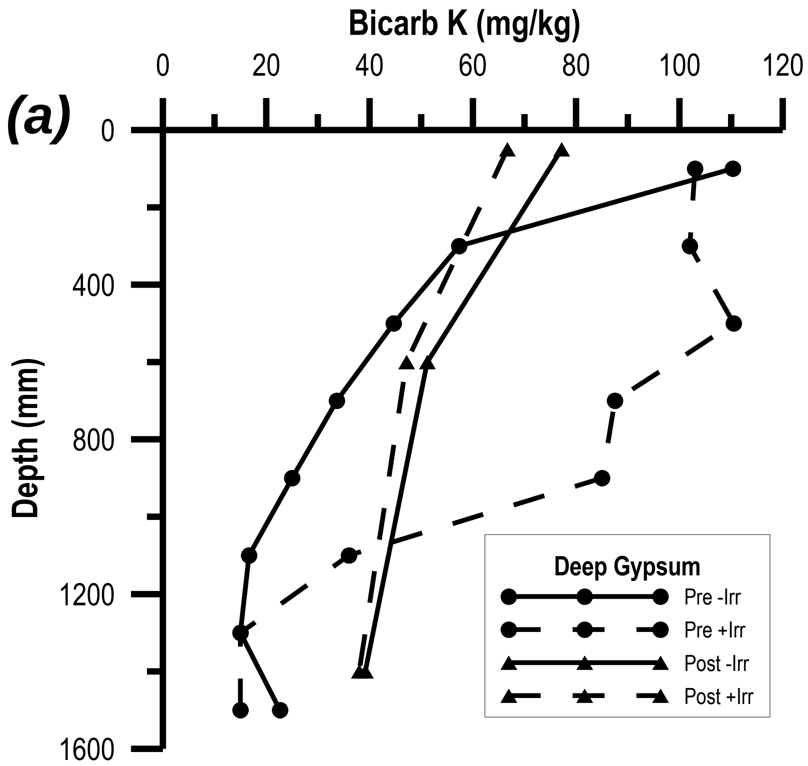

(a)
Exch Ca (cmol/kg)
0
4
8
12
Depth (mm)
0
400
800
1200
1600
Deep Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr
(b)
Exch Ca (cmol/kg)
0
4
8
12
Depth (cm)
0
400
800
1200
1600
Shallow Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr

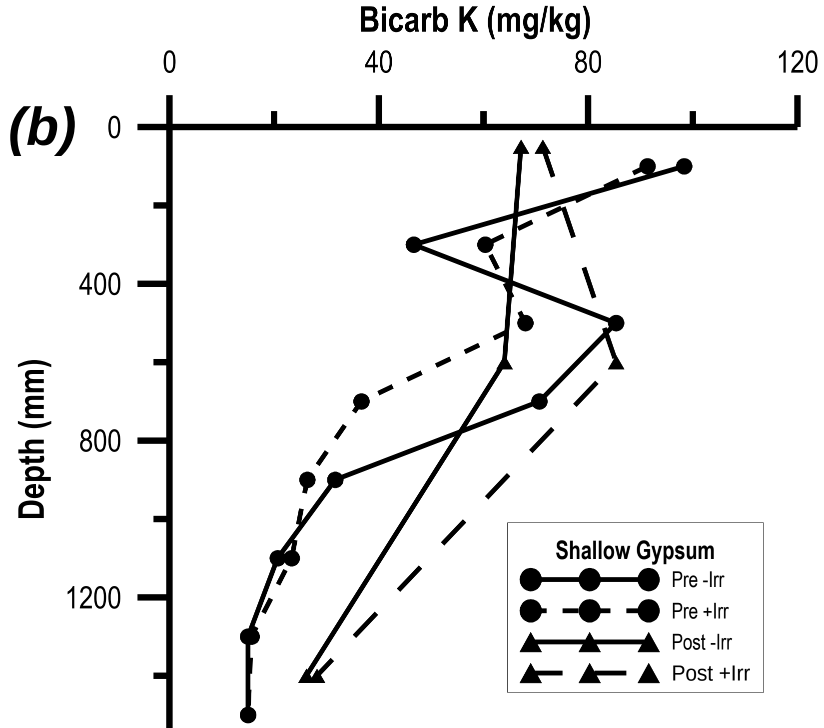

(a)
Exch Na (cmol/kg)
0.0
0.2
0.4
0.6
0.8
1.0
0
400
800
1200
1600
Depth (mm)
Deep Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr


(b)
Exch Na (cmol/kg)
0.0
0.2
0.4
0.6
0.8
1.0
0
400
800
1200
1600
Depth (mm)
Shallow Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr


(a)
Avail S (mg/kg)
0
1000
2000
3000
4000
Depth (mm)
0
400
800
1200
1600
Deep Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr


(b)
Avail S (mg/kg)
0
1000
2000
3000
4000
Depth (mm)
0
400
800
1200
1600
Shallow Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr


Bicarb K (mg/kg)
0
20
40
60
80
100
120
(a)
0
400
800
1200
1600
Depth (mm)
Deep Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr


Bicarb K (mg/kg)
0
40
80
120
(b)
0
400
800
1200
1600
Depth (mm)
Shallow Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr

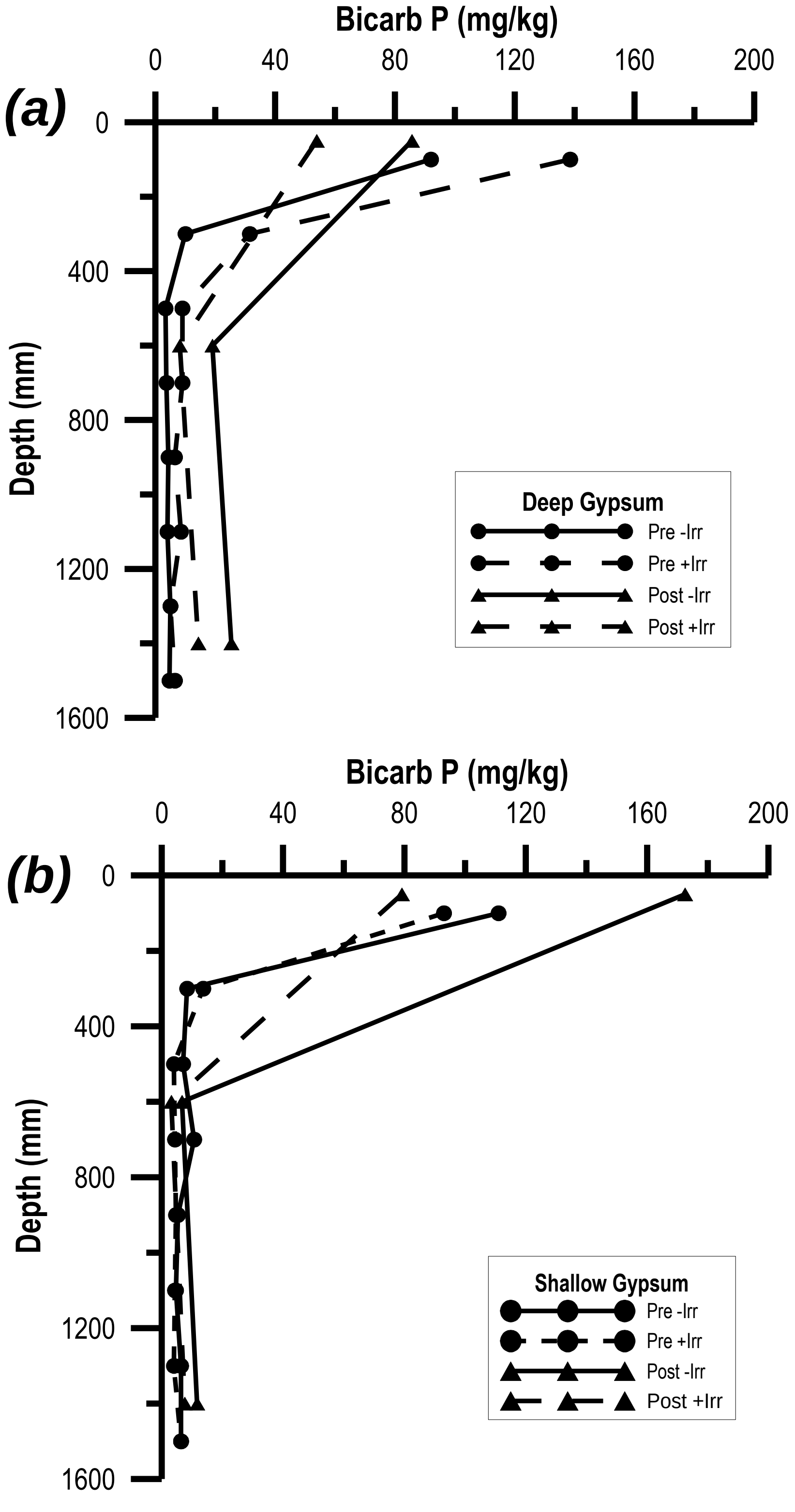
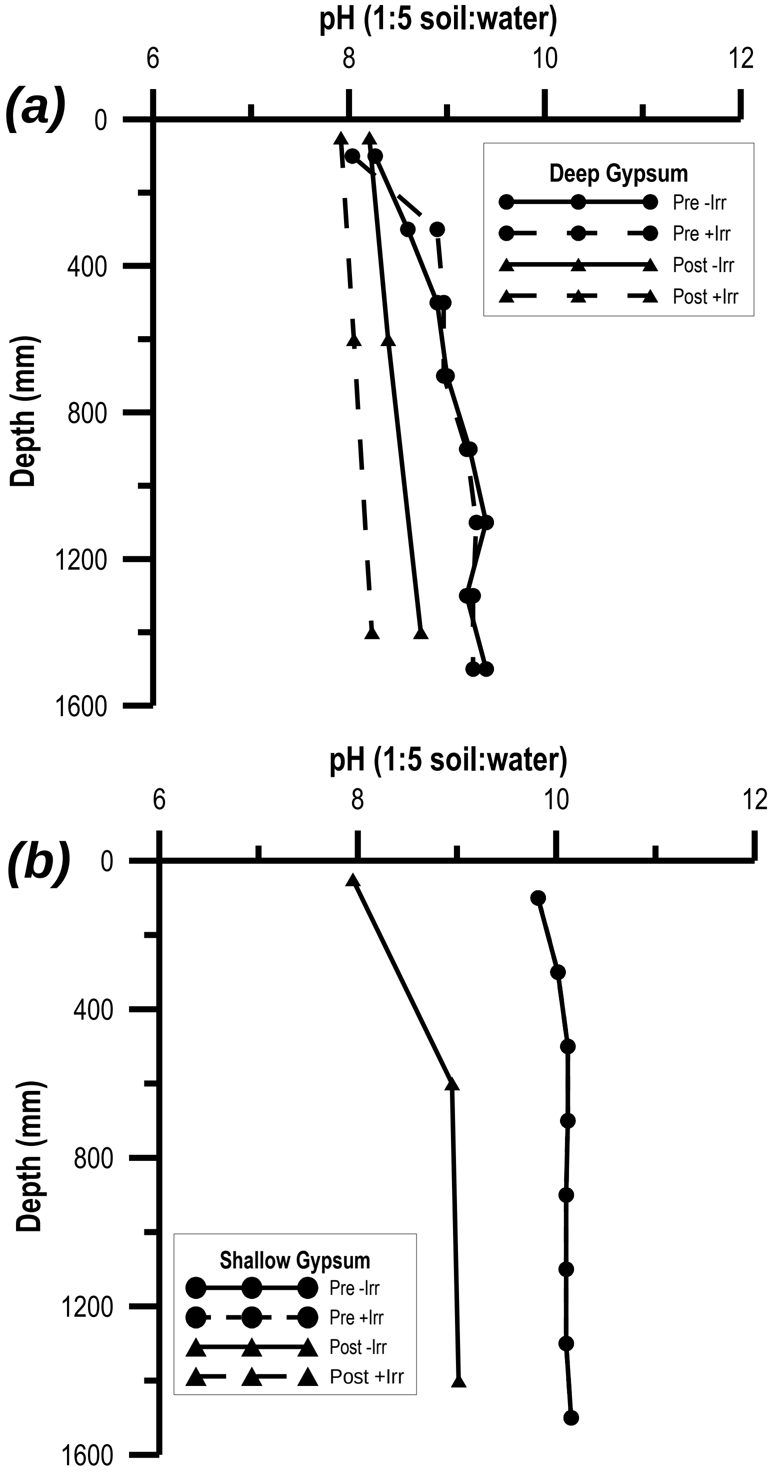
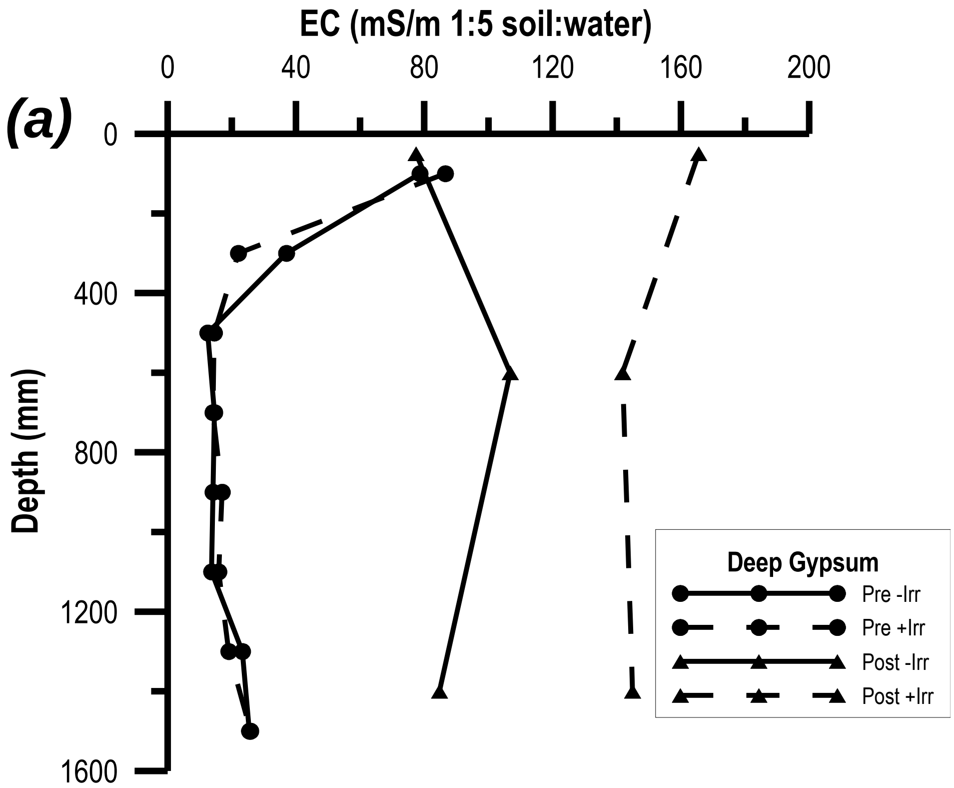
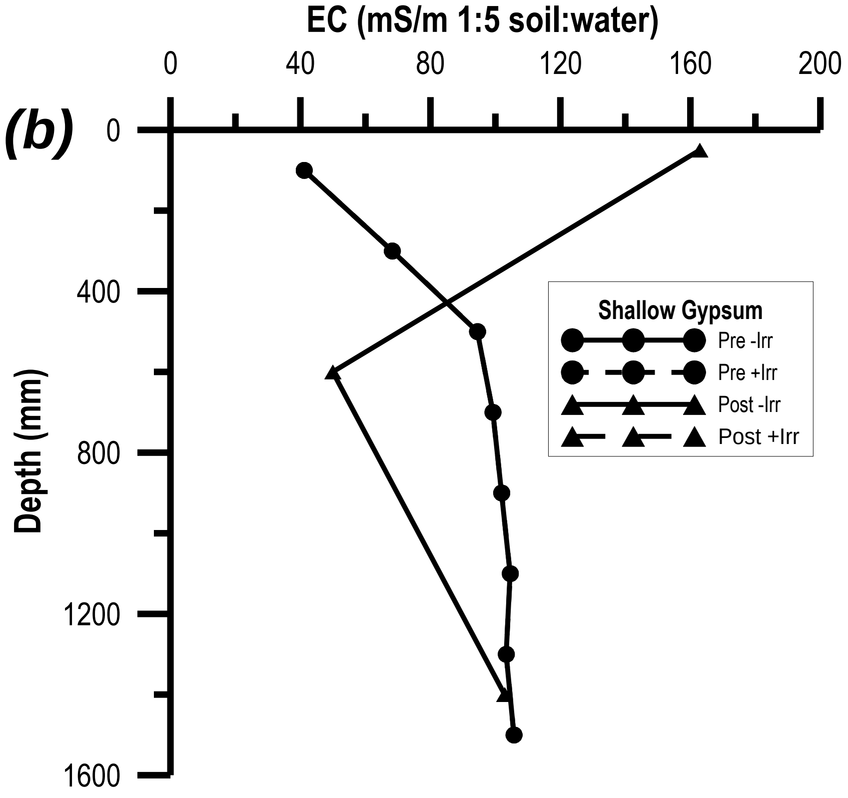
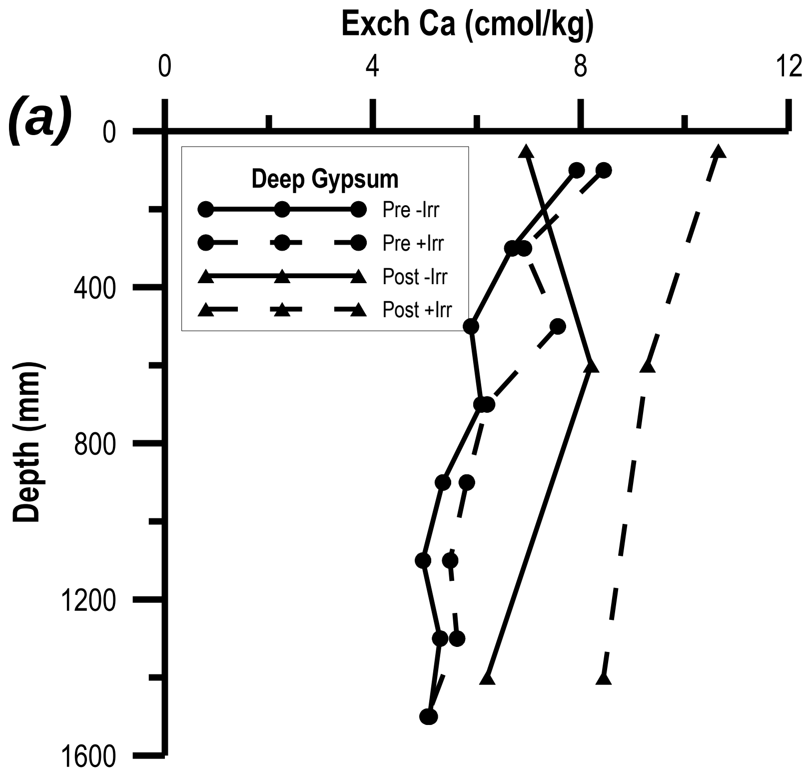


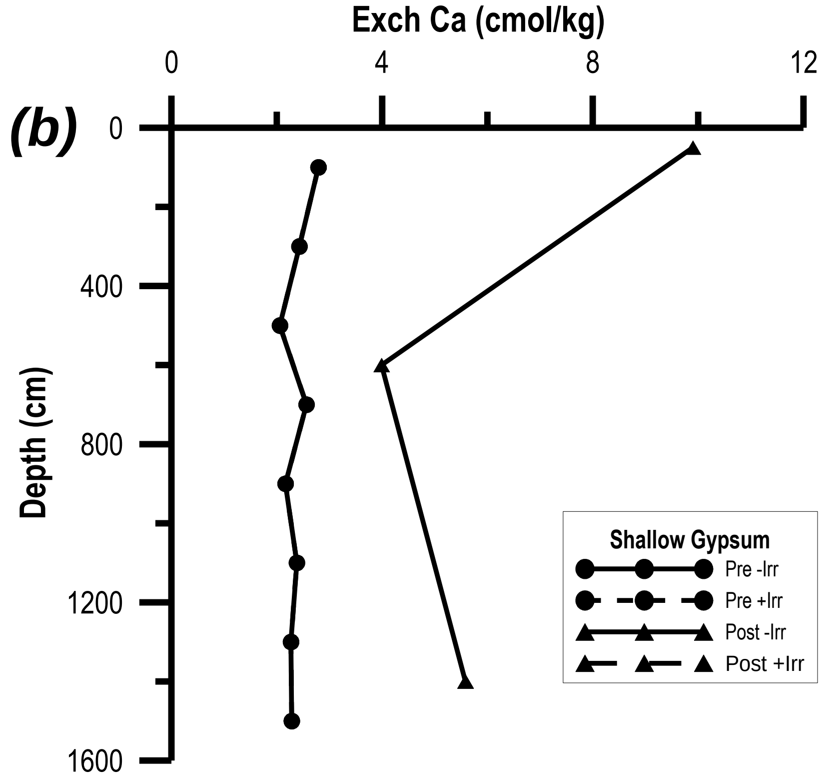
Figure 3. Pinjarra gypsum irrigation trial – effects of (a) deep or (b) shallow gypsum incorporation on the vertical distribution of pH, EC, exchangeable Ca, exchangeable Na, available S, available K and available P. Values presented are for pre- and post- gypsum incorporation, and minus and plus irrigation

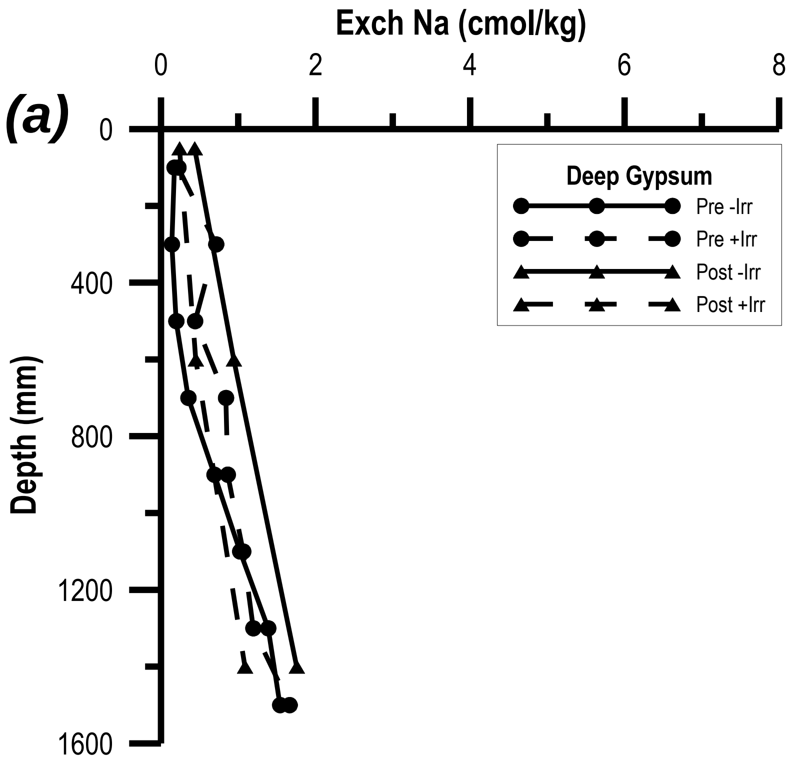

(a)
pH (1:5 soil:water)
6
8
10
12
0
400
800
1200
1600
Depth (mm)
Deep Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr
(b)
pH (1:5 soil:water)
6
8
10
12
0
400
800
1200
1600
Depth (mm)
Shallow Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr

