Effect of using reclaimed water on soil health and crop sustainability

Dr Belinda Rawnsley
South Australia Research & Development Institute (SARDI)

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Final report MT09097

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This report presents results of investigations to assess the use of reclaimed irrigation water on soil health and crop sustainability in the Northern Adelaide Plains.

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SARDI Disclaimer

HAL Disclaimer

Contents

Definition:
Reclaimed water. Water that has been derived from sewage systems of industry processes and treated to a standard that is appropriate for its intended use (EPA, Victoria 2003).

1 Media summary

The SA Water Bolivar wastewater treatment plant treats about 46,000 ML of wastewater annually to produce reclaimed water for irrigation purposes in the Northern Adelaide Plains. Water is available through the Virginia Pipeline Scheme which is the first and largest recycled water scheme in Australia serving around 250 horticultural growers.

In recent years, a combination of dry conditions and expansion of horticultural industries has increased demand of reclaimed water for crop production. Growers are concerned by water quality parameters and the potential risk of soil salinity caused by using saline irrigation water. Reclaimed water can contain high levels of salts which contribute to an already rising saline water table. Salts can reduce water availability, be toxic to the plant, reduce nutrient availability and have negative impact on soil structure. There is concern of the cumulative effect that reclaimed water can have on soil, water, crop quality and yield.

This project was established to investigate the use of reclaimed irrigation water for perennial and vegetable crops and the effect on soil health and crop sustainability. It was initiated in consultation with growers in the Northern Adelaide Plains, South Australia who observed high level of salt toxicity on almond trees irrigated with reclaimed water. This project was requested by the Virginia Irrigation Association (VIA) to scientifically substantiate changes in soil health under crops irrigated by reclaimed water.

Soil sampling was conducted at three almond sites to compare the use of reclaimed and bore irrigation water. One vegetable site was included in the study. The study found that long term use of poor quality reclaimed water and saline bore water is not viable for almond crop production. Reclaimed water and saline bore water increased the risk of salt accumulation in the rootzone and growers are limited by the availability of good quality irrigation water in the Northern Adelaide Plains to manage soil salinity. Accumulation of salts and high concentration of chloride and sodium causes salt toxicity which ultimately impairs almond productivity. In comparison, many vegetables are able to tolerate a higher level of salinity than almond crops. Salinity of irrigation water was within the acceptable range for vegetable production.

With increasing pressure on water availability and predicted low rainfall conditions in Australia, an increase in reclaimed water salinity will continue. If reclaimed water was non-saline and within the range of crop tolerance, appropriate volumes of reclaimed water as a leaching source would assist management of rootzone salinity. As it stands, bore water and reclaimed water available to the Northern Adelaide Plains is unsuitable for long term irrigation of almonds and tailored soil management strategies are essential to minimise the high risk of soil salinity, sodicity and associated soil structural decline.

2 Technical summary

The aim of the project was to evaluate soil properties under reclaimed irrigation water to verify the effect on soil health and crop sustainability.

Soil sampling was conducted at three paired almond production sites in the Northern Adelaide Plains. A paired vegetable site was included in the study. Sites were irrigated with reclaimed and bore irrigation water to assess:

(i) short-term reclaimed water use vs. non-saline bore water
(ii) long -term reclaimed water use vs. saline bore water
(iii) long-term reclaimed water use vs. non-saline bore water

In addition, the establishment of a new almond orchard block was assessed.

The key findings of this research were:

- Water salinity in reclaimed water was higher than the acceptable salt tolerance of almonds.
- Use of poor quality reclaimed water increased soil water salinity.
- High salts in irrigation water increased the risk of soil structural degradation.
- Soil biological activity was very low in almond orchards irrigated by poor quality irrigation water.
- Soil organic carbon was low in almond orchards and has a detrimental effect on soil structure, drainage and nutrient holding capacity of the soil.
- Good winter rainfall was not effective at leaching salts down the profile at most sites following long term use of saline irrigation water.
- Growers are limited by the availability of good quality irrigation water to manage soil salinity.
- Salinity of irrigation water was within the acceptable range for vegetable production.
- Discrepancies between reclaimed water quality properties from Bolivar wastewater treatment plant and actual water for use on farm.

Irrigation of almond orchards with reclaimed water or saline bore water poses a potential risk for crop production and long term soil sustainability. Irrigation water quality is suitable for vegetable production.

Careful monitoring of salts in the soil and irrigation water is critical to mitigate salinity risks. To manage soil salinity, it is recommended that salts are leached down the soil profile away from the rootzone with additional irrigation applications. However with water restrictions and unsuitable irrigation water quality, leaching will not alleviate soil salinity.