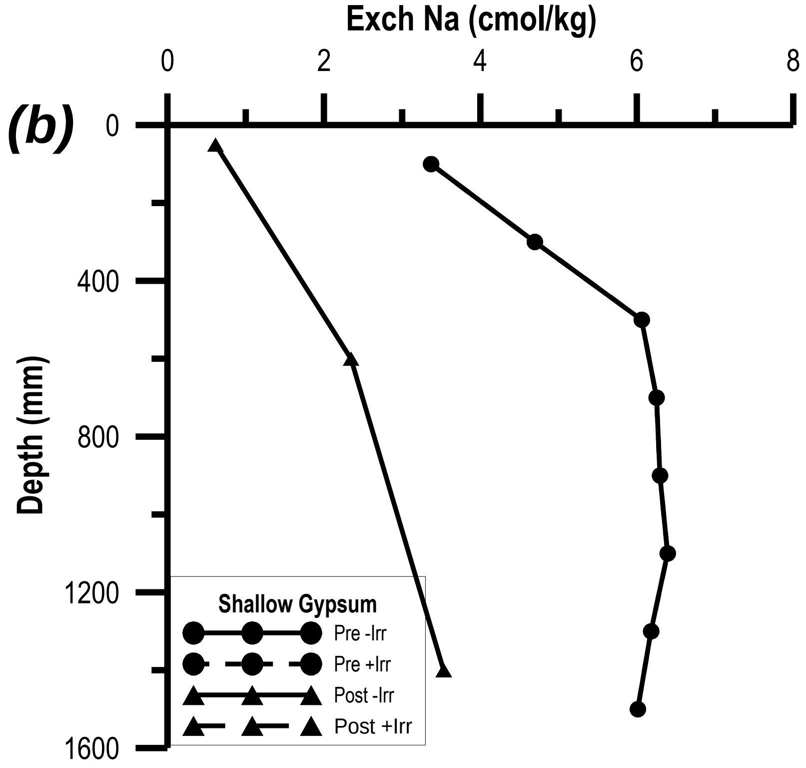

(a)
EC (mS/m 1:5 soil:water)
0
40
80
120
160
200
Depth (mm)
0
400
800
1200
1600
Deep Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr

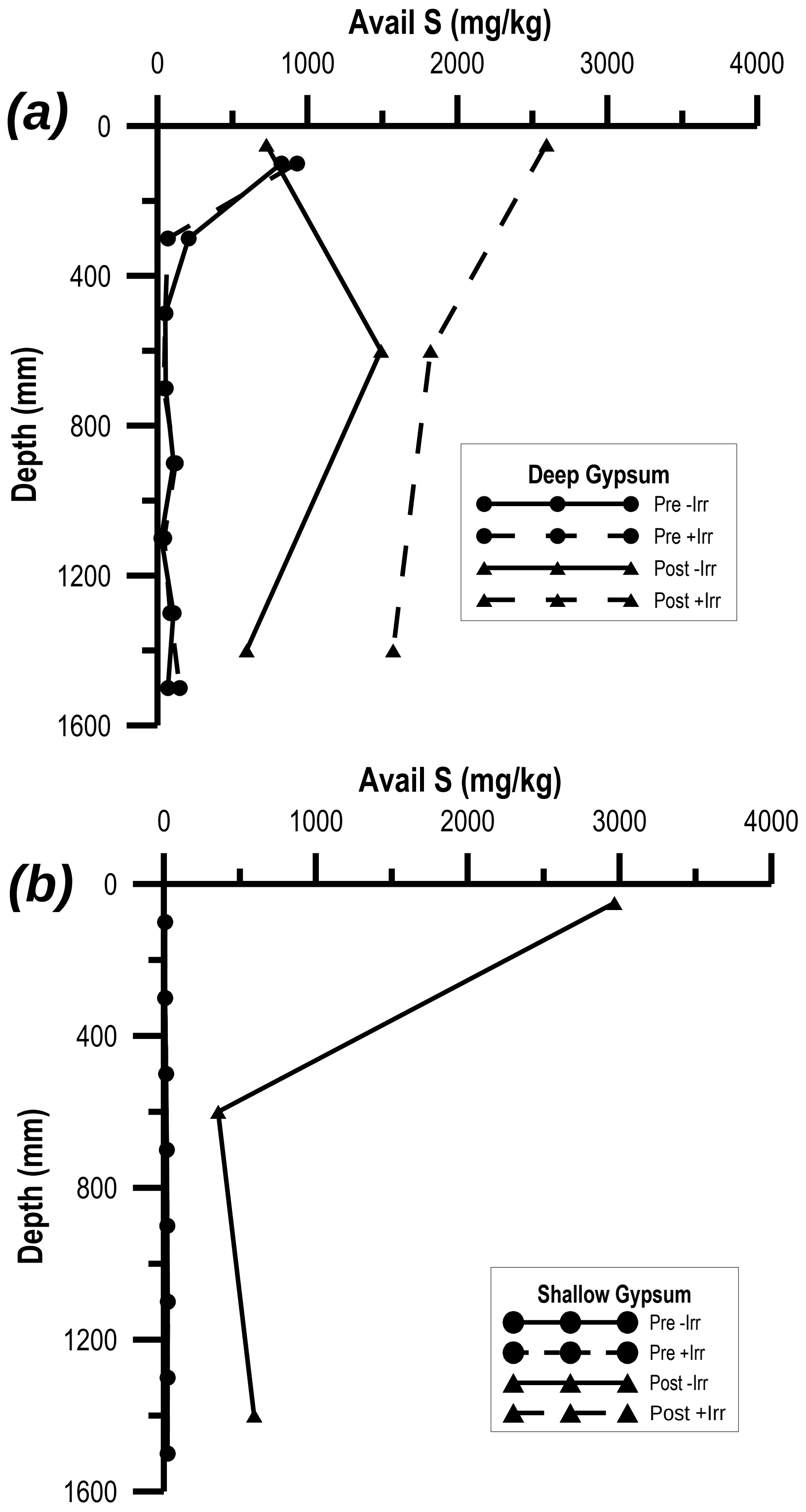

(b)
EC (mS/m 1:5 soil:water)
0
40
80
120
160
200
Depth (mm)
0
400
800
1200
1600
Shallow Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr

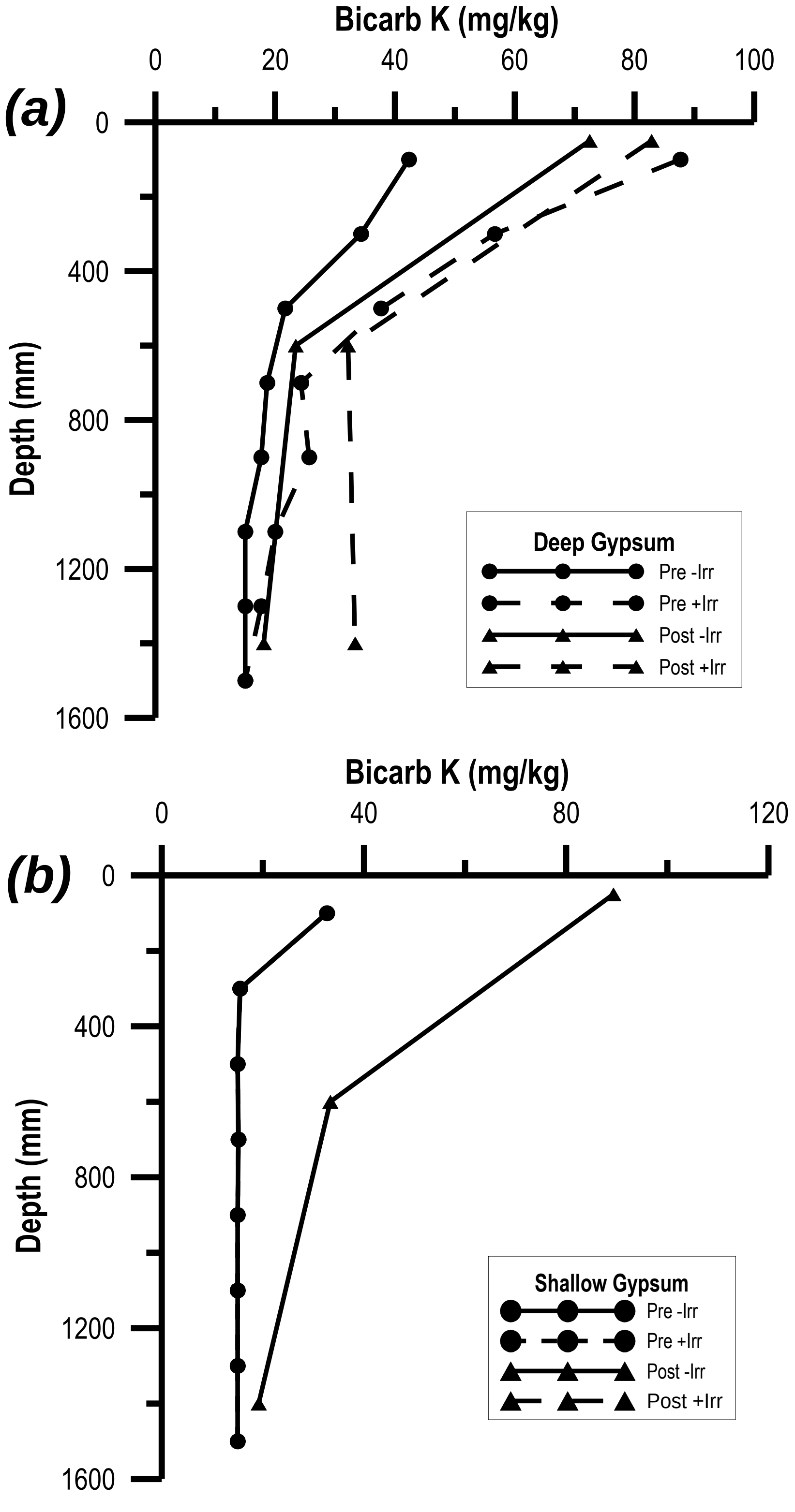

(a)
Exch Ca (cmol/kg)
0
4
8
12
Depth (mm)
0
400
800
1200
1600
Deep Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr


(b)
Exch Ca (cmol/kg)
0
4
8
12
Depth (cm)
0
400
800
1200
1600
Shallow Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr


(a)
Exch Na (cmol/kg)
0
2
4
6
8
Depth (mm)
0
400
800
1200
1600
Deep Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr


(b)
Exch Na (cmol/kg)
0
2
4
6
8
Depth (mm)
0
400
800
1200
1600
Shallow Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr


(a)
Avail S (mg/kg)
0
1000
2000
3000
4000
0
400
800
1200
1600
Depth (mm)
Deep Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr
(b)
Avail S (mg/kg)
0
1000
2000
3000
4000
0
400
800
1200
1600
Depth (mm)
Shallow Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr


(a)
Bicarb K (mg/kg)
0
20
40
60
80
100
Depth (mm)
0
400
800
1200
1600
Deep Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr
(b)
Bicarb K (mg/kg)
0
40
80
120
Depth (mm)
0
400
800
1200
1600
Shallow Gypsum
Pre -Irr
Pre +Irr
Post -Irr
Post +Irr

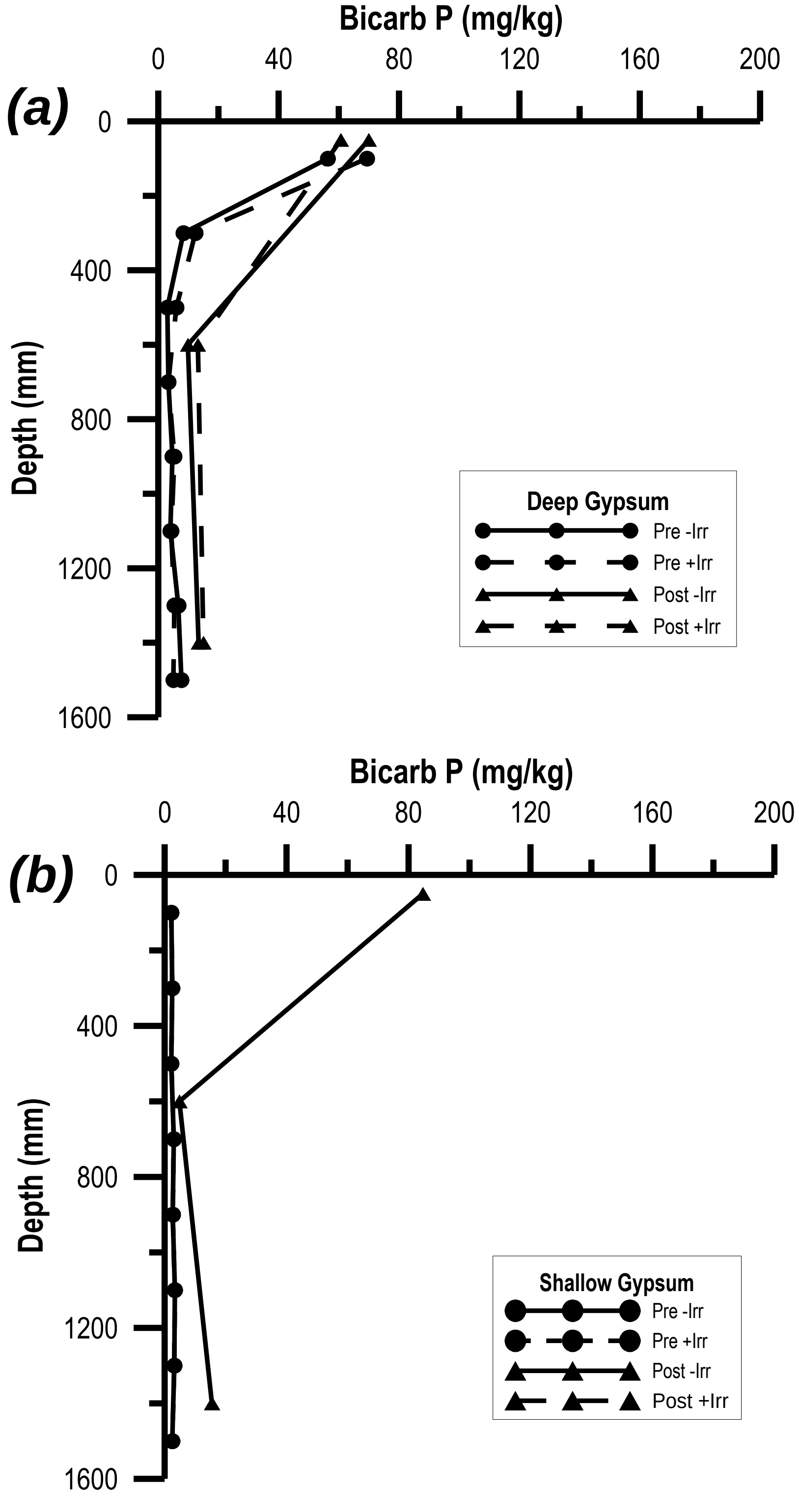
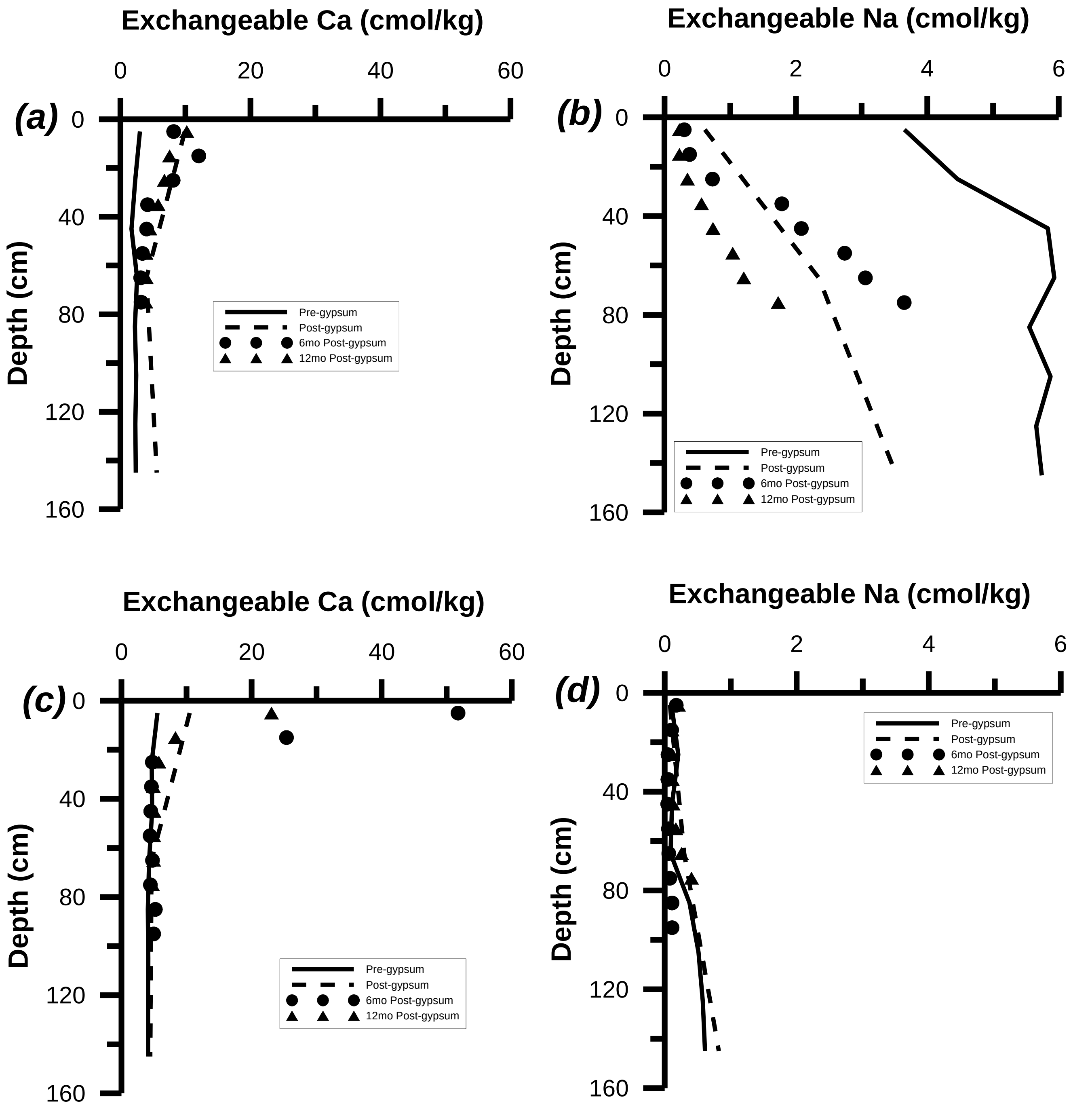
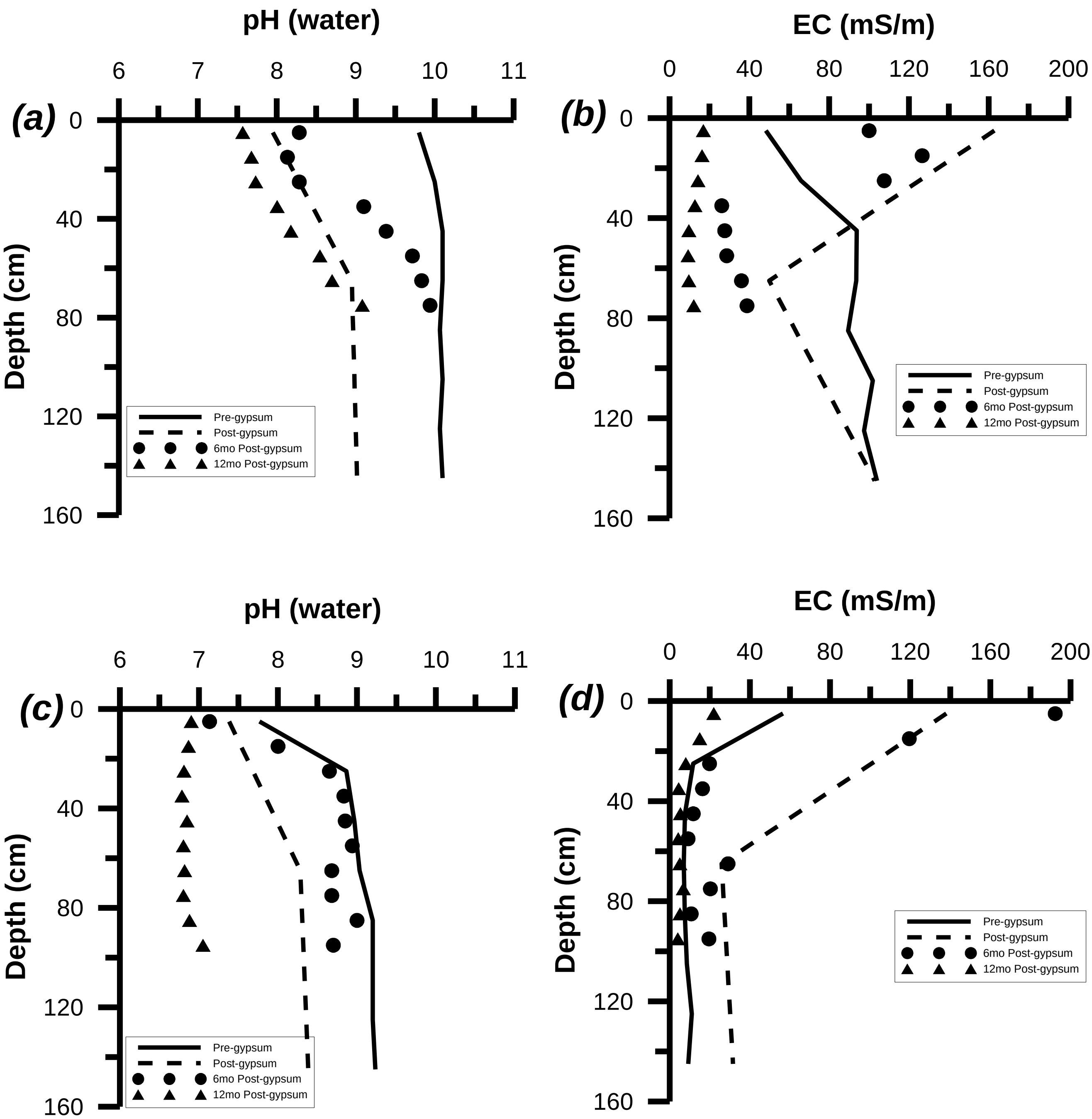


Figure 4. Kwinana gypsum irrigation trial – effects of (a) deep or (b) shallow gypsum incorporation on the vertical distribution of pH, EC, exchangeable Ca, exchangeable Na, available S, available K and available P. Values presented are for pre- and post- gypsum incorporation, and minus and plus irrigation.


(a)
Exchangeable Ca (cmol/kg)
0
20
40
60
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
(b)
Exchangeable Na (cmol/kg)
0
2
4
6
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
(c)
Exchangeable Ca (cmol/kg)
0
20
40
60
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
(d)
Exchangeable Na (cmol/kg)
0
2
4
6
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum


(a)
pH (water)
6
7
8
9
10
11
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
(b)
EC (mS/m)
0
40
80
120
160
200
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
(c)
pH (water)
6
7
8
9
10
11
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
(d)
EC (mS/m)
0
40
80
120
160
200
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum

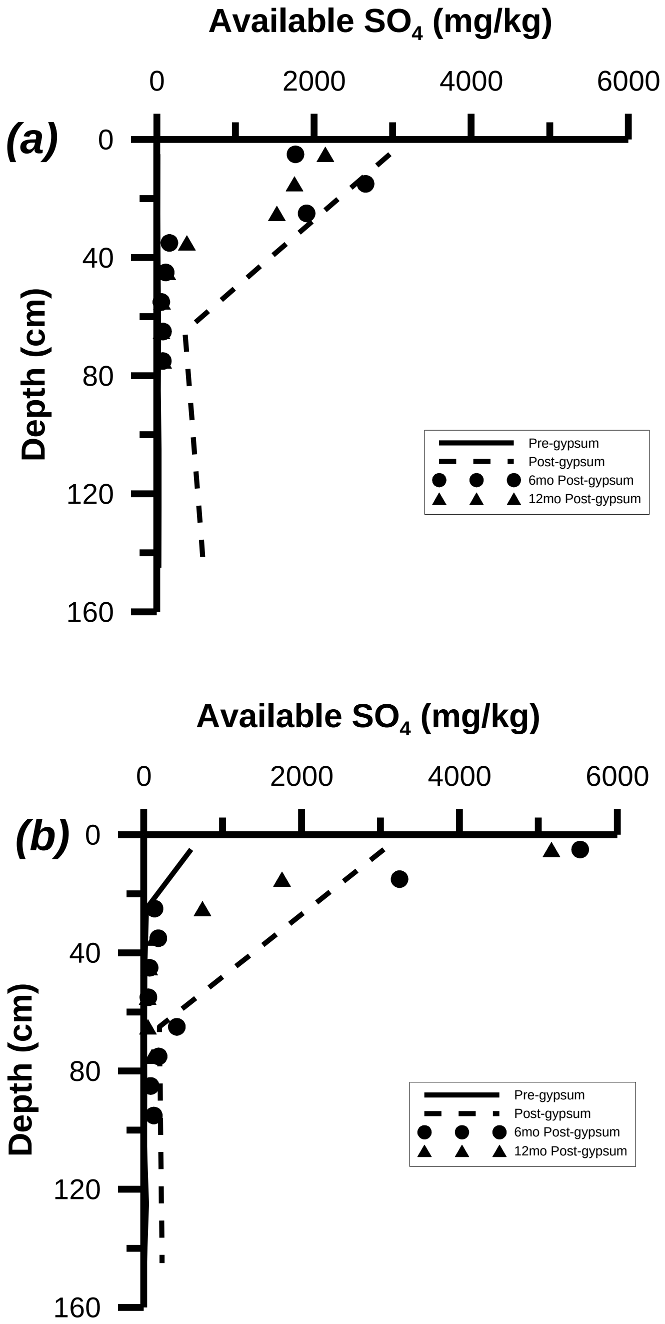
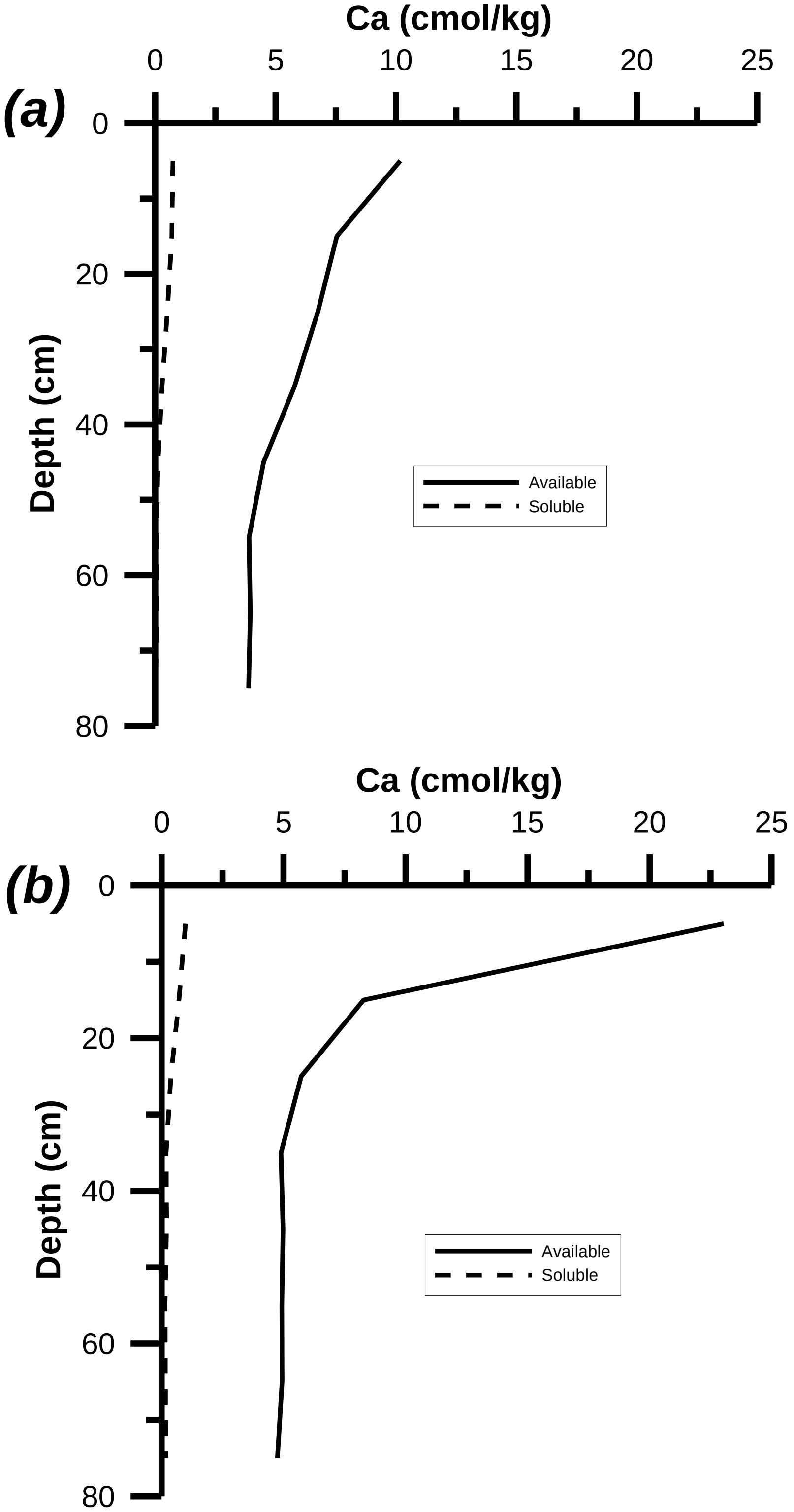
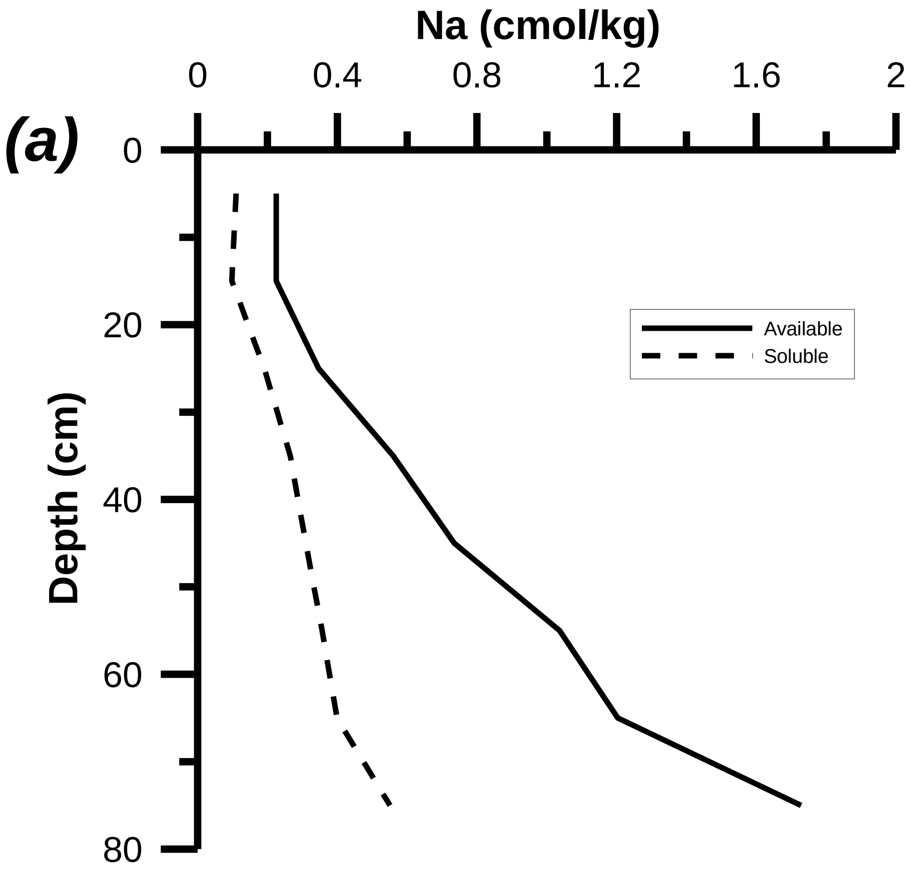
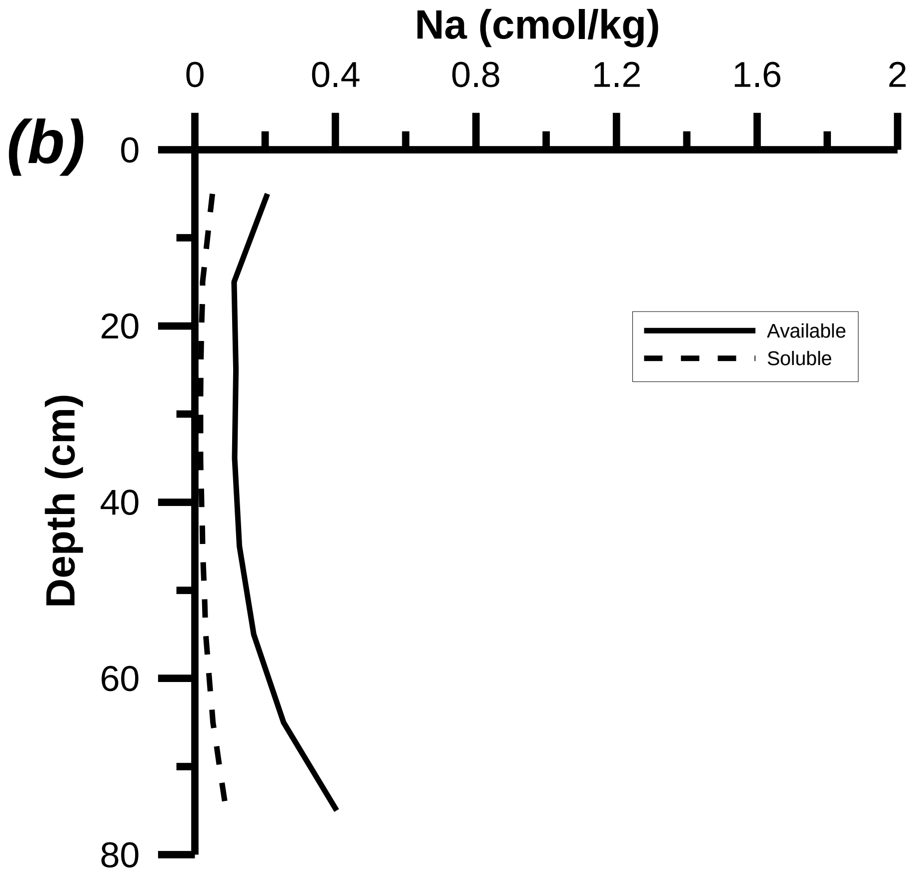
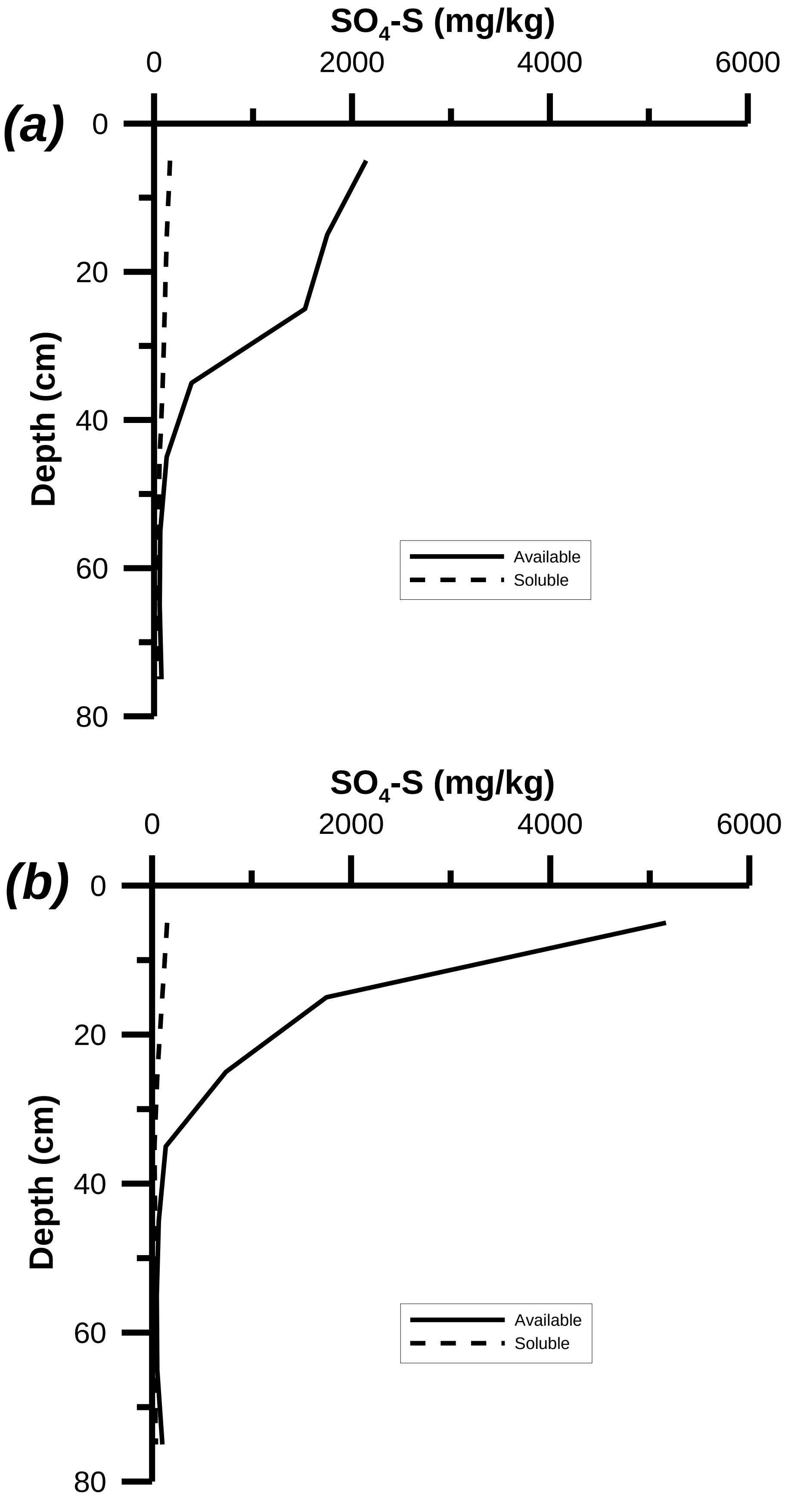


Figure 5. Effect of time (pre- and post- (0, 6 and 12 months) after gypsum incorporation, on fertilizer and gypsum transport, and selected chemical properties. Values presented are for pre- and post-shallow gypsum incorporation, and minus irrigation. For each set of 4 graphs, (a) and (b) refer to data for the Kwinana trial, and (c) and (d) refer to data for the Pinjarra trial. For available S, (a) refers to data for the Kwinana trial, and (b) refers to data for the Pinjarra trial.


(a)
Ca (cmol/kg)
0
5
10
15
20
25
Depth (cm)
0
20
40
60
80
Available
Soluble
(b)
Ca (cmol/kg)
0
5
10
15
20
25
Depth (cm)
0
20
40
60
80
Available
Soluble


(a)
Na (cmol/kg)
0
0.4
0.8
1.2
1.6
2
Depth (cm)
0
20
40
60
80
Available
Soluble


(b)
Na (cmol/kg)
0
0.4
0.8
1.2
1.6
2
Depth (cm)
0
20
40
60
80
Available
Soluble


(a)
SO4-S (mg/kg)
0
2000
4000
6000
0
20
40
60
80
Depth (cm)
Available
Soluble
(b)
SO4-S (mg/kg)
0
2000
4000
6000
0
20
40
60
80
Depth (cm)
Available
Soluble

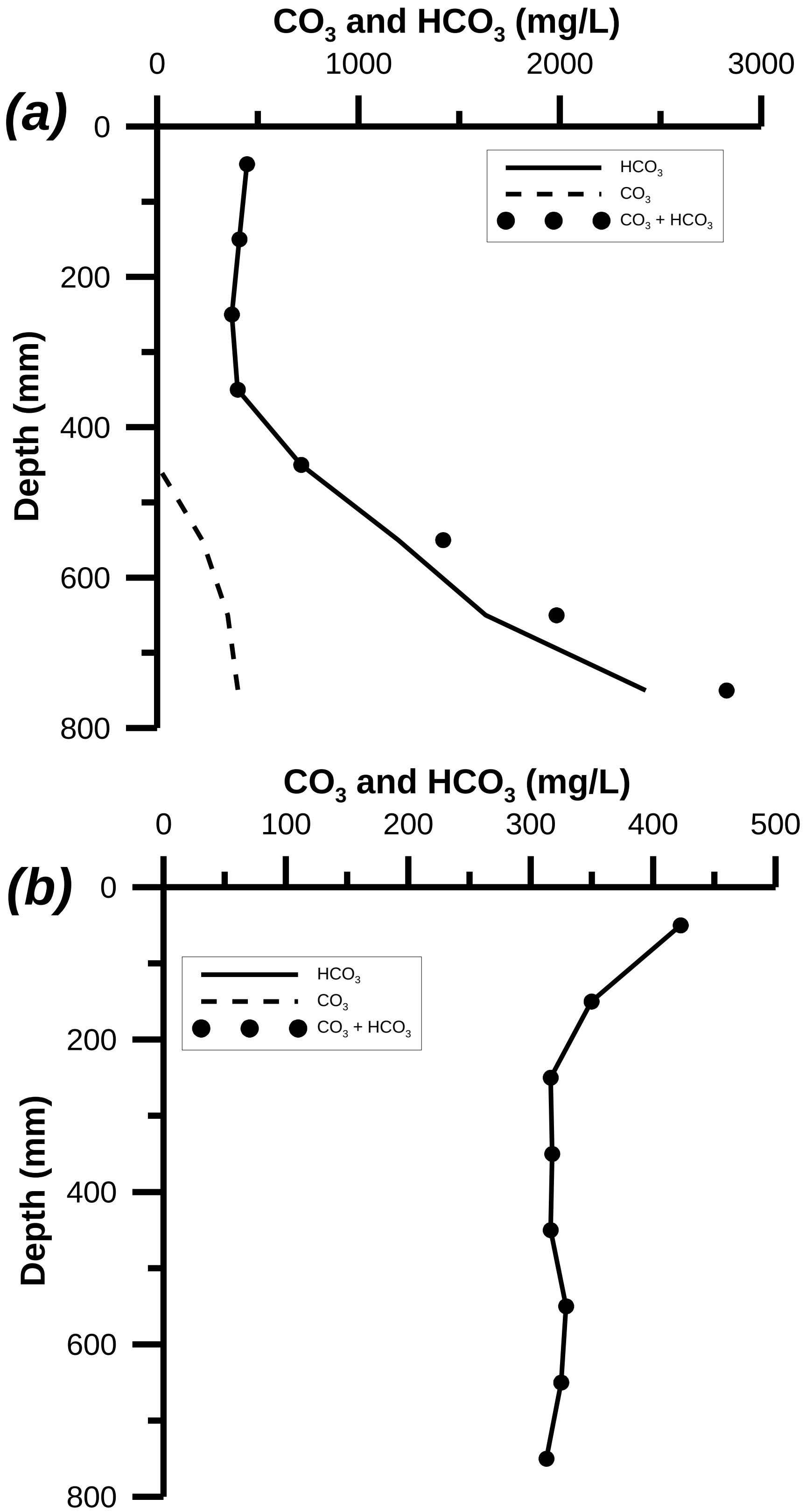


Figure 6. Vertical distribution of Ca, Na and SO_4 in the water-soluble and solid (available phase) fractions, and soluble alkalinity, for residue sand 12 months after shallow gypsum incorporation. For each set of 2 graphs, (a) refers to data for the Kwinana trial, and (b) refers to data for the Pinjarra trial