Almond growers are limited by the availability of good quality water in the region to adequately manage soil salinity caused by the application of saline irrigation water. Soil management strategies are essential to minimise the high risk of soil salinity, sodicity and associated soil structural decline.

3 Introduction

This project investigated the use of reclaimed water to perennial and vegetable crops and the effect on soil health. It was initiated in consultation with growers in the Northern Adelaide Plains, South Australia who observed high level of salt toxicity on almond trees irrigated with reclaimed water. Growers were concerned high salt levels in soil were attributed to the use of reclaimed water and may have a detrimental effect on long term crop production and overall soil health. This project was requested by the Virginia Irrigation Association (VIA) to scientifically substantiate the status of soil health under crops irrigated by reclaimed water, particularly in dry conditions.

3.1 Water use in Northern Adelaide Plains

The SA Water Bolivar wastewater treatment plant treats about 46,000 ML of wastewater annually to produce reclaimed water for irrigation purposes in the Northern Adelaide Plains. Water is available through the Virginia Pipeline Scheme which is the first and largest recycled water scheme in Australia serving around 250 horticultural growers. Since its inception, growers in the Northern Adelaide Plains have recognised the potential of wastewater as a new water source that could provide a secure supply for irrigation.

In recent years however, a combination of dry conditions and expansion of horticultural industries has increased demand of reclaimed water for crop production. The volume of recycled water use has increased from 6 000 ML in 1999 to 12 100ML in 2005 (Thomas, 2006). The current production area of about 4000 ha under wastewater irrigation in Northern Adelaide Plains will be increased to about 9000 ha with expanded irrigation. A current lack in available water is the most limiting factor to economic growth within the horticultural sectors (Australian Bureau of Statistics, 2004-05).

One of the main concerns with using reclaimed water is salt accumulation. Water analysis has shown that reclaimed water can contain high levels of salts which contribute to an already rising saline water table. Salts are concentrated in the soil by evaporation of water from the surface and by the plant which remove water but absorb little of the salts. If there is no leaching due to insufficient rainfall, high salt levels may cause poor plant health. Salts can reduce water availability and be toxic to the plant. In addition, salts may reduce the uptake of many other essential nutrients. Since sodium and chloride ions are toxic at low tissue concentrations, plants have been particularly stressed during recent extreme heat and drought conditions. There is concern of the cumulative effect that reclaimed water constituents (eg. salts) can have on soil, water, crop quality and yield if not managed appropriately.

In 2003, Stevens et al. reported on the use of reclaimed water in the Northern Adelaide Plains region and suggested the sodium absorption ratio (SAR) of reclaimed water needed to be reduced to protect rising soil salinity in the future. The SAR is the concentration of sodium to calcium and magnesium in the soil and soils with a high SAR are deemed sodic. If irrigated with saline water, soils can become sodic which generally have poor physical properties including reduced water infiltration, poor drainage and aeration. Good physical properties are imperative to promoting good root health and increased soil biological activity.

3.2 Salinity and crop production

Almonds (*Prunus dulcis*) are a high water use crop with an annual water requirement of about 850-1000 mm (DPI Victoria). Almonds are sensitive to salts. Growth reduction in almonds begins at a salt tolerance threshold of 0.9 dS/m ECse in clay soils, and typically 1.5 dS/m is used as a guide before yield loss is a concern (Unkovich *et al*. 2004). Salinity tolerance of other crops grown in the region (e.g. olives and vegetable crops such as Brassica) highlights the sensitivity of almonds to saline water and the high risk of yield loss (Table 1).

Salinity affects plant growth in a number of ways. This includes:

- Reduced ability for the plant to extract water from saline soil
- Indirect effects of salts on nutrient uptake
- Direct toxicity of salts
- Negative impact on soil structure through the effect of sodicity (Stevens, 2009).

Some almond growers in the Northern Adelaide Plains observed poor plant growth and symptoms of salt toxicity believed to be associated with the use of reclaimed water. Growers observed reduced yields following irrigation with reclaimed water after one or more years, with significant salt damage to trees, particularly on the rootstock Nemaguard which is susceptible to salt toxicity. For this reason, almond trees had to be removed and replaced with salt tolerant varieties.