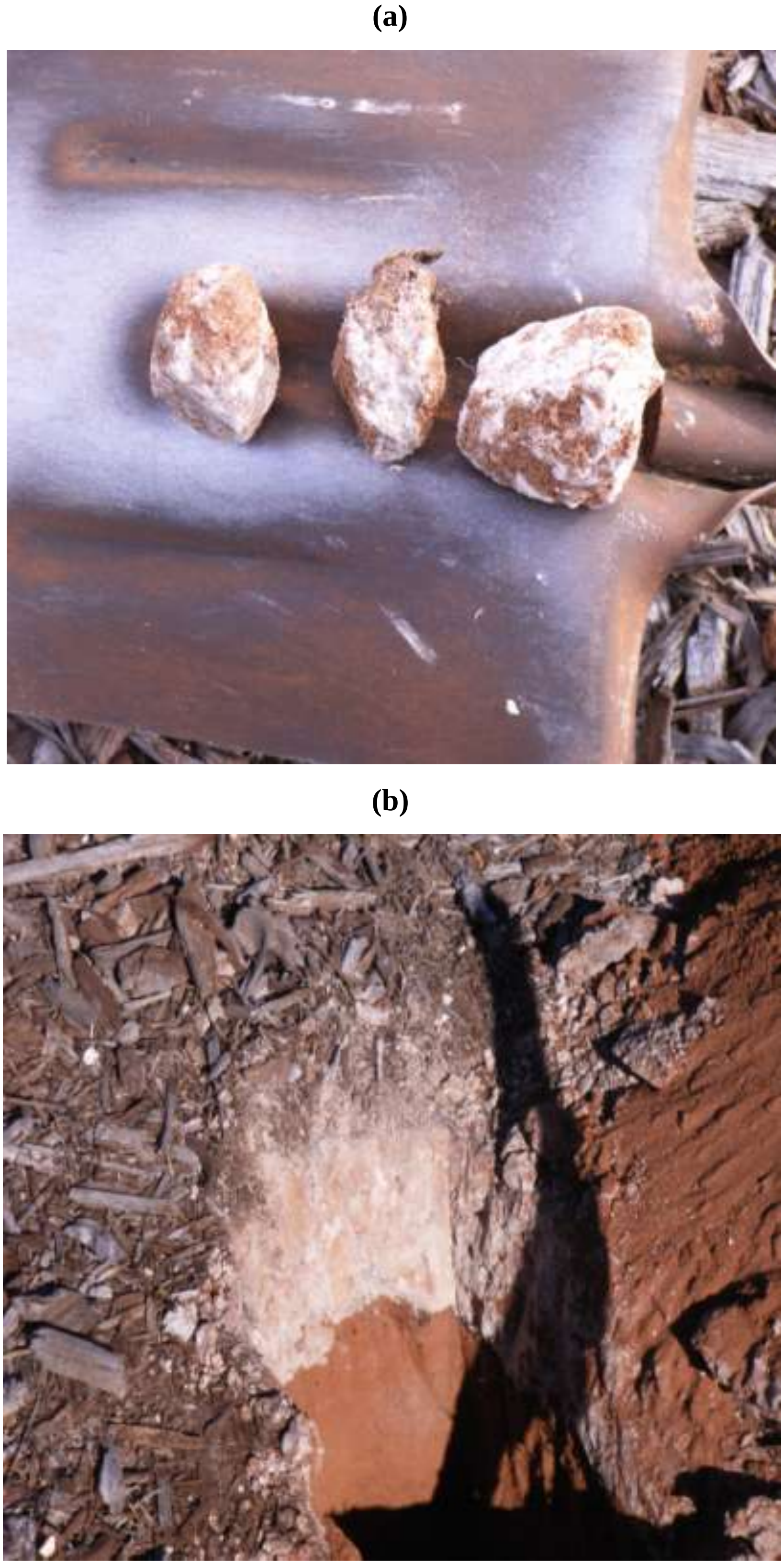


Figure 7. (a) Large pieces of gypsum present within the residue sand profile, and (b) high concentrations of gypsum in the 0 – 200 mm depth interval at the shallow gypsum incorporation trial.

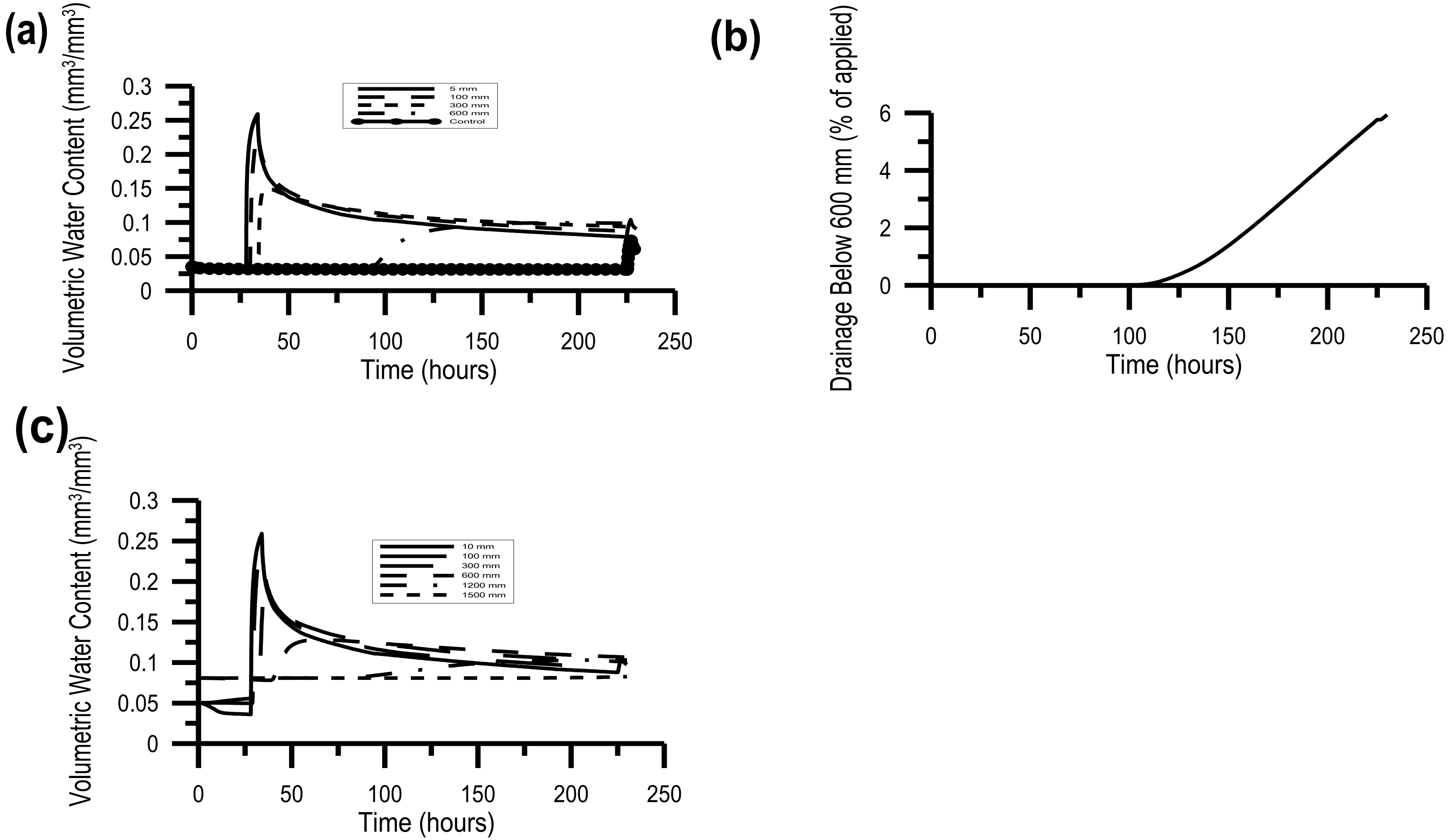


Figure 8. Simulated (HYDRUS-1D) water content at specific depths within the (a) 600 and (c) 1500 mm depth interval, and the amount of drainage following a single irrigation event

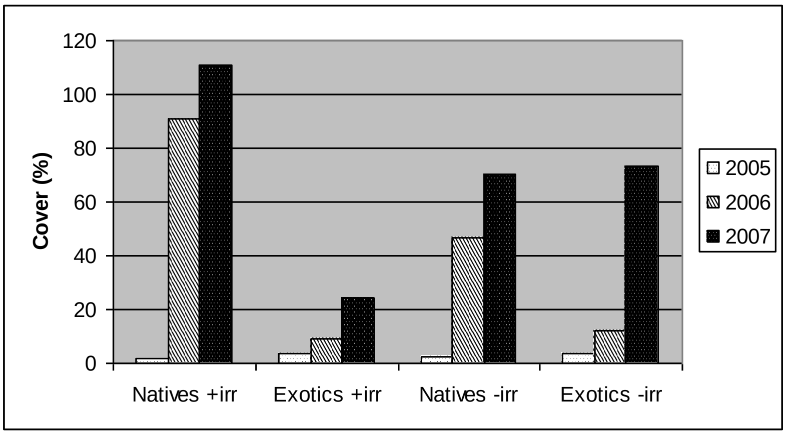


Figure 9. Comparison of cover of natives and exotics in irrigated and non-irrigated plots over 3 monitoring years at Pinjarra.

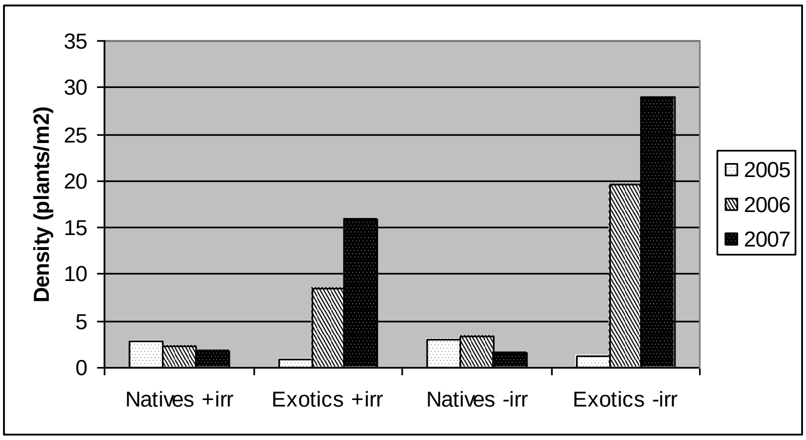


Figure 10. Comparison of density of natives and exotics in irrigated and non-irrigated plots over 3 monitoring years at Pinjarra

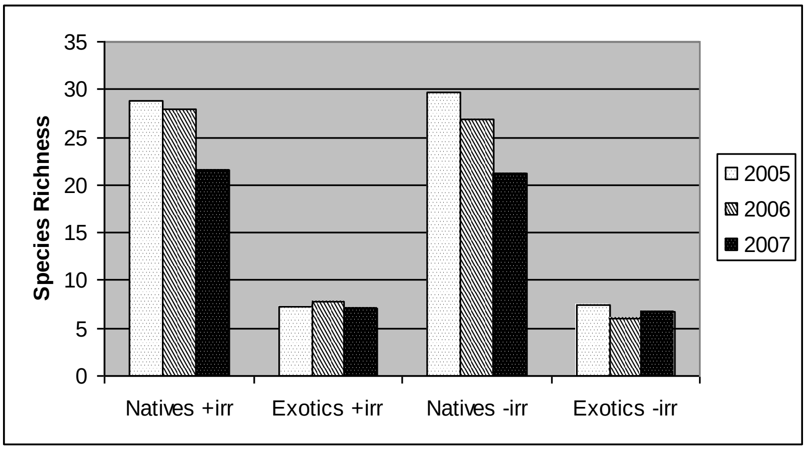


Figure 11. Comparison of species richness of natives and exotics in irrigated and non-irrigated plots over 3 monitoring years at Pinjarra

Figure 12. Rehabilitation in Block 1 at Pinjarra with few exotics

Figure 13. Rehabilitation in Block 3 at Pinjarra showing a groundcover of exotic species including *Medicago polymorpha* and *Lupinus cosentinii*

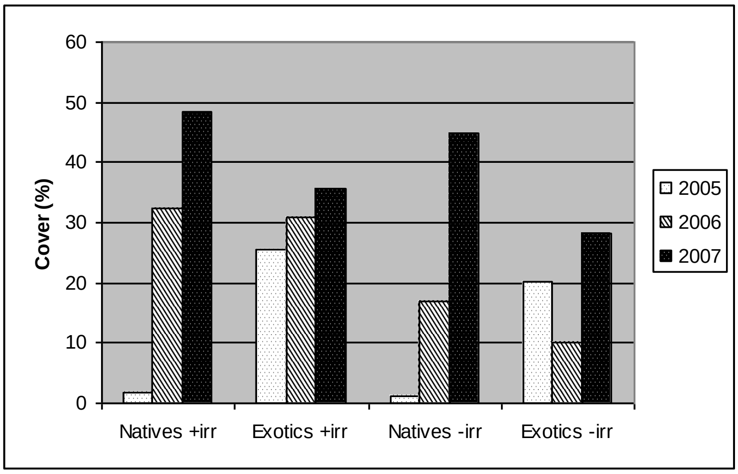


Figure 14. Comparison of cover of natives and exotics in irrigated and non-irrigated plots over 3 monitoring years at Kwinana

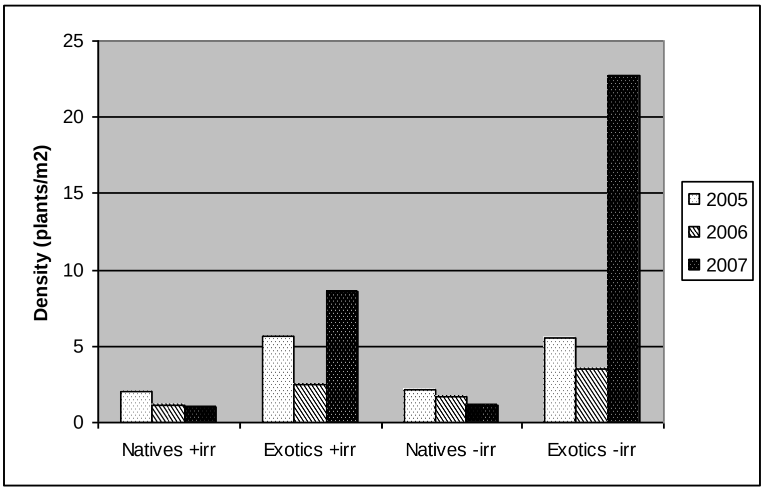


Figure 15. Comparison of density of natives and exotics in irrigated and non-irrigated plots over 3 monitoring years at Kwinana

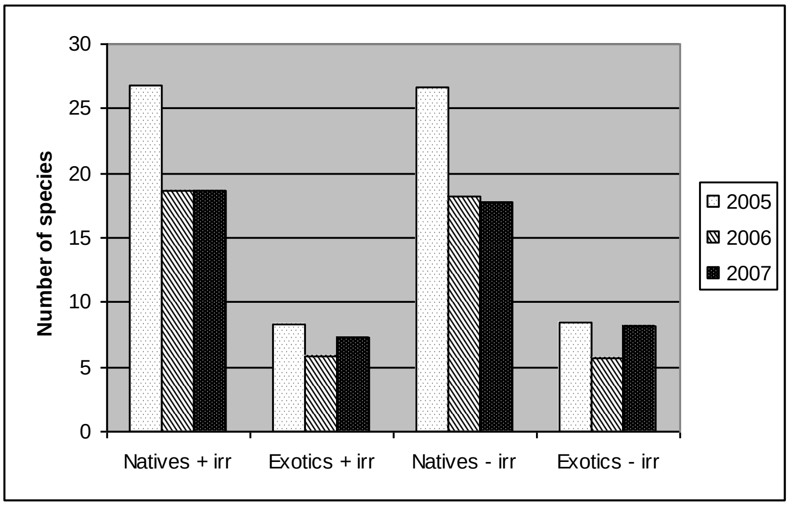


Figure 16. Comparison of species richness of natives and exotics in irrigated and non-irrigated plots over 3 monitoring years at Kwinana

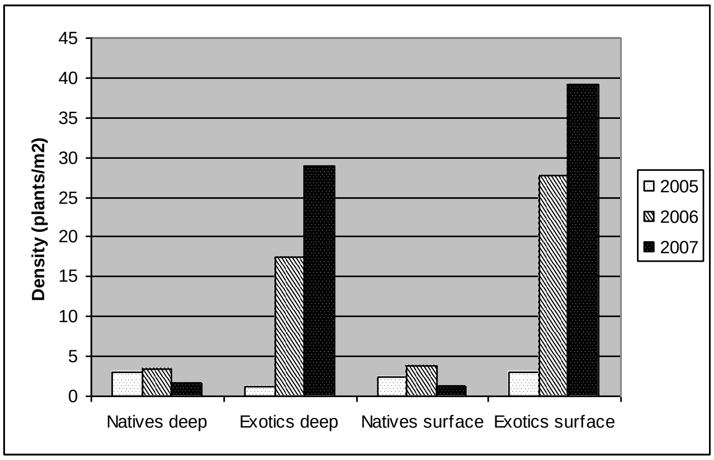


Figure 17. Comparison of density of natives and exotics in surface and deep gypsum plots over 3 monitoring years at Pinjarra

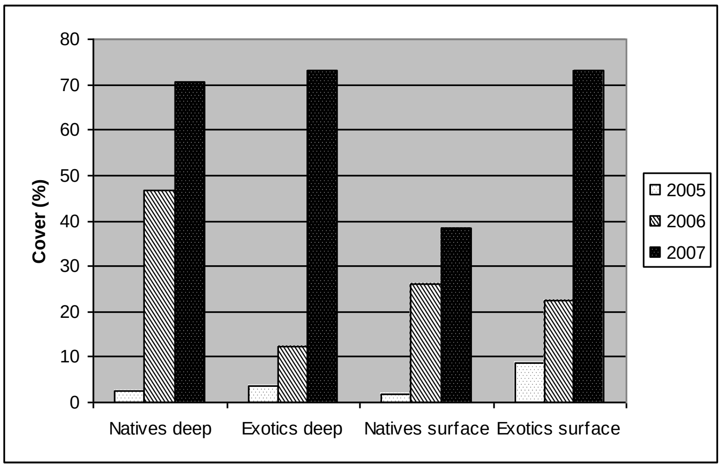


Figure 18. Comparison of cover of natives and exotics in surface and deep gypsum plots over 3 monitoring years at Pinjarra

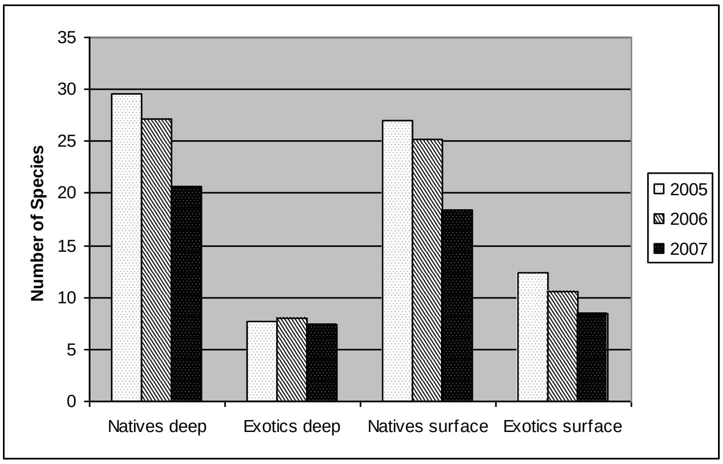


Figure 19. Comparison of species richness of natives and exotics in surface and deep gypsum plots over 3 monitoring years at Pinjarra

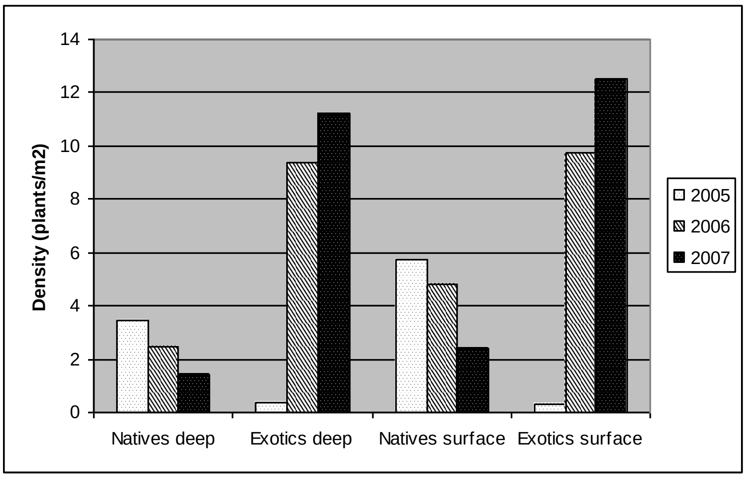


Figure 20. Comparison of density of natives and exotics in surface and deep gypsum plots over 3 monitoring years at Kwinana

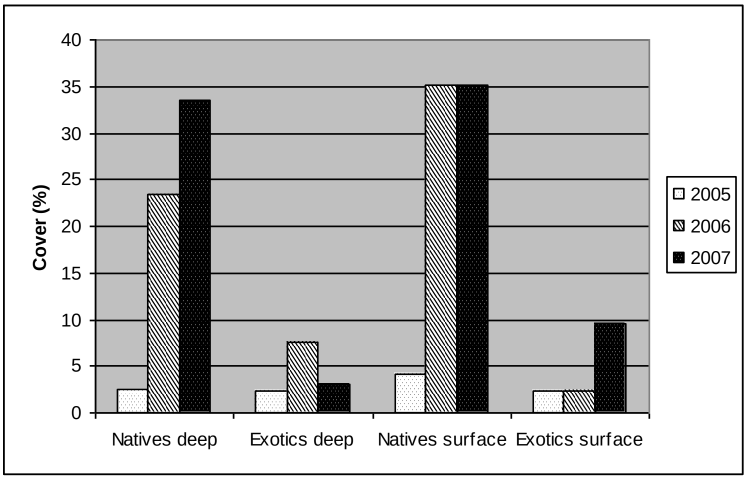


Figure 23. Comparison of cover of natives and exotics in surface and deep gypsum plots over 3 monitoring years at Kwinana