Harvey and Strudwick (2010) reported soil salinity of properties evaluated in the Northern Adelaide Plains was common enough to reduce crop yield potential by 50% as a result of leaf tip burn and reduced water availability. Soil salinity was elevated by the use of saline irrigation water coupled with very poorly drained heavy clay soil. The greatest accumulation of salts is typically beneath the irrigation line and decreases with distance from the irrigation source (Nightingale et al. 1991).

A common practice to reduce the build up of salts in many irrigated agricultural production systems is to applying leaching irrigation. Leaching, either by rainfall or irrigation, occurs when water application raises the water content of the soil above field capacity (Nicolas, 2004). When irrigation water salinity is moderate (> 0.4 dS/m), extra water is regularly needed to move accumulated salts out of the rootzone. Drought conditions and limited availability to low saline water in the Northern Adelaide Plains, has restricted the process of leaching.

Table 1. Average root zone salinity tolerance of a range of vegetable and fruit crops, threshold irrigation water salinities according to soil type and percentage yield loss/dS/m after the threshold is reached (Unkovich *et al*. 2004).

Common name	*Scientific name*	Average root salinity tolerance (ECse dS/m)	Maximum irrigation water salinity before yield loss dS/m sandy soil	loamy soil	clay soil	% Yield loss /dS ECse
Beet sugar	*Beta vulgaris*	7.0	11.0	6.3	3.7	9.0
Kale	*Brassica campestris*	6.5	3.3	4.7	2.7	
Zucchini	*Cucurbita pepo melopepo*	4.7	7.3	4.2	2.4	9.4
Rosemary	*Rosmarinus lockwoodii*	4.5	5.7	3.3	1.9	
Asparagus	*Asparagus officinalis*	4.1	5.2	3.0	1.7	2.0
Beet, garden	*Beta vulgaris*	4.0	6.5	3.7	2.1	
Olive	*Olea europaea*	4.0	5.1	2.9	1.7	
Peach	*Prunus persica*	3.2	4.7	2.7	1.6	21.0
Squash, scallop	*Cucurbita pepo melopepo*	3.2	4.8	2.7	1.6	16.0
Broccoli	*Brassica oleracee*	2.8	3.3	2.8	1.6	9.2
Cauliflower	*Brassica oleracea*	2.5	3.3	1.8	1.1	
Cucumber	*Cucumis sativus*	2.5	3.3	2.4	1.4	13.0
Pea	*Pisum sativum L.*	2.5	3.3	1.8	1.1	10.6
Squash	*Cucurbita maxima*	2.5	3.2	1.8	1.1	
Tomato	*Lycopersicon esculentum*	2.3	3.5	2.0	1.2	9.9
Rockrnelon	*Cucumis melo*	2.2	4.6	2.6	1.5	8.4
Spinach	*Spinacia oleracea*	2.0	4.2	2.4	1.4	7.6
Cabbage	*Brassica oleracea (var. Capitata)*	1.8	3.5	2.0	1.2	9.7
Celery	*Apium graveolens*	1.8	3.3	2.5	1.4	6.2
Grapefruit	*Citrus paradisi*	1.8	3.3	1.7	1.0	13.5
Orange	*Citrus sinensis*	1.7	3.3	1.7	1.0	13.1
Potato	*Solanum tuberosum*	1.7	3.2	1.8	1.1	12.0
Pumpkin	*Cucurbita pepo pepo*	1.7				
Sweet corn	*Zea mays*	1.7	3.3	1.8	1.1	12.0
Broad bean	*Vicia faba*	1.6	3.3	1.9	1.1	
Almond	*Prunus dulcis*	1.5	2.7	1.5	0.9	19.0
Grape	*Vitis S pp.*	1.5	3.3	1.9	1.1	9.6
Pepper	*Capsicum annum*	1.5	3.3	1.6	0.9	14.0
Plum	*Prunus domestica*	1.5	2.5	1.4	0.8	31.0
Sweet potato	*Ipomoea batatas*	1.5	3.0	1.7	1.0	
Avocado	*Persea Americana*	1.3	2.3	1.3	0.8	
Avocado	*Persea americana*	1.3	2.3	1.3	0.8	
Lettuce	*Lactuca sativa*	1.3	3.3	1.5	0.9	13.0
Onion	*Allium cepa*	1.2	3.3	1.3	0.8	16.0
Radish	*Raphanus sativus*	1.2	1.5	0.9	0.5	13.0
Eggplant	*Solanum melongena*	1.1	3.2	1.8	1.1	6.9
Apple	*Malus sylvestris*	1.0	2.0	1.2	0.7	
Bean	*Phaseolus vulgaris*	1.0	1.9	1.1	0.6	19.0
Carrot	*Daucus carota*	1.0	3.3	1.2	0.7	14.0
Lemon	*Citrus limon*	1.0	1.3	0.7	0.4	12.8
Pear	*Pyrus spp.*	1.0	1.3	0.7	0.4	
Strawberry	*Fragaria spp*	1.0	1.6	0.9	0.5	33.0
Turnip	*Brassica rapus*	0.9	2.5	1.4	0.8	