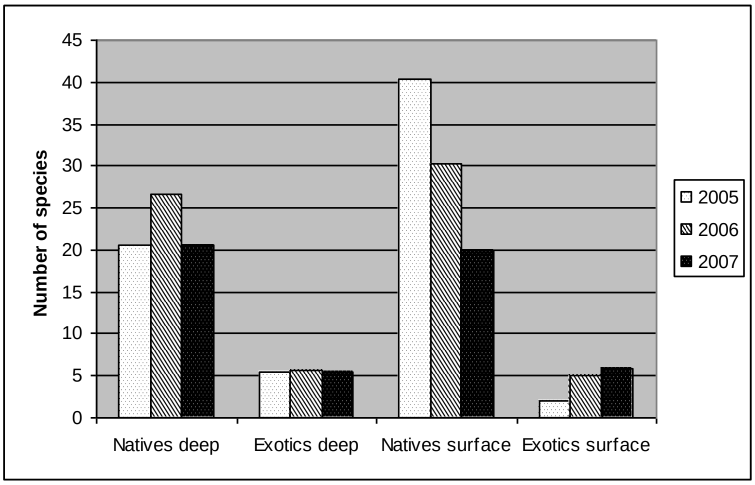


Figure 24. Comparison of species richness of natives and exotics in surface and deep gypsum plots over 3 monitoring years at Kwinana

Appendix 1. Chemical composition of di-ammonium phosphate (DAP) fertiliser and tablets

Chemical Composition of DAP Fertiliser

Component	Rate	Active Element Rate
DAP	1500kg/ha	P = 300kg/ha N = 265kg/ha
K_2S0_4 (granulated)		K= 300kg/ha
$CuS0_4$		Cu = 10kg/ha
$ZnS0_4$ (Granulated)		Zn = 16kg/ha
$MgS0_4$		Mg = 30kg/ha
$MnS0_4$ (granulated)		Mn = 15kg/ha
NaMo		Mo = 0.25kg/ha
Boron (Granulated)		B = 1.5kg/ha

Chemical Composition of DAP Tablet (50 g)	Concentration
Total Nitrogen (N)	14.4%
Total Phosphorous (P)	16.0%
Total Potassium (K)	6.3%
Sulphur (S)	1.1%
Calcium (Ca)	0.01%
Chloride (Cl)	5.7%
Iron (Fe)	0.01%
Manganese (Mn)	1.3%
Copper (Cu)	0.64%
Zinc (Zn)	0.34%

Appendix 2a. Summary of species used, whether they were planted and/or seeded and the quantity of seeds or planted seedlings used

Species	Spp code	Planted/seeded		Seeds used (g/ha)	Planted (/ha)			
					Pinjarra block 1	Pinjarra block 2&3	Kwinana Gypsum	Kwinana Irrigation
Acacia cochlearis	ACACOC	P	S	7.6	14	14	14	14
Acacia Cyclops	ACACYC	P	S	35.3	39	39	39	39
Acacia huegelii	ACAHUE	P	S	5.0	48	48	48	42
Acacia lasiocarpa	ACALAS	P	S	28.4	236	237	236	236
Acacia pulchella	ACAPUL	P			18	18	18	18
Acacia rostellifera	ACAROS	P	S	15.1	18	18	18	18
Acacia saligna	ACASAL	P	S	1.0	18	19	18	18
Acacia truncate	ACATRU	P	S	46.0	76	77	76	76
Agonis flexuosa	AGOFLE	P	S	1.7	80	80	80	80
Allocasuarina fraseriana	ALLFRA	P			65	66	65	65
Allocasuarina humilis	ALLHUM	P			21	21	21	21
Brachyscome iberidifolia	BRAIBE		S	14.8				
Callitris preissii	CALPRE		S	51.0	8	0	8	8
Calothamnus quadrifidus	CALQUA	P	S	17.7	99	100	99	99
Carpobrotus virescens	CARVIR	P			81	56	81	81
Conospermum triplinervum	CONTRI	P			24	24	24	24
Conostylis aculeate	CONACU	P	S	17.7	148	149	148	148
Conostylis candicans	CONCAN	P	S	11.7	80	80	80	80
Daviesia divaricata	DAVDIV	P	S	127.1	26	26	26	26
Daviesia nudiflora	DAVNUD		S	2.5				
Dianella revolute	DIAREV	P			153	154	153	153
Dichopogon capillipes	DICCAP	P			15	15	15	15
Diplolaena dampiera	DIPDAM	P			15	15	15	15
Dodonaea aptera	DODAPT	P	S	45.4	16	16	16	16
Dodonaea hackettiana	DODHAC	P	S	5.0	35	35	35	35
Dryandra lindleyana	DRYLIN		S	3.1				
Dryandra sessilis	DRYSES	P	S	10.1	22	22	22	22
Eremophila glabra	EREGLA	P			93	94	93	93
Eucalyptus decipiens	EUCDEC	P	S	10.1	31	31	31	31
Eucalyptus foecunda	EUCFOE	P	S	11.4	29	29	29	29
Eucalyptus gomphocephala	EUCGOM	P	S	20.2	106	107	106	106
Gompholobium tomentosum	GOMTOM	P	S	37.3	28	28	28	28
Grevillea crithmifolia	GRECRI	P			118	118	118	118
Grevillea thelmanniana	GRETHE	P			45	45	45	45
Guichenotia ledifolia	GUILED	P			52	52	52	52
Hakea lissocarpha	HAKLIS	P	S	19.8	85	85	85	85

Species	Spp code	Planted/seeded		Seeds used (g/ha)	Planted (/ha)			
					Pinjarra block 1	Pinjarra block 2&3	Kwinana Gypsum	Kwinana Irrigation
Hakea prostrata	HAKPRO	P	S	30.3	19	19	19	19
Hakea trifurcata	HAKTRI	P	S	6.2	112	113	112	112
Hardenbergia comptoniana	HARCOM		S	201.9				
Hovea pungens	HOVPUN		S	105.9				
Isolepis nodosa	ISONOD	P	S	20.2	181	182	181	181
Jacksonia furcellata	JACFUR	P	S	22.7	24	25	24	24
Jacksonia sternbergiana	JACSTE		S	7.6				
Kennedia prostrata	KENPRO	P	S	201.6	13	0	13	0
Leucophyta brownii	LEUBRO	P			119	119	119	119
Macrozamia riedlei	MACREI		S	7600, 1250, 9660[1]				
Melaleuca acerosa	MELACE	P	S	31.1	100	100	100	100
Melaleuca huegelii	MELHUE		S	12.6				
Melaleuca lanceolata	MELLAN	P	S	0.9	67	67	67	67
Melaleuca nesophila	MELNES	P			48	48	48	48
Melaleuca viminea	MELVIM	P			73	73	73	73
Myoporum insulare	MYOINS	P			60	60	60	60
Nemcia capitatum	NEMCAP	P			43	43	43	43
Olearia axillaris	OLEAXI	P	S	25.2	74	74	74	74
Olearia rudis	OLERUD	P	S	15.5	29	25	29	29
Petrophile serruriae	PETSER		S	12.6				
Phyllanthus calycinus	PHYCAL	P	S	151.4	56	57	56	56
Pimelea ferruginea	PIMFER	P			77	78	77	77
Podotheca gnaphalioides	PODGNA		S	20.2				
Rhagodia baccata	RHABAC	P	S	35.3	92	92	92	92
Scaevola crassifolia	SCACRA	P	S	76.1	64	64	64	64
Sollya heterophylla	SOLHET	P	S	151.4	57	57	57	57
Spyridium globulosum	SPYGLO	P	S	7.7	49	49	49	49
Templetonia retusa	TEMRET	P	S	15.1	18	18	18	18
Trachymene coerulea	TRACOE		S	50.5				
Trymalium ledifolium	TRYLED		S	9.0				
Viminaria juncea	VIMJUN	P	S	7.6	19	19	19	19
Xanthorrhoea preissii	XANPRE	P	S	116.0	145	145	145	145

[1] A different quantity of *Macrozamia riedlei* seeds were planted at Pinjarra, Kwinana gypsum trial and Kwinana irrigation trial respectively.

Appendix 2b. Location and treatments applied to each botanical monitoring plot

			Treatment							
Site	**Permanent plot number**	**Location**	**Block**	**Gypsum**	**Irrigation**	**Slope**	**Easting**	**Northing**	**Peg position**	**Plot**
Pinjarra	66	RSA5	1	shallow	no	upper	397948	6388588	NW	6x6 and 20x20m
Pinjarra	67	RSA5	1	shallow	no	lower	397951	6388558	NW	6x6m
Pinjarra	68	RSA5	1	deep	yes	upper	398001	6388587	NW	6x6m
Pinjarra	69	RSA5	1	deep	yes	lower	398006	6388552	NW	6x6m
Pinjarra	70	RSA5	1	deep	yes		397996	6388580	NW	20x20m
Pinjarra	71	RSA5	1	deep	no	upper	398054	6388581	NW	6x6 and 20x20m
Pinjarra	72	RSA5	1	deep	no	lower	398051	6388559	NW	6x6m
Pinjarra	73	RSA5	1	shallow	yes	upper	398110	6388584	NW	6x6m
Pinjarra	74	RSA5	1	shallow	yes	lower	398108	6388566	NW	6x6m
Pinjarra	75	RSA5	1	shallow	yes		398101	6388583	NW	20x20m
Pinjarra	76	RSA4	2	deep	no	upper	397716	6387350	NW	6x6m
Pinjarra	77	RSA4	2	deep	no	lower	397706	6387342	NW	6x6 and 20x20m
Pinjarra	78	RSA4	2	shallow	yes	upper	397736	6387295	NW	6x6m
Pinjarra	79	RSA4	2	shallow	yes	lower	397743	6387292	NW	6x6m
Pinjarra	80	RSA4	2	shallow	yes		397724	6387315	NW	20x20m
Pinjarra	81	RSA4	2	deep	yes	upper	397756	6387257	NW	6x6m
Pinjarra	82	RSA4	2	deep	yes	lower	397743	6387255	NW	6x6m
Pinjarra	83	RSA4	2	deep	yes		397748	6387257	NW	20x20m
Pinjarra	84	RSA4	2	shallow	no	upper	397828	6387181	NW	6x6m
Pinjarra	85	RSA4	2	shallow	no	lower	397821	6387170	NW	6x6m
Pinjarra	86	RSA4	2	shallow	no		397814	6387184	NW	20x20m
Pinjarra	87	RSA4	3	deep	no	upper	397886	6387167	NW	6x6m
Pinjarra	88	RSA4	3	deep	no	lower	397874	6387146	NW	6x6m
Pinjarra	89	RSA4	3	deep	no		397872	6387154	NW	20x20m
Pinjarra	90	RSA4	3	deep	yes	upper	397927	6387137	NW	6x6 and 20x20m
Pinjarra	91	RSA4	3	deep	yes	lower	397933	6387133	NW	6x6m
Pinjarra	92	RSA4	3	shallow	yes	upper	397987	6387156	NW	6x6m
Pinjarra	93	RSA4	3	shallow	yes	lower	397981	6387138	NW	6x6m
Pinjarra	94	RSA4	3	shallow	yes		397973	6387153	NW	20x20m
Pinjarra	95	RSA4	3	shallow	no	upper	398144	6387154	NW	6x6 and 20x20m
Pinjarra	96	RSA4	3	shallow	no	lower	398158	6387141	NW	6x6m
Kwinana	97	RSAF4/5	na	deep	no	upper	389486	6435783	NW	6x6m
Kwinana	98	RSAF4/5	na	deep	no	lower	389498	6435765	NW	6x6m
Kwinana	99	RSAF4/5	na	deep	no		389506	6435758	A	10x40m
Kwinana	100	RSAF4/5	na	deep	no	upper	389497	6435794	NW	6x6m

			Treatment							
Site	**Permanent plot number**	**Location**	**Block**	**Gypsum**	**Irrigation**	**Slope**	**Easting**	**Northing**	**Peg position**	**Plot**
Kwinana	101	RSAF4/5	na	deep	no	lower	389510	6435783	NW	6x6m
Kwinana	102	RSAF4/5	na	deep	no		389516	6435773	A	10x40m
Kwinana	103	RSAF4/5	na	shallow	no	upper	389510	6435826	NW	6x6m
Kwinana	104	RSAF4/5	na	shallow	no	lower	389517	6435799	NW	6x6m
Kwinana	105	RSAF4/5	na	shallow	no		389527	6435802	A	10x40m
Kwinana	106	RSAF4/5	na	shallow	no	upper	389519	6435825	NW	6x6m
Kwinana	107	RSAF4/5	na	shallow	no	lower	389532	6435816	NW	6x6m
Kwinana	108	RSAF4/5	na	shallow	no		389545	6435798	A	10x40m
Kwinana	109	RSAF4/5	na	shallow	no	upper	389529	6435840	NW	6x6m
Kwinana	110	RSAF4/5	na	shallow	no	lower	389546	6435831	NW	6x6m
Kwinana	111	RSAF4/5	na	shallow	no		389550	6435818	A	10x40m
Kwinana	112	RSAF4/5	na	deep	no	upper	389546	6435858	NW	6x6m
Kwinana	113	RSAF4/5	na	deep	no	lower	389554	6435849	NW	6x6m
Kwinana	114	RSAF4/5	na	deep	no		389564	6435837	A	10x40m
Kwinana	115	RSAF3	1	deep	no	na	390035	6436313	NW	6x6m
Kwinana	116	RSAF3	1	deep	no	na	390050	6436345	NW	6x6m
Kwinana	117	RSAF3	1	deep	yes	na	390015	6436323	B	10x40m
Kwinana	118	RSAF3	1	deep	yes	na	390081	6436381	NW	6x6m
Kwinana	119	RSAF3	1	deep	yes	na	390091	6436403	NW	6x6m
Kwinana	120	RSAF3	1	deep	yes	na	390076	6436377	B	10x40m
Kwinana	121	RSAF3	2	deep	yes	na	390119	6436435	NW	6x6m
Kwinana	122	RSAF3	2	deep	yes	na	390132	6436452	NW	6x6m
Kwinana	123	RSAF3	2	deep	yes	na	390106	6436422	B	10x40m
Kwinana	124	RSAF3	2	deep	no	na	390161	6436489	NW	6x6m
Kwinana	125	RSAF3	2	deep	no	na	390180	6436511	NW	6x6m
Kwinana	126	RSAF3	2	deep	no	na	390148	6436481	B	10x40m
Kwinana	127	RSAF3	3	deep	yes	na	390205	6436547	NW	6x6m
Kwinana	128	RSAF3	3	deep	yes	na	390213	6436554	NW	6x6m
Kwinana	129	RSAF3	3	deep	yes	na	390189	6436527	B	10x40m
Kwinana	130	RSAF3	3	deep	no	na	390247	6436599	NW	6x6m
Kwinana	131	RSAF3	3	deep	no	na	390247	6436615	NW	6x6m
Kwinana	132	RSAF3	3	deep	no	na	390228	6436592	B	10x40m

Appendix 3. Chemical properties of residue sand pre- and post- gypsum incorporation for the Pinjarra site

Pre-Gypsum Incorporation

Treatment	**Depth**	**NO_3**	**NH_4**	**Bicarb-P**	**Bicarb-K**	**Avail-S**	**Org C**	**Ox-Fe**	**EC**	**pH**	**pH**	**Ex Ca**	**Ex Mg**	**Ex Na**	**Ex K**	**ECEC**	**ESP**
	(mm)	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(%)**	**(mg/kg)**	**(mS/m)**	**($CaCl_2$)**	**(H_2O)**	**(cmol/kg)**	**(cmol/kg)**	**(cmol/kg)**	**(cmol/kg)**	**(cmol/kg)**	**(%)**
No irrig + Deep gyp	100	4.67	1.00	92.00	110.33	169.43	0.44	2574	26	7.63	8.23	4.87	0.16	0.17	0.21	5.41	3
No irrig + Deep gyp	300	2.00	1.00	10.00	57.33	9.97	0.15	3813	7	8.07	8.93	4.53	0.07	0.14	0.12	4.86	3
No irrig + Deep gyp	500	1.33	1.00	3.33	44.67	5.97	0.12	3373	7	8.10	9.07	4.32	0.05	0.24	0.09	4.70	5
No irrig + Deep gyp	700	1.33	1.00	3.67	33.67	6.50	0.11	3723	7	8.27	9.23	4.17	0.06	0.36	0.08	4.67	7
No irrig + Deep gyp	900	1.33	1.00	4.33	25.00	9.73	0.13	3354	8	8.30	9.30	4.17	0.06	0.51	0.05	4.78	10
No irrig + Deep gyp	1100	1.33	1.00	4.00	16.67	13.27	0.17	3484	9	8.33	9.27	4.02	0.07	0.64	0.04	4.76	13
No irrig + Deep gyp	1300	1.33	1.00	5.00	15.00	13.63	0.12	3948	10	8.30	9.23	3.74	0.07	0.62	0.03	4.46	13
No irrig + Deep gyp	1500	2.00	1.00	4.67	22.67	10.10	0.21	3913	12	8.33	9.23	4.97	0.27	0.74	0.03	6.01	13
Plus irrig + Deep gyp	100	7.00	1.00	138.50	103.00	31.75	0.67	2211	10	7.50	8.10	5.05	0.49	0.15	0.20	5.88	3
Plus irrig + Deep gyp	300	1.50	1.00	31.50	102.00	4.30	0.14	3740	7	8.15	8.85	3.73	0.11	0.07	0.19	4.09	2
Plus irrig + Deep gyp	500	1.50	1.00	9.00	110.50	4.15	0.11	4325	7	8.10	9.00	4.32	0.07	0.12	0.20	4.71	2
Plus irrig + Deep gyp	700	1.50	1.00	9.00	87.50	2.80	0.10	3618	6	8.20	9.10	3.97	0.06	0.17	0.17	4.36	4
Plus irrig + Deep gyp	900	1.50	1.00	6.50	85.00	4.15	0.09	3372	8	8.25	9.20	3.84	0.07	0.38	0.13	4.42	8
Plus irrig + Deep gyp	1100	1.50	1.00	8.50	36.00	3.65	0.13	3086	8	8.25	9.15	3.87	0.08	0.58	0.08	4.61	12
Plus irrig + Deep gyp	1300	1.50	1.00	5.00	15.00	4.20	0.09	2594	8	8.30	9.25	3.91	0.11	0.61	0.02	4.65	13
Plus irrig + Deep gyp	1500	1.50	1.00	6.50	15.00	3.80	0.12	3048	8	8.30	9.35	3.78	0.10	0.60	0.03	4.50	13
No irrig + Shallow gyp	100	6.33	1.00	111.00	98.33	601.80	0.62	2277	57	7.30	7.77	5.52	0.20	0.10	0.17	5.99	2

No irrig + Shallow gyp	300	1.33	1.00	8.33	46.67	35.53	0.13	2998	12	8.03	8.87	4.65	0.06	0.21	0.11	5.02	4
No irrig + Shallow gyp	500	1.33	1.00	7.00	85.33	12.40	0.13	3337	8	8.00	8.97	4.71	0.07	0.11	0.15	5.04	2
No irrig + Shallow gyp	700	1.33	1.00	10.67	70.67	9.57	0.17	3482	7	8.10	9.03	4.26	0.08	0.09	0.13	4.57	2
No irrig + Shallow gyp	900	1.33	1.00	5.33	31.67	10.13	0.12	3728	8	8.23	9.20	4.05	0.06	0.38	0.07	4.56	8
No irrig + Shallow gyp	1100	1.33	1.00	4.67	20.67	8.63	0.12	4227	9	8.27	9.20	4.12	0.07	0.51	0.04	4.74	10
No irrig + Shallow gyp	1300	1.33	1.00	6.33	15.00	34.70	0.16	4203	11	8.30	9.20	4.10	0.08	0.58	0.03	4.78	11
No irrig + Shallow gyp	1500	1.33	1.00	6.33	15.00	9.07	0.12	4310	9	8.30	9.23	4.10	0.11	0.61	0.02	4.85	12
Plus irrig + Shallow gyp	100	6.33	1.00	93.00	91.33	63.97	0.57	3045	17	7.63	8.23	4.95	0.18	0.10	0.19	5.42	2
Plus irrig + Shallow gyp	300	1.33	1.00	13.67	60.33	15.93	0.16	3850	8	8.03	8.97	4.70	0.07	0.07	0.11	4.95	1
Plus irrig + Shallow gyp	500	1.33	1.00	4.00	68.00	15.97	0.11	3530	7	8.10	9.07	4.25	0.05	0.12	0.13	4.55	3
Plus irrig + Shallow gyp	700	1.33	1.00	4.33	36.67	8.23	0.12	2759	6	8.30	9.27	4.22	0.06	0.26	0.08	4.62	6
Plus irrig + Shallow gyp	900	1.33	1.00	4.67	26.33	5.23	0.12	3789	7	8.33	9.30	4.14	0.06	0.45	0.05	4.69	9
Plus irrig + Shallow gyp	1100	1.33	1.00	4.33	23.33	9.67	0.13	3599	8	8.43	9.50	4.13	0.06	0.58	0.04	4.82	12
Plus irrig + Shallow gyp	1300	1.67	1.00	4.00	15.67	9.27	0.12	3873	10	8.33	9.37	3.99	0.08	0.71	0.03	4.81	15
Plus irrig + Shallow gyp	1500	1.33	1.00	6.33	15.00	6.30	0.20	3242	10	8.37	9.47	3.93	0.18	0.80	0.02	4.93	16

Post-Gypsum Incorporation

Treatment	Depth	NO_3	NH_4	Bicarb-P	Bicarb-K	Avail-S	Org C	Ox-Fe	EC	pH	pH	Ex Ca	Ex Mg	Ex Na	Ex K
	(cm)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(%)	(mg/kg)	(mS/m)	$(CaCl_2)$	(H_2O)	(cmol/kg)	(cmol/kg)	(cmol/kg)	(cmol/kg)
No irrig + Deep gyp	5	1.00	1.00	85.67	77.17	444.7	0.19	911	49	7.57	7.95	4.80	0.19	0.12	0.15
No irrig + Deep gyp	60	1.67	1.00	19.00	51.17	929.2	0.20	945	82	7.63	7.98	5.61	0.19	0.18	0.10
No irrig + Deep gyp	140	4.50	1.00	25.33	39.17	1007.5	0.23	887	93	7.75	8.20	5.99	0.23	0.64	0.09
Plus irrig + Deep gyp	5	1.33	1.00	53.83	66.67	244.5	0.18	1020	28	7.55	8.03	4.54	0.18	0.12	0.16
Plus irrig + Deep gyp	60	1.50	1.00	8.17	47.17	411.8	0.14	1061	43	7.72	8.13	4.63	0.14	0.20	0.10
Plus irrig + Deep gyp	140	4.17	1.00	14.33	38.00	459.3	0.14	1111	51	7.85	8.28	5.03	0.14	0.44	0.09
No irrig + Shallow gyp	5	1.00	1.00	172.50	67.17	3042.7	0.28	760	138	7.25	7.38	10.49	0.28	0.08	0.14
No irrig + Shallow gyp	60	1.17	1.00	6.67	64.00	199.6	0.11	1161	26	7.63	8.28	4.63	0.10	0.30	0.13
No irrig + Shallow gyp	140	1.83	1.00	11.67	26.17	233.0	0.11	1173	32	7.87	8.38	4.43	0.11	0.82	0.06
Plus irrig + Shallow gyp	5	1.17	1.00	79.17	71.33	2892.8	0.32	736	150	7.47	7.68	9.04	0.32	0.10	0.14
Plus irrig + Shallow gyp	60	1.00	1.00	3.17	85.33	160.0	0.10	1134	24	7.55	8.25	4.83	0.09	0.12	0.15
Plus irrig + Shallow gyp	140	1.83	1.00	7.58	28.17	474.1	0.10	1328	49	7.90	8.35	4.74	0.10	0.65	0.06