3.3 Soil chemical properties

Water and nutrient availability to the plant is highly influenced by soil chemical properties and the quality of irrigation water. Soil pH, salinity and the three nutrients: nitrogen, phosphorus and potassium, can be highly affected by irrigation water. The concentration of other micro and macro nutrients found in irrigation water will generally not impact the soil environment (Stevens, 2009).

Soil reaction (pH)

The pH is a measure of soil acidity or alkalinity and relates to the activity of hydrogen ion concentration in the soil. The pH characterises the chemical soil environment and affects the availability of certain nutrients to plants. The pH is therefore a good guide of some expected nutrient deficiencies and toxic effects (Hazelton and Murphy, 2007). Typically soil pH(water) 6.5 – 7.5 is ideal for almond production (DPI Victoria).

Salinity

Soil salinity refers to the accumulation of water soluble salts (sodium and also potassium, calcium and magnesium) and the associated anions chloride, sulphate and bicarbonate. Sodium chloride normally comprises about two thirds or more of the total salt load. Salinity is determined using the electrical conductivity of saturated extracts (ECe) reported as deciSiemen per metre (dS/m) which is a more reliable measure than electrical conductivity of a 1:5 soil:water extract (Thomas, 2009).

Soil nitrogen

Much of the total nitrogen (N) in soils is held in organic matter and is not immediately available to plants (Hazelton and Murphy, 2004). Nitrogen has to be in a mineralised form (nitrate or ammonium) to be available to plants: nitrate (NO_3^-) is more readily than the ammonium (NH_4^+) form. However measurements of soil nitrogen are notoriously unreliable as indices of available N for predicting fertilizer responsiveness and requirements of crops (Holford and Doyle, 1992). Rainfall causes high variability to the rate of N mineralisation and N is very vulnerable to leaching.

Phosphorus

Phosphorus (P) is typically low in Australian soils. Added phosphorus is quickly fixed into insoluble minerals and only becomes available to plant roots very slowly (Nicolas, 2004). Soil microbes play an important role in making P available to plant roots. Laboratories measure P availability by extracting P from iron and aluminium phosphates (Colwell method) or from calcium phosphates (Bray method). The relationship between both tests is not consistent. Phosphorus levels in soils can be used a guide for phosphate fertilizer requirements for plant growth.

Potassium

Potassium (K) is a nutrient required in large quantities by the plant and is one of the most abundant elements in soil (Stevens, 2009). In clay soils, potassium can bind to soil particles affecting the soil pH. The use of potassium fertiliser can lead to acidification of the soil (Thomas, 2009).

Soil organic carbon

The measurement of soil organic carbon (SOC) is a useful indicator of soil organic matter. Soil organic matter plays a key role in nutrient cycling and soil structure. Carbon makes up approximately 57% of the molecules in organic matter. Organic carbon influences many soil characteristics including colour, nutrient holding capacity (cation and anion exchange capacity), nutrient turnover and stability (Pluske et al. 2010) and is hence a good indicator of overall soil health (Table 2).

Table 2. Proposed ratings for soil carbon to assess soil health (Hazelton and Murphy, 2007).

Level of organic matter (%) (g/100 g)	Level of organic carbon (%) (g/100 g)	Rating	Band	Interpretation*
<0.70	<0.40	extremely low	1	Subsoils or severely eroded, highly degraded surface soils.
0.70–1.00	0.40–0.59	very low	2	Very poor structural condition, very low structural stability.
1.01–1.36	0.60–0.79	low L1	3	Poor to moderate structural condition, low to moderate structural stability.
1.38–1.71	0.80–0.99	low L2	4	
1.72–2.14	1.00–1.19	moderate M1	5	The following improve with increasing soil carbon levels: structural stability, pH buffering capacity, soil nutrient levels (especially nitrogen), water holding capacity.
2.15–2.57	1.20–139	moderate M2	6	
2.58–3.09	1.40–1.59	moderate M3	7	
3.10–3.43	1.60–1.79	high H1	8	Good structural condition, high structural stability, pH buffering capacity, soil nutrient levels (especially nitrogen), water holding capacity.
3.44–4.29	1.80–1.99	high H2	9	
4.30–5.15	2.00–2.19	very high VH1	10	Soils with very good soil structure and high buffering capacity with sufficient organic matter to decrease bulk density and improve water holding capacity.
	2.20–2.39	very high VH2	11	
	2.40–2.59	very high VH3	12	
	2.60–2.99	very high VH4	13	
5.16–15.00	3.00–8.70	extremely high	14	Soils obviously have high levels of organic matter (dark coloured, greasy to touch and large amount of organic material in the soil). Usually associated with undisturbed woodlands and forested areas.
>15.00	>8.70	organic soil material	15	Highly organic soil including peat.