Appendix 4. Chemical properties of residue sand pre- and post- gypsum incorporation for the Kwinana site

Pre-Gypsum Incorporation

Treatment	**Depth**	**NO_3**	**NH_4**	**Bicarb-P**	**Bicarb-K**	**Avail-S**	**Org C**	**Ox-Fe**	**EC**	**pH**	**pH**	**Ex Ca**	**Ex Mg**	**Ex Na**	**Ex K**	**ECEC**	**ESP**
	(cm)	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(%)**	**(mg/kg)**	**(mS/m)**	**($CaCl_2$)**	**(H_2O)**	**(cmol/kg)**	**(cmol/kg)**	**(cmol/kg)**	**(cmol/kg)**	**(cmol/kg)**	**(%)**
No irrig + Deep gyp	10	2.00	1.00	56.33	42.33	826	0.41	2007	79	7.80	8.27	7.92	0.11	0.17	0.08	8.29	2
No irrig + Deep gyp	30	2.00	1.00	8.33	34.33	207	0.14	2132	37	7.87	8.60	6.68	0.08	0.14	0.08	6.98	2
No irrig + Deep gyp	50	2.00	1.00	3.00	21.67	51	0.09	2642	12	7.97	8.90	5.89	0.11	0.20	0.05	6.24	3
No irrig + Deep gyp	70	2.33	1.00	3.33	18.67	54	0.10	3370	15	8.03	9.00	6.09	0.10	0.35	0.03	6.58	5
No irrig + Deep gyp	90	2.00	1.00	4.67	17.67	107	0.14	3453	14	8.30	9.23	5.35	0.12	0.69	0.03	6.19	11
No irrig + Deep gyp	110	2.00	1.00	4.00	15.00	25	0.11	3456	14	8.27	9.40	4.96	0.09	1.02	0.01	6.09	17
No irrig + Deep gyp	130	2.00	1.00	6.67	15.00	106	0.16	3519	23	8.27	9.20	5.29	0.08	1.39	0.02	6.78	20
No irrig + Deep gyp	150	2.00	1.00	7.67	15.00	69	0.10	2925	25	8.23	9.40	5.09	0.09	1.54	0.02	6.74	23
Plus irrig + Deep gyp	10	3.67	1.00	69.33	87.67	930	0.63	1784	87	7.63	8.03	8.44	0.20	0.22	0.14	9.00	3
Plus irrig + Deep gyp	30	2.00	1.00	12.33	56.67	69	0.20	2662	22	8.07	8.90	6.91	0.17	0.71	0.11	7.90	8
Plus irrig + Deep gyp	50	2.00	1.00	6.00	37.67	52	0.15	2787	15	8.00	8.97	7.56	0.17	0.44	0.08	8.25	5
Plus irrig + Deep gyp	70	2.00	1.00	3.33	24.33	42	0.11	3259	14	8.07	8.97	6.20	0.11	0.84	0.03	7.18	11
Plus irrig + Deep gyp	90	2.00	1.00	5.33	25.67	121	0.11	3308	17	8.23	9.20	5.81	0.09	0.86	0.04	6.80	12
Plus irrig + Deep gyp	110	2.33	1.00	4.33	20.00	44	0.13	3603	16	8.23	9.30	5.49	0.09	1.06	0.03	6.67	15
Plus irrig + Deep gyp	130	2.00	1.00	5.33	17.67	84	0.10	3413	19	8.27	9.27	5.62	0.08	1.19	0.03	6.92	17
Plus irrig + Deep gyp	150	2.33	1.00	5.00	15.00	148	0.10	2871	26	8.20	9.27	5.05	0.08	1.66	0.02	6.82	24
No irrig + Shallow gyp	10	1.00	1.00	2.17	32.67	8	0.23	4004	41	8.07	9.82	2.79	0.09	3.37	0.10	6.35	51
No irrig + Shallow gyp	30	1.00	1.00	2.50	15.50	8	0.21	3933	68	8.13	10.02	2.43	0.06	4.70	0.04	7.22	64
No irrig + Shallow gyp	50	1.00	1.00	2.17	15.00	14	0.20	4440	94	8.18	10.12	2.06	0.06	6.06	0.04	8.22	74
No irrig + Shallow gyp	70	1.00	1.00	3.00	15.17	19	0.19	4069	99	8.23	10.12	2.56	0.08	6.25	0.03	8.92	70
No irrig + Shallow gyp	90	1.00	1.00	2.67	15.00	22	0.19	4236	102	8.18	10.10	2.17	0.06	6.30	0.03	8.56	73
No irrig + Shallow gyp	110	1.00	1.00	3.33	15.00	25	0.17	4098	105	8.30	10.10	2.38	0.07	6.39	0.03	8.88	72
No irrig + Shallow gyp	130	1.00	1.00	3.17	15.00	24	0.16	4002	103	8.23	10.10	2.27	0.06	6.18	0.03	8.54	72
No irrig + Shallow gyp	150	1.00	1.00	2.50	15.00	24	0.19	3917	106	8.28	10.15	2.28	0.08	6.01	0.03	8.41	71

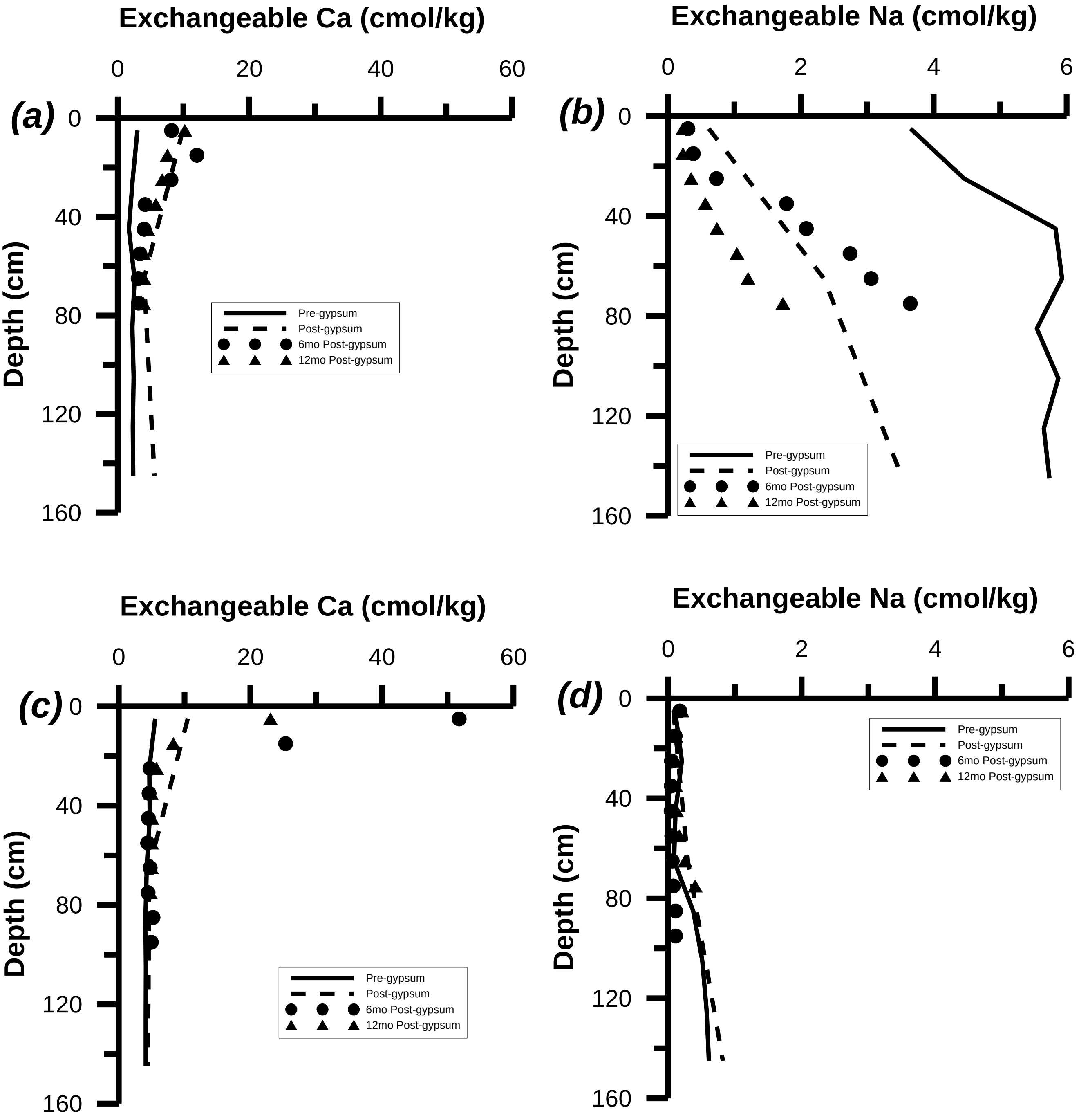
Plus irrig + Shallow gyp	10	1.00	1.00	2.17	32.67	8	0.23	4004	41	8.07	9.82	2.79	0.09	3.37	0.10	6.35	51
Plus irrig + Shallow gyp	30	1.00	1.00	2.50	15.50	8	0.21	3933	68	8.13	10.02	2.43	0.06	4.70	0.04	7.22	64
Plus irrig + Shallow gyp	50	1.00	1.00	2.17	15.00	14	0.20	4440	94	8.18	10.12	2.06	0.06	6.06	0.04	8.22	74
Plus irrig + Shallow gyp	70	1.00	1.00	3.00	15.17	19	0.19	4069	99	8.23	10.12	2.56	0.08	6.25	0.03	8.92	70
Plus irrig + Shallow gyp	90	1.00	1.00	2.67	15.00	22	0.19	4236	102	8.18	10.10	2.17	0.06	6.30	0.03	8.56	73
Plus irrig + Shallow gyp	110	1.00	1.00	3.33	15.00	25	0.17	4098	105	8.30	10.10	2.38	0.07	6.39	0.03	8.88	72
Plus irrig + Shallow gyp	130	1.00	1.00	3.17	15.00	24	0.16	4002	103	8.23	10.10	2.27	0.06	6.18	0.03	8.54	72
Plus irrig + Shallow gyp	150	1.00	1.00	2.50	15.00	24	0.19	3917	106	8.28	10.15	2.28	0.08	6.01	0.03	8.41	71

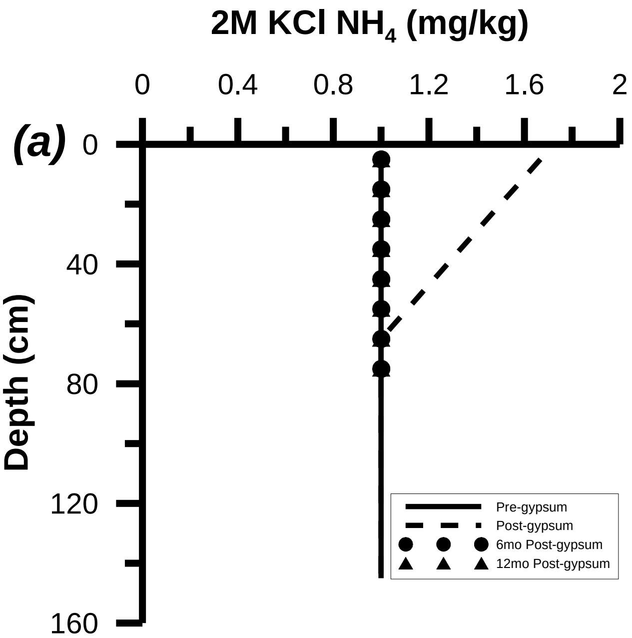
Post-Gypsum Incorporation

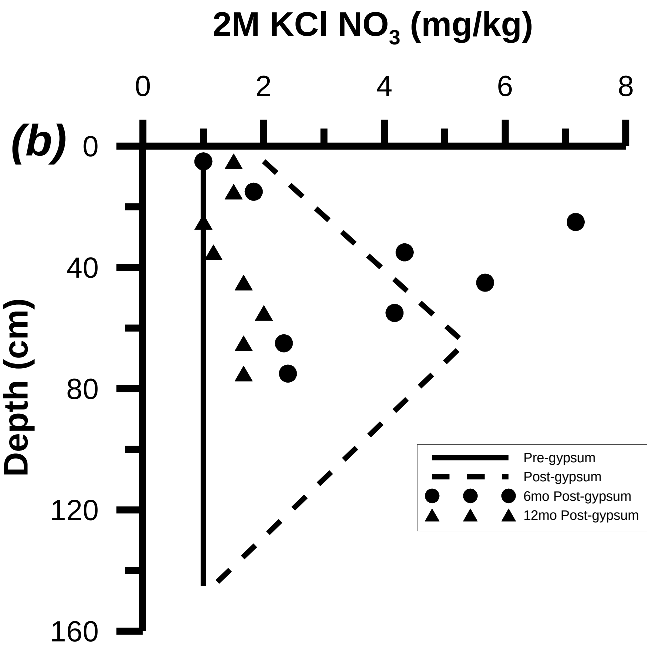
Treatment	**Depth**	**NO_3**	**NH_4**	**Bicarb-P**	**Bicarb-K**	**Avail-S**	**Org C**	**Ox-Fe**	**EC**	**pH**	**pH**	**Ex Ca**	**Ex Mg**	**Ex Na**	**Ex K**	**ECEC**	**ESP**	**Total N**	**Total P**
	(cm)	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(%)**	**(mg/kg)**	**(mS/m)**	**($CaCl_2$)**	**(H_2O)**	**(cmol/kg)**	**(cmol/kg)**	**(cmol/kg)**	**(cmol/kg)**	**(cmol/kg)**	**(%)**	**(%)**	**(mg/kg)**
No irrig + Deep gyp	5	2.33	1.17	69.92	72.50	726	0.22	2241	77	7.83	8.21	6.95	0.21	0.44	0.14	7.74	6	0.028	167
No irrig + Deep gyp	60	7.25	1.00	9.83	23.42	1490	0.14	2417	107	8.03	8.40	8.20	0.19	0.94	0.05	9.39	12	0.023	60
No irrig + Deep gyp	140	1.17	1.00	13.42	18.08	593	0.10	2354	85	8.22	8.73	6.20	0.16	1.76	0.04	8.17	22	0.028	51
Plus irrig + Deep gyp	5	1.83	1.00	60.67	82.83	2594	0.27	2103	166	7.57	7.92	10.65	0.18	0.24	0.13	11.21	2	0.023	191
Plus irrig + Deep gyp	60	10.17	1.00	13.17	32.17	1821	0.16	1875	142	7.77	8.05	9.28	0.20	0.45	0.06	10.00	5	0.020	70
Plus irrig + Deep gyp	140	1.33	1.00	15.00	33.33	1571	0.11	2183	145	8.02	8.23	8.44	0.16	1.09	0.07	9.76	11	0.022	54
No irrig + Shallow gyp	5	2.00	1.67	84.67	89.33	2965	0.37	2965	163	7.75	7.95	9.90	0.24	0.61	0.18	10.94	6	0.028	198
No irrig + Shallow gyp	60	5.33	1.00	4.83	33.33	357	0.10	2965	50	8.10	8.95	3.99	0.14	2.35	0.08	6.56	36	0.027	40
No irrig + Shallow gyp	140	1.17	1.00	15.50	19.17	594	0.11	2975	103	8.32	9.02	5.58	0.14	3.53	0.04	9.31	40	0.030	48

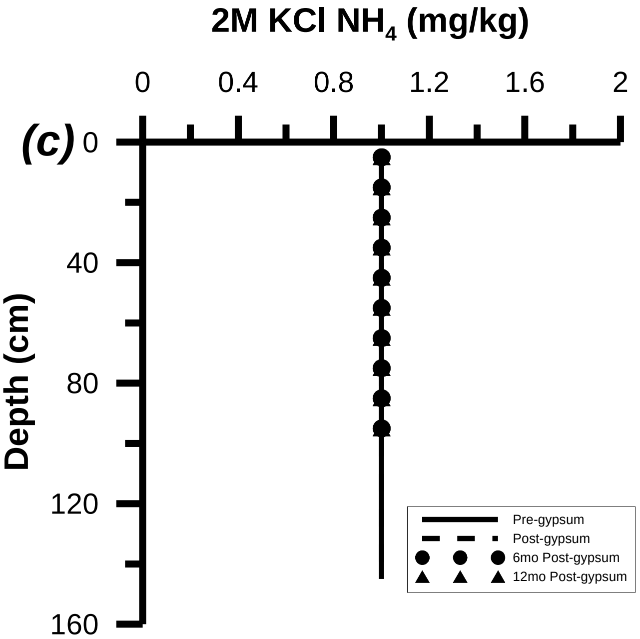
Plus irrig + Shallow gyp	5	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
Plus irrig + Shallow gyp	60	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
Plus irrig + Shallow gyp	140	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M

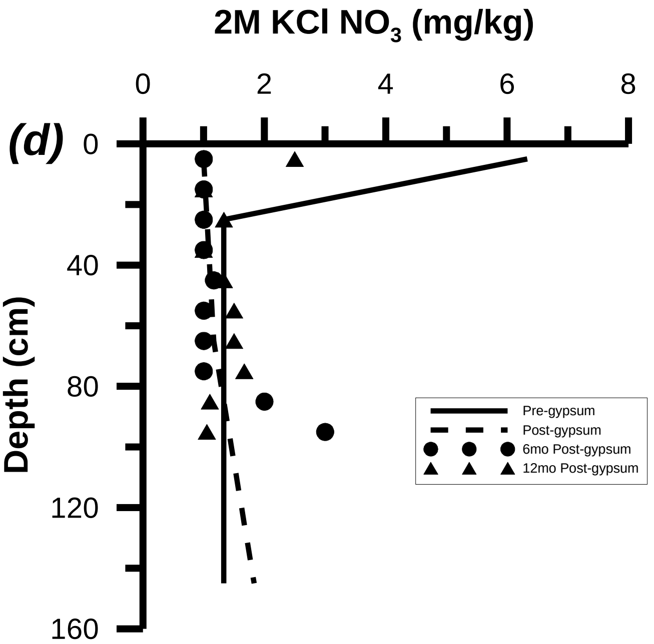
Appendix 5. Effect of time (pre- and post- (0, 6 and 12 months) after gypsum incorporation, on fertilizer and gypsum transport, and selected chemical properties. Values presented are for pre- and post- shallow gypsum incorporation, and minus irrigation. For each set of 4 graphs, (a) and (b) refer to data for the Kwinana trial, and (c) and (d) refer to data for the Pinjarra trial.