3.4 Soil health

Soil health reflects the ability of a soil to function properly to support plant growth. There are a number of indicators of soil health, including physical, chemical and biological soil properties. The understanding and importance of physical and chemical properties to soil health and plant growth are widely acknowledged, whereas the importance of soil biology is not as well understood.

Soil microbes are vital to:

- break-down organic matter and release of nutrients into plant available forms
- suppress soil borne diseases
- maintain and improve soil structure
- degrade chemical compounds.

The main biological indicators examined in current soil health tests include measurement of soil microorganisms (fungi, bacteria) and microfauna (protozoa and nematodes). Soil organic matter is essential for nutrient cycling and soil structural stability, but is difficult to measure directly as it changes slowly over time.

One of the most common soil biological measurements used by commercial laboratories is soil microbial biomass. Soil microbial biomass represents the living component of the soil involved in mineralisation (decomposition of organic matter into nutrients) and is strongly correlated with organic carbon (Zornoza et al. 2009). Microbial biomass responds rapidly to changes in soil management and gives an early indication of changes in soil properties before they can be detected by chemical and physical analysis.

Bacteria and fungi are essential for nutrient cycling, decomposition of plant material and soil structural stability essential for plant growth. The fungi:bacteria ratio compares the levels of these microorganisms in the soil and appears to be sensitive to land use (Dalal, 1998). Fungi can breakdown woody organic matter and degrade cellulose and lignin from plant material, so are likely to survive long periods. Bacteria are involved in early stages of decomposition and populations respond rapidly to changes in the soil moisture, temperature and carbon (Wichern and Hafeel, 2004).

Other microfauna includes counts of protozoa and nematodes. Protozoa feed on bacteria and play an important role in mineralising nutrients and making them available for use by plants and other soil organisms. Nematodes can be beneficial, predatory or plant parasitic. Some nematode species feed on bacteria and fungi and hence influence decomposition and nutrient turnover in soils. More detailed analysis of nematodes can reveal abundance, diversity and community structure.

Microbial communities are highly influenced by soil properties. Soil type has a large effect on microbial biomass and activity. Bacterial communities have been correlated with soil electrical conductivity (EC), soil texture, inorganic carbon and nitrogen content in almond orchards (Johnson, 2003). This highlights the importance of correlating biological parameters with physical and chemical properties of the soil.

Rawnsley (2008) showed that the use of reclaimed water on grape vines in McLaren Vale improved microbial activity with no detrimental effect on vine productivity, however reclaimed water sourced from SA Water Christies Beach treatment plant was much less saline than the SA Water Bolivar derived water used in the Northern Adelaide Plains. Analysis of soil health under almond trees irrigated with saline reclaimed water has not been reported.

4 Technical report

4.1 Methods

4.1.1 Site selection

Field sites were located in the Northern Adelaide Plains, 35 km north of Adelaide, South Australia. The Northern Adelaide Plains has an area extent of approximately 540 km^2 and lies within the St Vincent Basin. The SA Water Bolivar wastewater treatment plant supplies water to the area through the Virginia Pipeline Scheme (Figure 1).

The region has a Mediterranean climate, consisting of hot summers and cool winters. The average rainfall is 445 mm. Rainfall was below average in 2009 (392 mm) and above average in 2010 (545 mm) (source: Bureau of Meteorology). This area is regarded as a high value horticultural region with the ideal climate, soil types, hydrology and groundwater resources for intensive horticultural production (Matheson, 1975).

Properties were selected on suitability of paired sites for comparison of reclaimed and bore irrigation water. Three paired almond sites were:

Site AL1 – short-term reclaimed water use vs. non-saline bore water which also included a new orchard establishment (Figure 2).
Site AL2 – long-term reclaimed water use vs. saline bore water
Site AL3 – long-term reclaimed water use vs. non-saline bore water

Two vegetable sites (VEG1 reclaimed water and VEG2 bore water) were included in the study. Vegetable properties in the region were typically irrigated by the same source of water and therefore it was not possible to compare reclaimed and bore water irrigation on the same property. Property details were obtained from the growers participating in this study (Table 3 and 4).