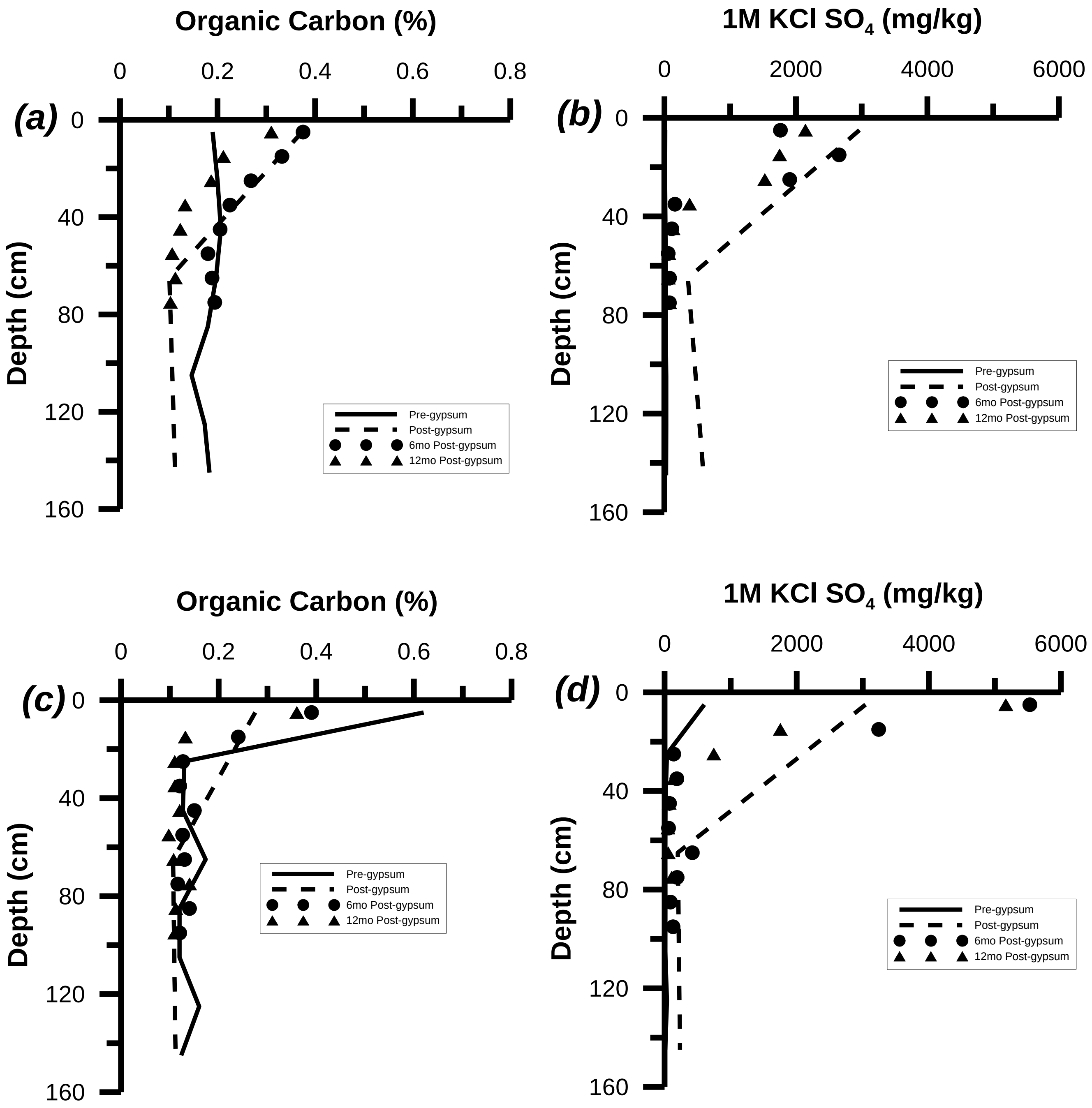


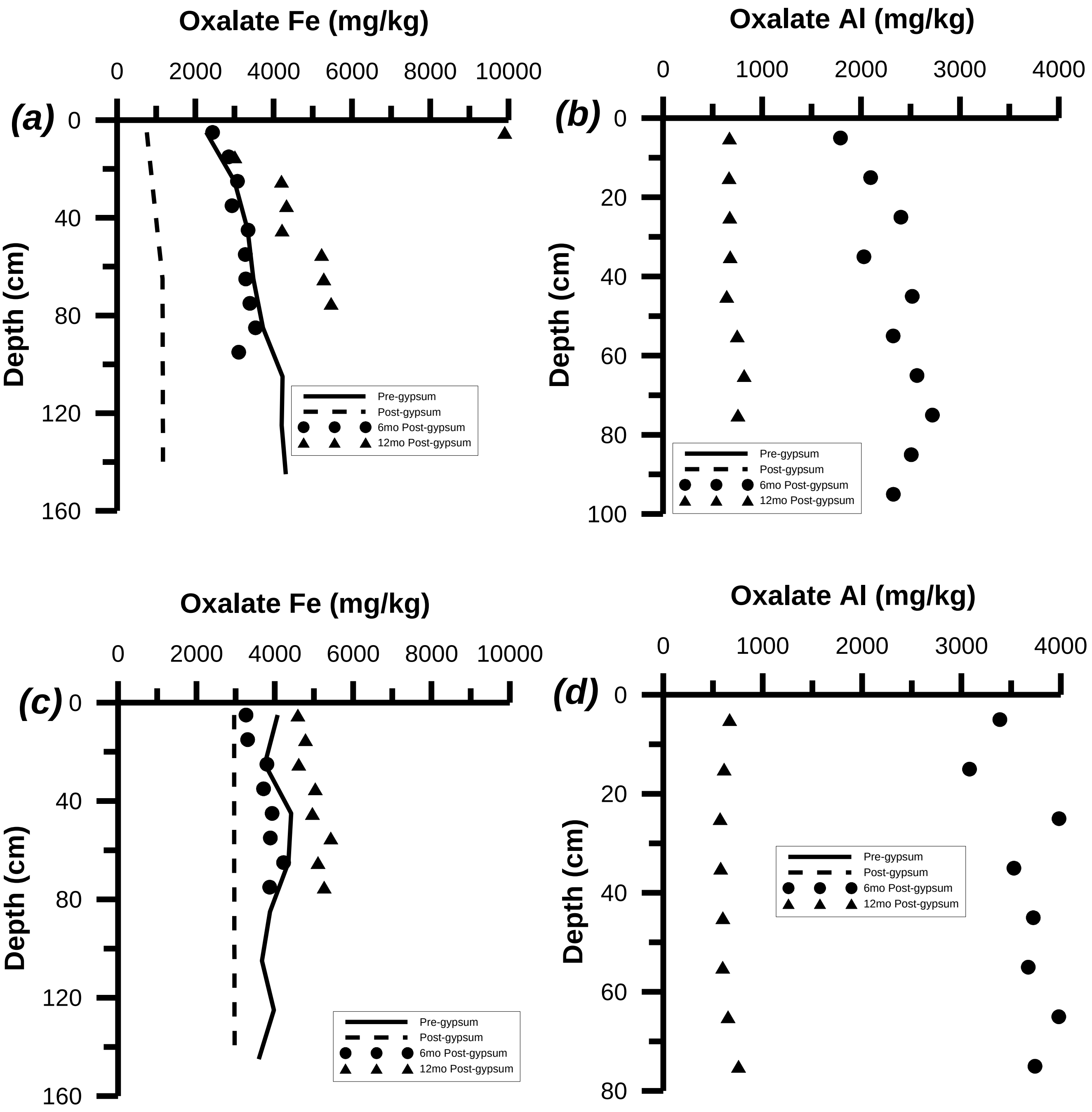

(a)
2M KCl NH4 (mg/kg)
0
0.4
0.8
1.2
1.6
2
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum

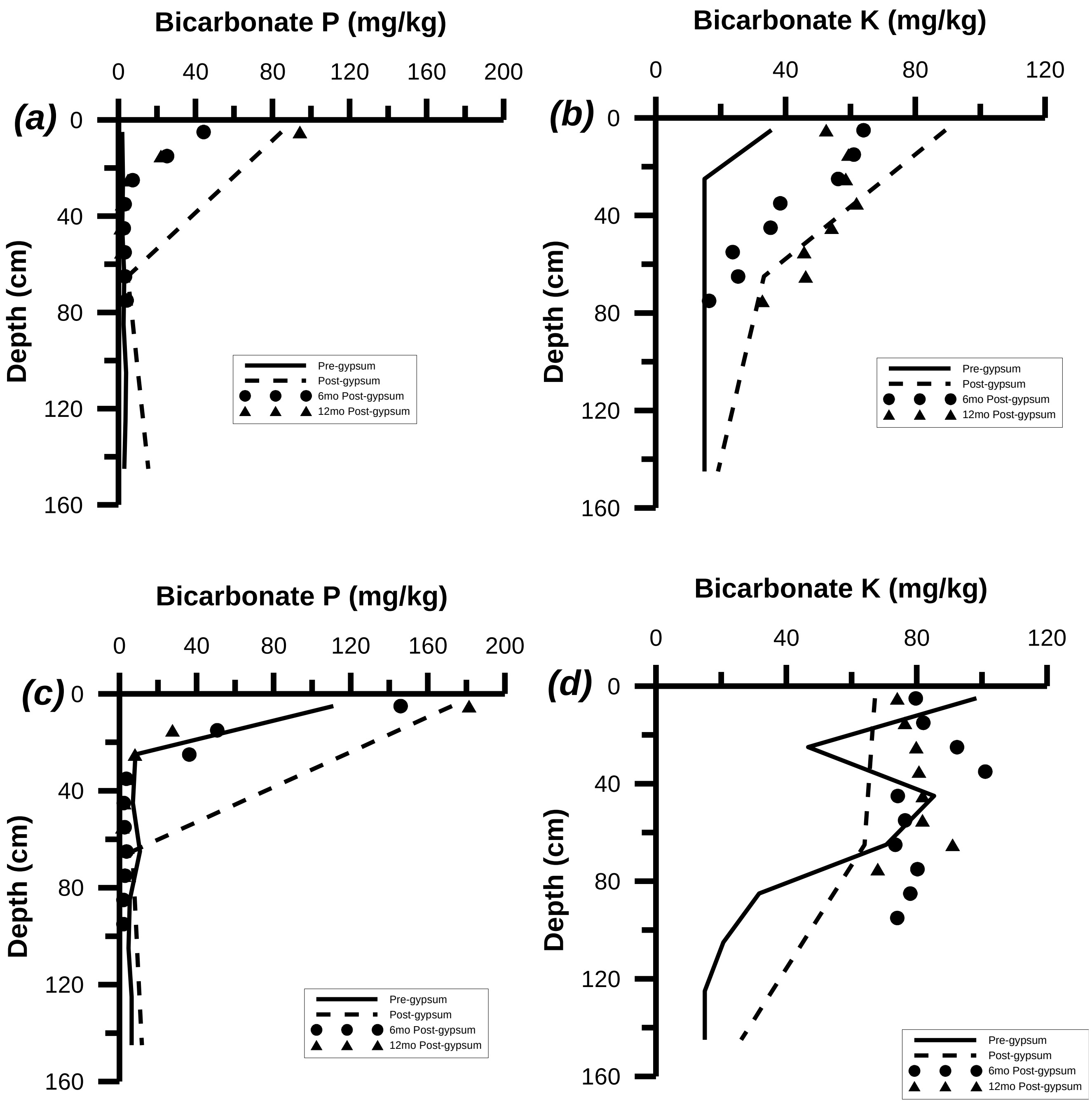

(b)
2M KCl NO3 (mg/kg)
0
2
4
6
8
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum

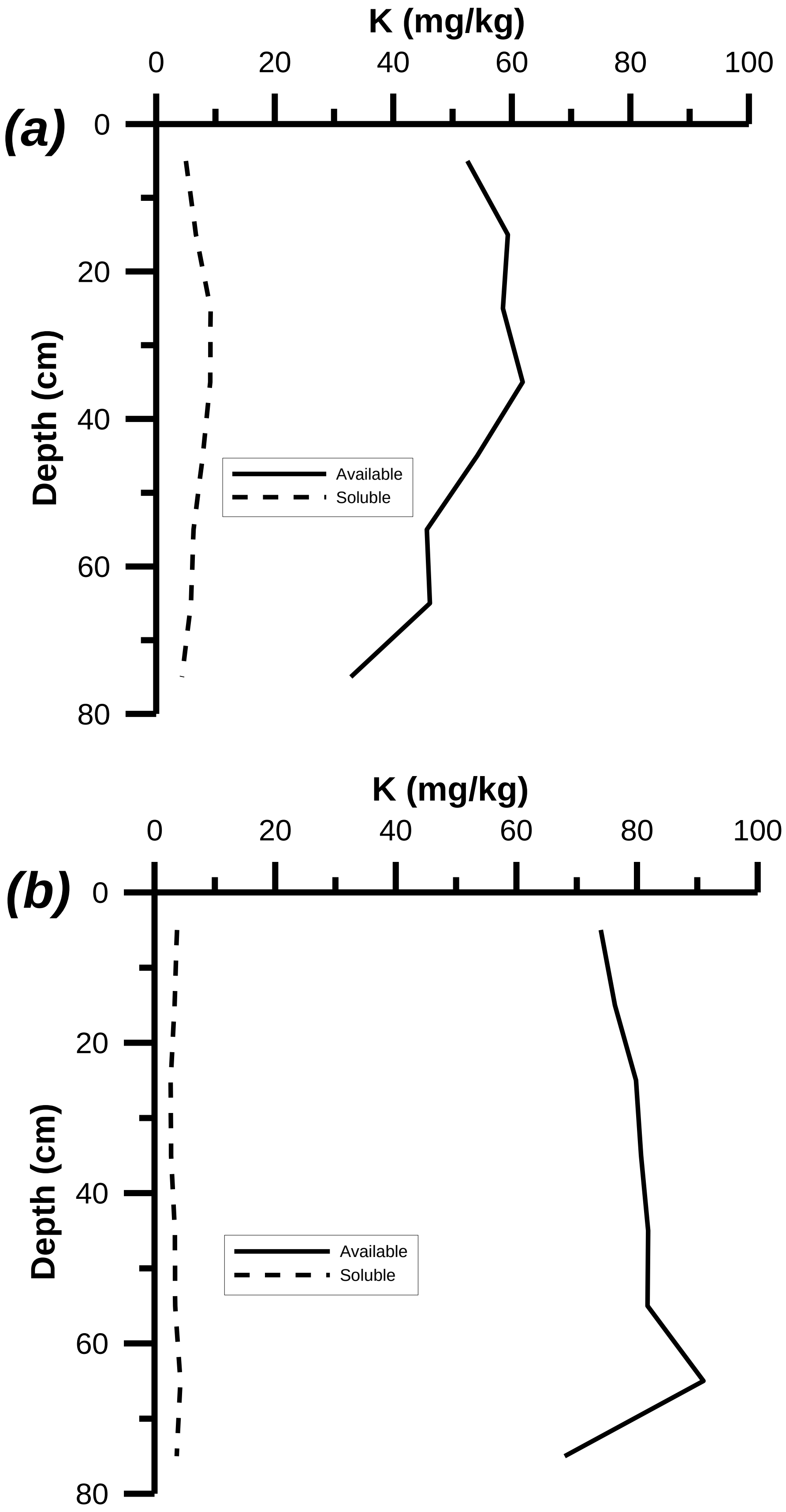

(c)
2M KCl NH4 (mg/kg)
0
0.4
0.8
1.2
1.6
2
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum

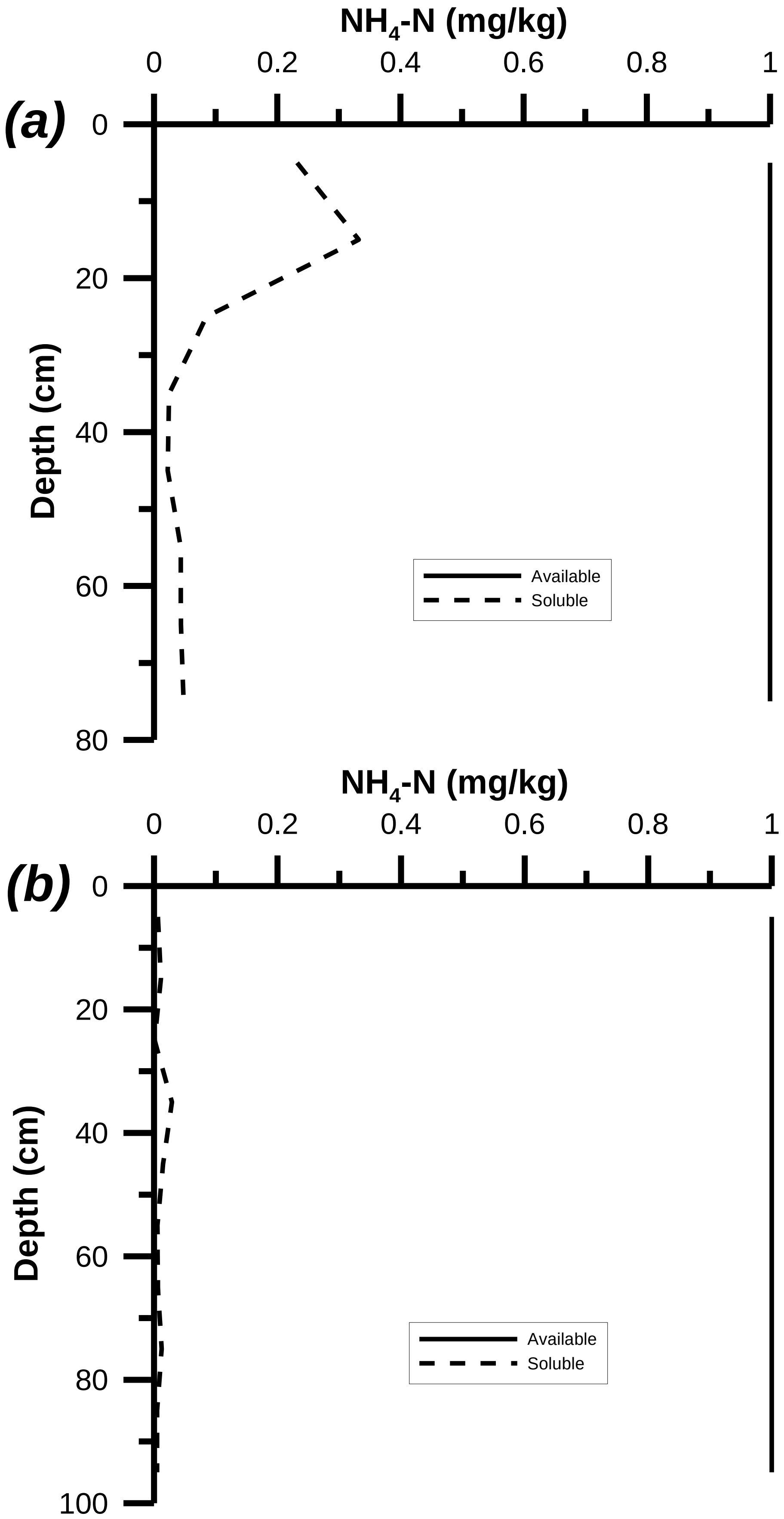

(d)
2M KCl NO3 (mg/kg)
0
2
4
6
8
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum

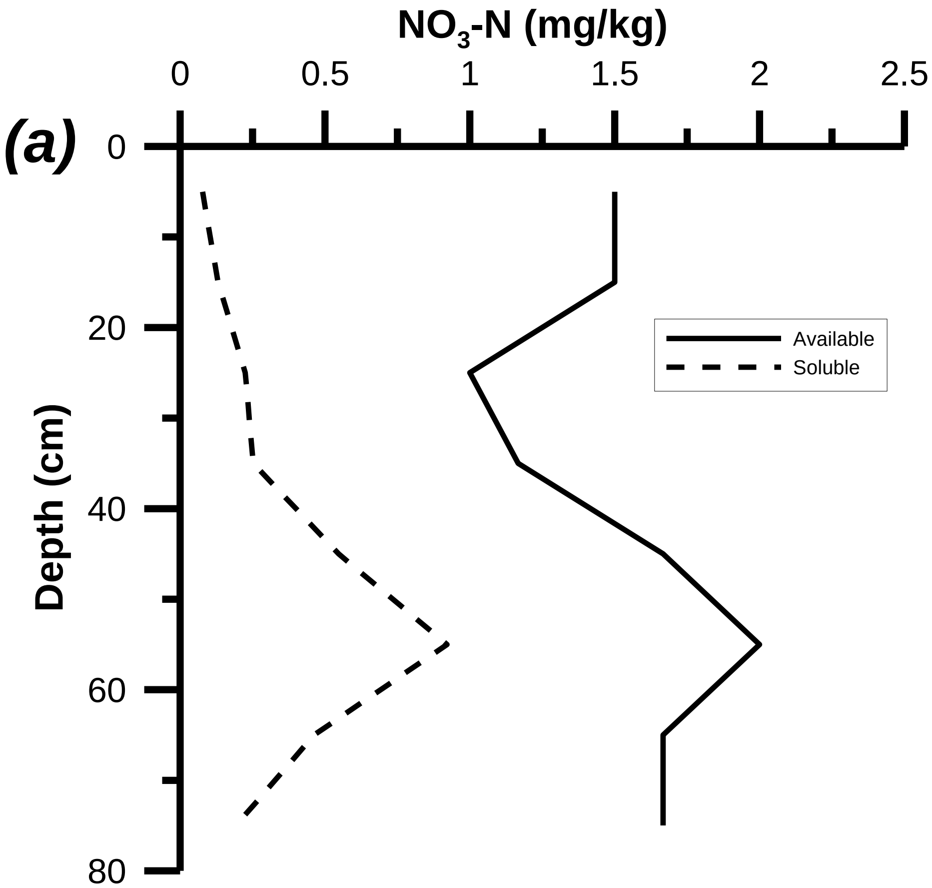

(a)
Organic Carbon (%)
0
0.2
0.4
0.6
0.8
Depth (cm)
0
40
80
120
160
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
(b)
1M KCl SO_4 (mg/kg)
0
2000
4000
6000
Depth (cm)
0
40
80
120
160
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
(c)
Organic Carbon (%)
0
0.2
0.4
0.6
0.8
Depth (cm)
0
40
80
120
160
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
(d)
1M KCl SO_4 (mg/kg)
0
2000
4000
6000
Depth (cm)
0
40
80
120
160
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum

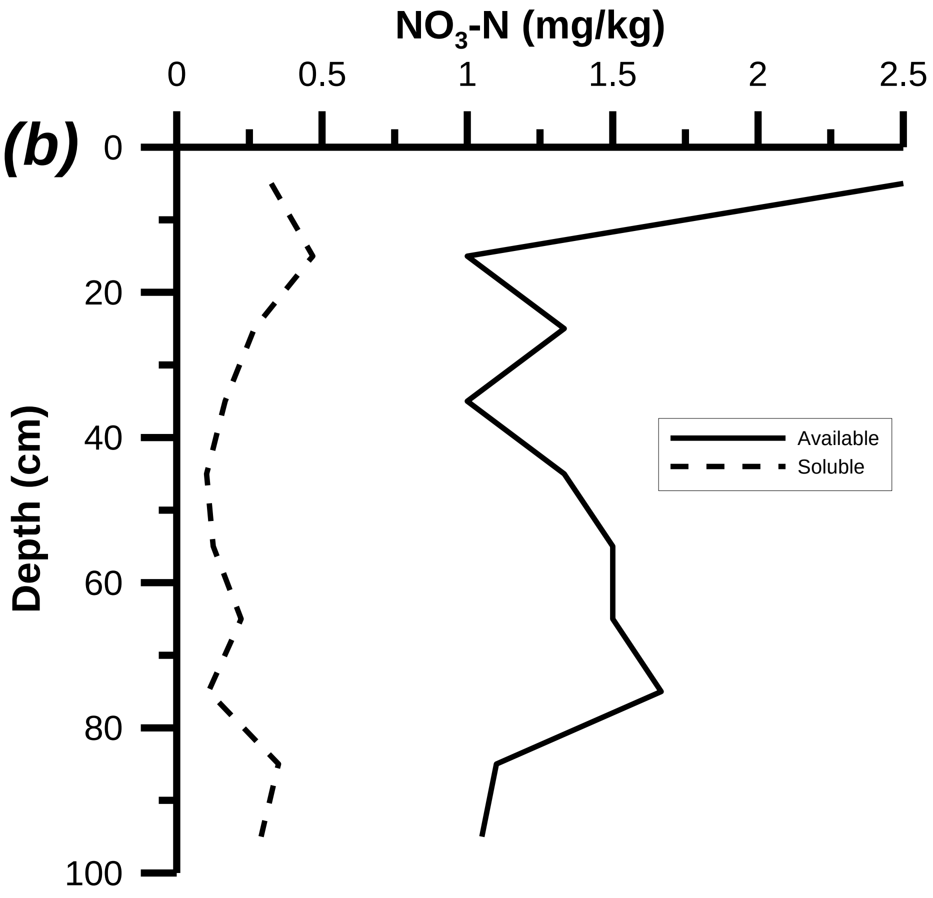

Oxalate Fe (mg/kg)
0
2000
4000
6000
8000
10000
(a)
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
Oxalate Al (mg/kg)
0
1000
2000
3000
4000
(b)
0
20
40
60
80
100
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
Oxalate Fe (mg/kg)
0
2000
4000
6000
8000
10000
(c)
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
Oxalate Al (mg/kg)
0
1000
2000
3000
4000
(d)
0
20
40
60
80
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum

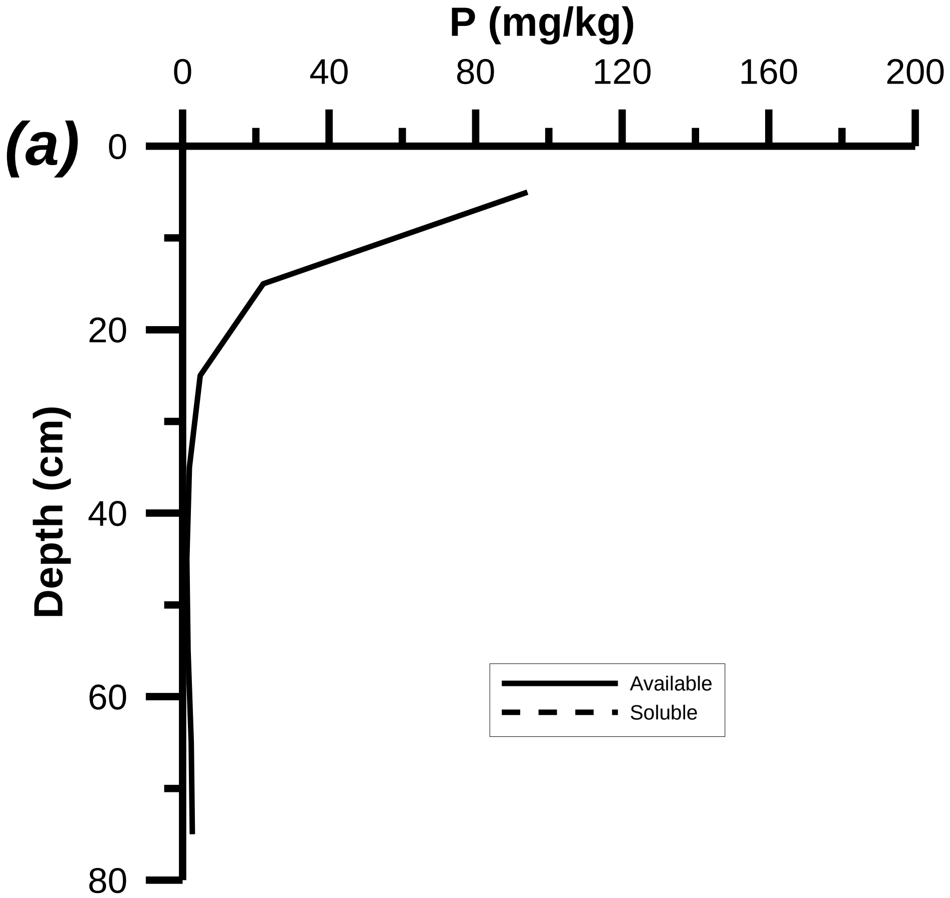

Bicarbonate P (mg/kg)
0
40
80
120
160
200
(a)
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
Bicarbonate K (mg/kg)
0
40
80
120
(b)
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
Bicarbonate P (mg/kg)
0
40
80
120
160
200
(c)
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum
Bicarbonate K (mg/kg)
0
40
80
120
(d)
0
40
80
120
160
Depth (cm)
Pre-gypsum
Post-gypsum
6mo Post-gypsum
12mo Post-gypsum

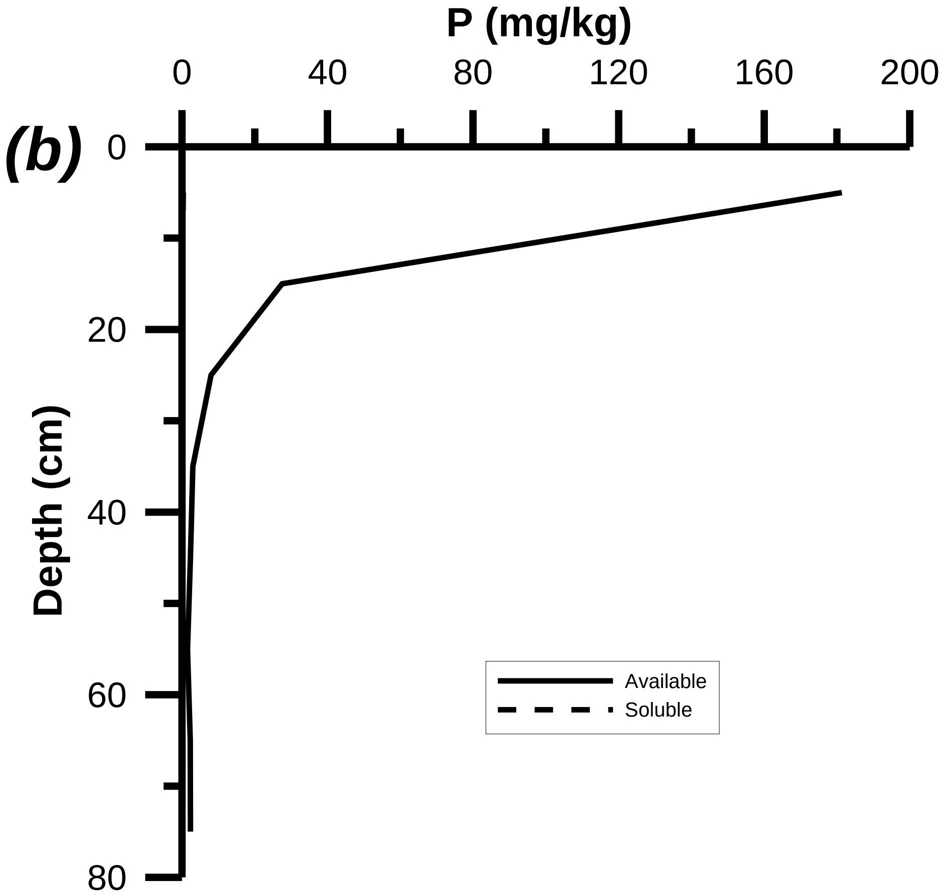

(a)
K (mg/kg)
0
20
40
60
80
100
Depth (cm)
0
20
40
60
80
Available
Soluble
(b)
K (mg/kg)
0
20
40
60
80
100
Depth (cm)
0
20
40
60
80
Available
Soluble


(a)
NH4-N (mg/kg)
0
0.2
0.4
0.6
0.8
1
Depth (cm)
0
20
40
60
80
Available
Soluble
(b)
NH4-N (mg/kg)
0
0.2
0.4
0.6
0.8
1
Depth (cm)
0
20
40
60
80
100
Available
Soluble


(a)
NO3-N (mg/kg)
0
0.5
1
1.5
2
2.5
Depth (cm)
0
20
40
60
80
Available
Soluble


(b)
NO3-N (mg/kg)
0
0.5
1
1.5
2
2.5
Depth (cm)
0
20
40
60
80
100
Available
Soluble


(a)
P (mg/kg)
0
40
80
120
160
200
0
20
40
60
80
Depth (cm)
Available
Soluble


(b)
P (mg/kg)
0
40
80
120
160
200
0
20
40
60
80
Depth (cm)
Available
Soluble

Appendix 6a. Chemical Characteristics of Natural Topsoil, and Residue Sand Before (unamended) and After (1% gypsum amended) Gypsum Addition

		Topsoil	***Unamended***	***Gypsum-amended (1% gypsum)***
Water-Soluble Fraction (Saturated paste analysis)				
Na	(mg/L)	34.04	2708	2677
Mg	(mg/L)	6.52	0.39	3.11
Al	(mg/L)	50.15	29.59	0.42
PO_4-P	(mg/L)	0.47	10.29	0.09
SO_4-S	(mg/L)	8.65	110	1804
Cl	(mg/L)	58.10	17.5	7.9
K	(mg/L)	4.96	13.1	40.6
Ca	(mg/L)	18.45	<0.01	111.9
Fe	(mg/L)	20.45	8.0	0.3
NH_4-N	(mg/L)	4.06	0.2	2.6
NO_3-N	(mg/L)	<0.01	0.6	0.7
EC	(mS/m)	4.1	11630	13730
pH		6.12	9.82	8.45
θg	(kg/kg)	0.32	0.30	0.32
HCO_3	(mg/L)	373.20	589	378
CO_3	(mg/L)	<0.01	18380	<0.01
Exchangeable or Available Fraction (after water-extraction)				
2M KCl NO_3-N	(mg/kg)	5.3	3.0	3.0
2M KCl NH_4-N	(mg/kg)	<0.01	1.0	1.0
Bicarbonate P	(mg/kg)	2.1	4.0	7.0
Bicarbonate K	(mg/kg)	37	24	36
Available S	(mg/kg)	4.67	24	634
Organic C	(%)	1.21	0.10	0.19
Amorphous-Fe	(mg/kg)	96	2350	2662
Amorphous-Al	(mg/kg)	33	871	1007
Exchangeable Ca	(cmol/kg)	3.35	3.63	5.76
Exchangeable Mg	(cmol/kg)	0.48	0.08	0.08
Exchangeable Na	(cmol/kg)	0.11	5.53	4.18
Exchangeable K	(cmol/kg)	0.04	0.06	0.09
Exchangeable Al	(cmol/kg)	0.01	0.02	0.03
Exchangeable Fe	(cmol/kg)	1.94	10.71	6.59
Total N	(%)	0.02	0.02	0.02
Total P	(mg/kg)	28.39	27	60
ECEC	(cmol/kg)	3.98	9.32	10.14

Appendix 6b. Chemical Characteristics of a 4-year old Rehabilitated Residue Sand Profile (Water-soluble and exchangeable parameters)

Exchangeable and Available Ions

Depth	1M KCl	1:5 (BRS:Water)	1:5 (BRS:Water)	1M $NH_4Cl/BaCl_2$	
	SO_4-S	EC	pH	Exch Ca	Exch Na
(cm)	(mg/kg)	(dS/m)		(cmol/kg)	(cmol/kg)
0 - 5	86	0.19	8.35	8.18	0.22
5 - 20	201	0.22	8.60	6.30	0.17
20 - 40	327	0.36	8.45	5.97	0.17
40 - 60	841	0.76	8.20	7.67	0.26
60 - 80	388	0.48	8.35	5.95	0.30
80 - 100	142	0.27	8.70	4.31	0.60
100 - 120	42	0.21	9.45	2.46	2.03
120 - 140	40	0.23	9.40	2.74	2.32
140 - 160	27	0.31	9.10	2.36	3.28
160 - 180	42	0.35	8.70	2.91	3.90
180 - 200	33	0.36	8.85	3.19	3.91
200 - 220	32	0.37	8.85	2.63	3.70
220 - 240	30	0.40	8.95	2.41	4.12
240 - 260	33	0.49	8.95	2.72	4.43
260 - 280	39	0.48	9.00	2.71	4.46
280 - 300	51	0.46	9.00	3.25	4.44

Water Soluble Ions

Depth									
	θ_g	EC	pH	Sol Ca	Sol Na	Sol SO_4-S	Sol CO_3^{2-}	Sol HCO_3^-	Sol Al
(cm)	(g/g)	(dS/m)		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
0 - 5	0.42	1.08	7.54	203	57	480	0	51	0.84
5 - 20	0.34	1.38	7.54	372	58	294	0	37	<0.01
20 - 40	0.35	1.74	7.34	491	67	379	0	26	<0.01
40 - 60	0.37	2.19	7.37	687	101	551	0	28	<0.01
60 - 80	0.37	1.95	7.31	589	115	468	0	27	<0.01
80 - 100	0.34	1.80	7.62	316	281	373	0	43	0.02
100 - 120	0.36	1.79	9.26	5	412	115	0	322	2.93
120 -	0.35	2.15	9.35	3	544	112	0	409	2.56

140									
140 - 160	0.35	2.77	9.94	3	714	54	0	627	5.77
160 - 180	0.38	3.26	9.99	2	897	77	399	0	5.96
180 - 200	0.36	3.45	10.02	2	958	69	401	0	6.38
200 - 220	0.36	3.48	10.05	1	966	75	298	0	6.48
220 - 240	0.36	3.74	10.08	1	1065	69	425	0	7.21
240 - 260	0.35	4.00	10.14	1	1163	80	473	0	5.92
260 - 280	0.35	4.34	10.14	1	1299	113	383	0	8.89
280 - 300	0.36	4.62	10.18	1	1398	136	375	0	10.20

Appendix 7. Summary of botanical monitoring undertaken from 2005 to 2007 at Kwinana and Pinjarra irrigation trials and associated ANOVA

Site	**Treatment**	**Block #**	**Year**	**Density /m2 Natives (Exotics)**	**Cover % Natives (Exotics)**	**Species Richness Natives (Exotics)**
Pinjarra	Irrigated (deep gypsum)	1	2005	1.8 (1.6)	2.2 (4.5)	27 (4.5)
			2006	1.3 (4.7)	83.5 (4.3)	26 (5.5)
			2007	1.6 (8.0)	93.9 (21.2)	22.5 (6)
		2	2005	4.1 (0.7)	1.7 (2.5)	32.5 (10)
			2006	2.8 (11.9)	112.9 (9.8)	30 (9.5)
			2007	1.7 (11.9)	146.0 (8.7)	22 (7.5)
		3	2005	2.7 (0.5)	2.3 (4.0)	27 (7)
			2006	3.0 (8.6)	76.9 (13.6)	28 (8.5)
			2007	2.1 (27.6)	93.1 (42.0)	20 (7.5)
		Average	**2005**	**2.9 (0.9)**	**2.1 (3.7)**	**28.8 (7.2)**
			2006	**2.4 (8.4)**	**91.1 (9.2)**	**28 (7.8)**
			2007	**1.8 (15.8)**	**111.0 (24.0)**	**21.5 (7)**
	Non-Irrigated (deep gypsum)	1	2005	1.8 (0.8)	2.4 (1.9)	22 (5.5)
			2006	1.4 (5.4)	44.1 (1.9)	18.5 (7)
			2007	2.3 (16.4)	76.2 (21.6)	18.5 (7)
		2	2005	2.4 (1.5)	1.7 (4.1)	31.5 (8.5)
			2006	2.2 (38.3)	42.7 (17.8)	27.5 (10)
			2007	1.0 (32.2)	54.2 (108.7)	19.5 (5.5)
		3	2005	4.8 (1.5)	3.1 (5.2)	35.5 (8.5)
			2006	6.6 (15.2)	53.0 (16.7)	34.5 (8)
			2007	1.5 (38.3)	81.0 (89.6)	25.5 (8)
		Average	**2005**	**3.0 (0.9)**	**2.4 (3.7)**	**29.7 (7.5)**
			2006	**3.4 (19.6)**	**46.6 (12.1)**	**26.8 (6)**
			2007	**1.6 (29.0)**	**70.5 (73.3)**	**21.2 (6.8)**
Kwinana	Irrigated (deep gypsum)	1	2005	3.1 (3.1)	2.6 (12.0)	28.5 (7)
			2006	1.6 (1.8)	37.1 (33.2)	24.5 (5)
			2007	1.4 (4.8)	56.9 (41.9)	21.5 (8)
		2	2005	1.4 (4.7)	1.7 (22.1)	27.5 (9)
			2006	0.8 (2.8)	29.9 (43.6)	13.5 (6.5)
			2007	0.7 (2.9)	39.4 (57.1)	15.5 (6.5)
		3	2005	1.5 (9.3)	0.7 (42.7)	24.5 (9)
			2006	1.1 (3.3)	30.6 (16.0)	18 (6)
			2007	1.0 (17.9)	49.3 (7.8)	19 (7.5)
		Average	**2005**	**2.0 (5.7)**	**1.7 (25.6)**	**26.8 (8.3)**
			2006	**1.2 (2.5)**	**32.5 (30.9)**	**18.7 (5.8)**
			2007	**1.0 (8.5)**	**48.5 (35.6)**	**18.7 (7.3)**
	Non-Irrigated (deep gypsum)	1	2005	0.8 (4.8)	1.1 (13.9)	17.5 (9.5)
			2006	1.0 (4.0)	20.8 (11.0)	11.5 (5)
			2007	0.5 (21.2)	47.0 (35.8)	12 (6)
		2	2005	2.7 (6.4)	1.5 (23.3)	32 (9)
			2006	2.6 (2.2)	20.2 (15.9)	23.5 (7.5)
			2007	1.5 (23.0)	47.6 (37.6)	22 (8.5)
		3	2005	2.9 (5.3)	0.8 (23.0)	30.5 (7)
			2006	1.6 (4.4)	9.7 (3.8)	19.5 (4.5)
			2007	1.5 (24.0)	40.0 (11.7)	19.5 (10)
		Average	**2005**	**2.1 (5.2)**	**1.1 (20.1)**	**26.7 (8.5)**
			2006	**1.7 (3.5)**	**16.9 (10.2)**	**18.2 (5.7)**
			2007	**1.2 (22.7)**	**44.9 (28.3)**	**17.8 (8.2)**

Summary of ANOVA for cover, density and species richness across variables of block, rep, irrigation prescription, site, species and age of rehab. Significance levels **p<0.001, *p<0.05.

Independent Variable	Cover	Density	Species Richness
Block (1, 2 &3)		*	*
Irrigation (irrigated & non-irrigated)		*	
Rep (1 & 2)			
Site (KW & PJ)	*	*	*
Species (Natives & Exotics)	**	**	**
Year (2005, 2006, 2007)	**	**	**

Appendix 8. Summary of botanical monitoring undertaken from 2005 to 2007 at Kwinana and Pinjarra gypsum trials and associated ANOVA

Site	**Treatment**	**Block #**	**Year**	**Density /m2 Natives (Exotics)**	**Cover % Natives (Exotics)**	**Species Richness Natives (Exotics)**
Pinjarra	Surface Gypsum (not irrigated)	1	2005	1.9 (1.0)	1.6 (3.3)	23.0 (8.0)
			2006	4.0 (8.8)	32.3 (4.0)	20.0 (9.5)
			2007	1.9 (36.4)	44.3 (24.1)	18.5 (10.5)
		2	2005	2.0 (2.6)	1.7 (9.3)	26.0 (12.5)
			2006	2.0 (28.8)	29.4 (32.0)	26.0 (9.5)
			2007	0.9 (33.8)	43.3 (100.3)	17.5 (7.5)
		3	2005	3.2 (5.4)	1.8 (13.8)	32.0 (16.5)
			2006	5.1 (45.6)	16.8 (31.5)	29.5 (12.5)
			2007	1.1 (47.1)	27.3 (94.9)	19.0 (7.5)
		Average	**2005**	**2.4 (3.0)**	**1.7 (8.8)**	**27.0 (12.3)**
			2006	**3.9 (27.7)**	**26.2 (22.5)**	**25.2 (10.5)**
			2007	**1.3 (39.1)**	**38.3 (73.1)**	**18.3 (8.5)**
	Deep Gypsum (not irrigated)	1	2005	1.8 (0.8)	2.5 (1.9)	22.0 (5.5)
			2006	1.4 (5.3)	44.1 (1.9)	19.0 (6.5)
			2007	2.2 (16.4)	76.2 (21.6)	18.5 (7.0)
		2	2005	2.4 (1.5)	1.7 (4.1)	31.0 (9.0)
			2006	2.3 (38.2)	42.7 (17.8)	27.5 (10.0)
			2007	1.0 (32.2)	54.2 (108.7)	18.5 (6.5)
		3	2005	4.8 (1.5)	3.2 (5.2)	35.5 (8.5)
			2006	6.7 (15.2)	53.0 (16.7)	35.0 (7.5)
			2007	1.5 (38.3)	81.0 (89.6)	25.0 (8.5)
		Average	**2005**	**3.0 (1.3)**	**2.5 (3.7)**	**29.5 (7.7)**
			2006	**3.5 (19.6)**	**46.6 (12.1)**	**27.2 (8.0)**
			2007	**1.6 (29.0)**	**70.5 (73.3)**	**20.7 (7.3)**
Kwinana	Surface Gypsum (not irrigated)	1	2005	7.6 (0.2)	5.0 (0.9)	40.0 (3.5)
			2006	4.4 (9.6)	37.5 (2.7)	34.5 (6.5)
			2007	2.1 (11.7)	41.0 (6.2)	21.0 (7.5)
		2	2005	5.0 (0.2)	3.7 (2.4)	42.0 (1.5)
			2006	7.3 (8.2)	30.4 (5.4)	27.0 (5.0)
			2007	3.2 (17.5)	29.7 (19.9)	19.5 (5.5)
		3	2005	4.7 (0.5)	3.7 (3.7)	39.0 (1.0)
			2006	2.6 (11.4)	37.4 (3.6)	29.5 (3.5)
			2007	1.9 (8.4)	34.4 (2.6)	19.5 (4.5)
		Average	**2005**	**5.8 (0.3)**	**4.1 (2.3)**	**40.3 (2.0)**
			2006	**4.8 (9.7)**	**35.1 (3.9)**	**30.3 (5.0)**
			2007	**2.4 (12.5)**	**35.0 (9.6)**	**20.0 (5.8)**
	Deep Gypsum (not irrigated)	1	2005	6.4 (0.2)	3.5 (2.5)	37.0 (3.5)
			2006	4.2 (4.8)	23.4 (2.6)	30.0 (7.0)
			2007	2.1 (18.9)	41.4 (4.9)	24.0 (6.5)
		2	2005	2.2 (0.1)	2.3 (1.6)	30.5 (3.0)
			2006	1.4 (6.2)	19.4 (1.7)	28.0 (5.5)
			2007	1.2 (4.1)	35.3 (0.6)	22.5 (5.5)
		3	2005	1.8 (0.7)	1.6 (3.0)	32.0 (3.0)
			2006	1.8 (17.1)	27.4 (18.4)	22.0 (4.5)
			2007	1.0 (10.7)	23.8 (3.6)	15.0 (4.5)
		Average	**2005**	**3.5 (0.3)**	**2.5 (2.4)**	**33.2 (3.2)**
			2006	**2.5 (9.4)**	**23.4 (7.6)**	**26.7 (5.7)**
			2007	**1.4 (11.2)**	**33.5 (3.0)**	**20.5 (5.5)**

Summary of ANOVA for cover, density and species richness across variables of block, rep, irrigation prescription, site, species and age of rehab. Significance levels **p<0.001, *p<0.05.

Independent Variable	**Cover**	**Density**	**Species Richness**
Block (1, 2 &3)			
Gypsum Depth (surface & deep)			
Rep (1 upper slope, 2 lower slope)			*
Site (KW & PJ)	**	**	
Species (Natives & Exotics)	*	**	**
Year (2005, 2006, 2007)	**	**	**