Figure 1. Location of the Northern Adelaide Plains, South Australia and Bolivar wastewater treatment plant (source: CSIRO).

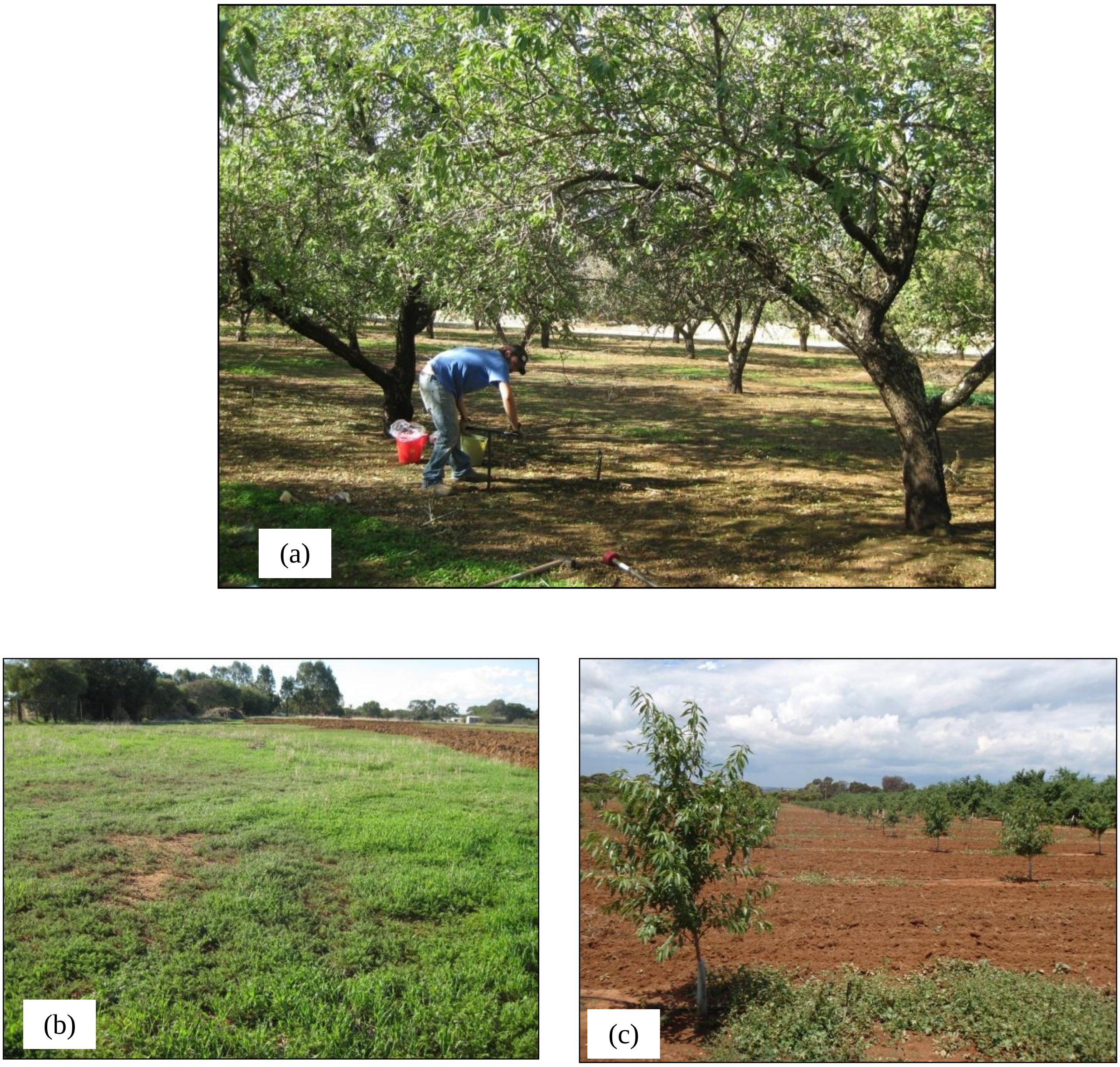


Figure 2. Site AL1 (a) almond orchard, (b) new block in April 2010 and (c) new block after orchard establishment in Dec 2010.

Table 3. Summary information for almond production sites.

Site	Crop	Water source	Irrigation commencement date	Irrigation method	Cultivar	Rootstock	Year Planted	Total area	Soil type	Soil management	Herbicide use	Cover crop	Comments
AL1	Almond	Reclaimed	2009	microspray located between each tree	Nonpareil, Fritz	Nemaguard, Hybrid and GF677	1992	8 ha	Loam/clay over hard red clay	HydroComplex (12-5-15), NPK, CaNO3, KNO3, Urea	Yes glyphosate	natural grass	Nemaguard salt toxicity, 90% affected in first year using reclaimed water.
AL1	Almond	Bore	1976	microspray located between each tree	Nonpareil, Fritz	Hybrid	1998	6 ha	Loam/clay over red clay			natural grass	
AL1	Almond	New Block - Reclaimed	Oct 2010	microspray located between each tree, Oct 2010	Nonpareil	Hybrid	July 2010	4 ha	Loam/clay over red clay	previously horse pasture, no inputs, rotary hoe, ripped and gypsum application at planting	Yes	none	
AL2	Almond	Reclaimed	1999	Sprinkler located in one lateral pipe every third tree along row	Fritz (gradually replaced), Nonpareil, Carmel	GF677 (all Nemaguard rootstock removed)	1976	32 ha	Sandy loam over clay	Adds more N, P, K to offset NaCl. Applied chicken manure over 3 years ago, CaNO3, KNO3, Urea	Yes	medic cover crop over winter	Yield reduced 20% due to salt toxicity .Can't apply leaching with bore water as salinity too high
AL2	Almond	Bore	1978	Sprinkler located in one lateral pipe every third tree along row	Nonpariel, Carmel	Hybrid	1976	8 ha	Sandy loam over clay			medic cover crop over winter	
AL3	Almond	Reclaimed	1997	Microspray located between every tree	Nonpariel, Carmel, N/plus	Replanting with GF677	1974 and 1995	7 ha	Clay over heavy clay	Saltero applied in Oct, Nov, Dec through irrigation to reduce NaCl, NPK, CaNO3, KNO3, Urea, foliar sprays	Yes	none	controlling salts with Saltero , Armillaria disease in poor-draining soils
AL3	Almond	Bore	1970s	Microdripper between every tree	Nonpariel, Carmel, N/plus	Hybrid	1971	8 ha	Clay over heavy clay	Natural fertilizers, chicken manure applied in May 09, Urea, Cu, KNO3, foliage spray	Yes	none	

Table 4. Summary information for annual vegetable production sites.

Site	Crop	Water source	Irrigation commencement date	Irrigation method	Total area	Soil type	Soil management
VEG1	Brassica	Reclaimed (mixed)	1999	Overhead sprinkler		loam over grey clay	gypsum, urea, NPK, $CaNO_3$
VEG2	Brassica	Bore	2002	Overhead sprinkler		Sandy loam over clay	Chicken manure annually, urea, NPK, $CaNO_3$, no KNO_3 in 2010, dynamic lifter

4.1.2 Water analysis

Water from each site was collected at or near the time of soil sampling. Bores were run for 30 mins prior to water collection. Reclaimed water was collected directly from the outlet pipe located on the site. A typical practice is for growers to "shandy" reclaimed water with bore water, in which case, additional water samples were collected from the tank where possible.

Samples were analysed by CSBP, WA. Assessment included measurements of phosphorus, potassium, sulphur, copper, zinc, manganese, calcium, magnesium, sodium, iron, boron, nitrate nitrogen, pH, conductivity and chloride.

Water analysis of reclaimed water at the Bolivar Wastewater Treatment Plant was provided by Michael O'Brien (Senior Technical Advisor, United Water).

4.1.3 Soil sampling

At each almond site, soil samples were collected under reclaimed or bore irrigated trees. In addition, a new block was established at site AL1 in July 2010. Soils from the new block were analysed prior to and after orchard establishment in the first year.

Soil and water sampling was conducted at paired almond sites (AL1, AL2 and AL3) at various times of the season:

- April 2010 - Initial sampling was conducted after almond harvest following drought conditions in the winter and growing season (2009/2010).
- December 2010 – Sampling occurred following good winter rainfall and irrigation water applied over 2-3 months.
- April 2011 – Sampling after harvest following a growing season of above average rainfall (2010/2011)

Soil and water was collected from the vegetable production sites (VEG1 and VEG 2) in April 2010. Analysis of the data collated at the vegetable sites showed these sites were unsuitable for further investigation (see results).

4.1.4 Soil chemical analysis

Eight replicate samples were collected using a hand auger and/or soil corer to a depth of 70 cm where possible. Soil horizons were separated at the time of collection. Soil horizons were allocated as Horizon A (topsoil), Horizon B (mid profile) and Horizon C (deep profile) based on soil texture and soil type. Horizon depth varied between each site (Figure 3 and 4).

At the almond production sites, a sampling area of eight trees across three rows was established in the orchard. Soils were collected under the canopy of almond trees, within 1 m from the source of irrigation.

At the vegetable sites, soil was randomly collected over an area 20 m X 20 m.

Soil analysis was conducted by CSBP Laboratories in Perth, WA. Each sample was analysed for the following:

- Physical properties; colour, texture, gravel content
- Ammonium-nitrogen
- Nitrate-nitrogen
- Phosphorus (Colwell method)
- Potassium (Colwell method)
- Sulphur
- Organic Carbon
- Electrical Conductivity – 1:5 soil:water extract
- Electrical Conductivity – saturated paste extract
- Soil pH (water)
- Soil pH (calcium chloride)
- Trace Elements (Cu, Fe, Mn, Zn)
- Aluminium
- Exchangeable Cations (Ca, Mg, K, Na)
- Boron
- Soluble chloride
- Saturation percentage

4.1.5 Soil biological analysis

Soil for biological assessment was collected from a depth of 0-20 cm under the almond tree canopy (rootzone) in close proximity to samples collected for chemical analysis. Eight replicate samples were bulked and soil health bioassay conducted by CSBP, Western Australia with interpretive analysis by ERA Sustainable, WA. The soil health bioassay included assessment of:

- Microbial biomass
- Fungi and bacteria
- Other fauna (inc. nematodes and protozoa)

Assessment of free-living and parasitic nematodes was conducted by Dr. Jackie Nobbs and Dr Greg Walker (SARDI).

Figure 3. Soil profiles of sites AL1 Reclaimed and VEG1 Reclaimed.

AL1 Reclaimed

A Horizon
0 to 30 cm
Loam

B Horizon
40 to 65 cm
Red clay

C Horizon
(not visible)
70 cm +
Yellow clay

VEG1 Reclaimed

A Horizon
0 to 30 cm
Dark loam

B Horizon
40 - 60 cm
Clay

C Horizon
60 cm +
Clay

Figure 4. Soil profiles at sites AL2 reclaimed and AL2 bore.

AL2 Reclaimed

A Horizon
0 to 30-40 cm
Sandy loam

B Horizon
30 cm to 65 cm
Light clay

C Horizon
(not visible)
65 cm + cm
heavy clay

AL2 Bore

A Horizon
0 - 40 cm
Sandy-clay loam

B Horizon
40 – 50 cm
Clay

C Horizon
60 cm +
heavy clay

4.2 Results and Discussion

4.2.1 Water analysis

4.2.1.1 pH

The pH (water) ranged from pH 7.7 – 8.4 indicating moderate alkalinity in bore and reclaimed water (Table 5). Bore water was more alkaline than reclaimed water at sites AL1 and AL2 at all sampling times. Similarly, bore water used to irrigate vegetable crops was more alkaline than reclaimed water.

In general, water pH was elevated in Dec 2010 compared to other times of the season, with the bore water at all sites ≥ pH8. At this level the water may contain high concentrations of bicarbonate. High bicarbonate in water can cause calcium to precipitate from the soil: this reduces the soil's exchangeable calcium content and increases soil sodicity. This effect was observed at site AL3 reclaimed irrigation where white crusting was observed on the soil surface.

In comparison, data obtained from the Bolivar wastewater treatment plant indicated lower pH than water derived from the pipeline on growers' properties (Table 5). This highlights the change in water quality derived at the wastewater treatment plant and actual water used on-farm.

Table 5. Irrigation water pH at three almond sites (AL) and vegetable sites (VEG) across one year compared with pH values obtained from Bolivar wastewater treatment plant.

	pH (water)					
	April 2010		Dec 2010		April 2011	
site	**Bore**	**Reclaimed**	**Bore**	**Reclaimed**	**Bore**	**Reclaimed**
AL1	7.75	7.25	8.1	8	7.9	7.5
AL2	7.75	7.45	8.3	7.8	7.8	7.3
AL3*	7.75	7.15	8	8.4	7.9	7.5
VEG	7.6	7.1				
Bolivar		6.7		6.9		6.8

*AL3 reclaimed mix pH 7.52

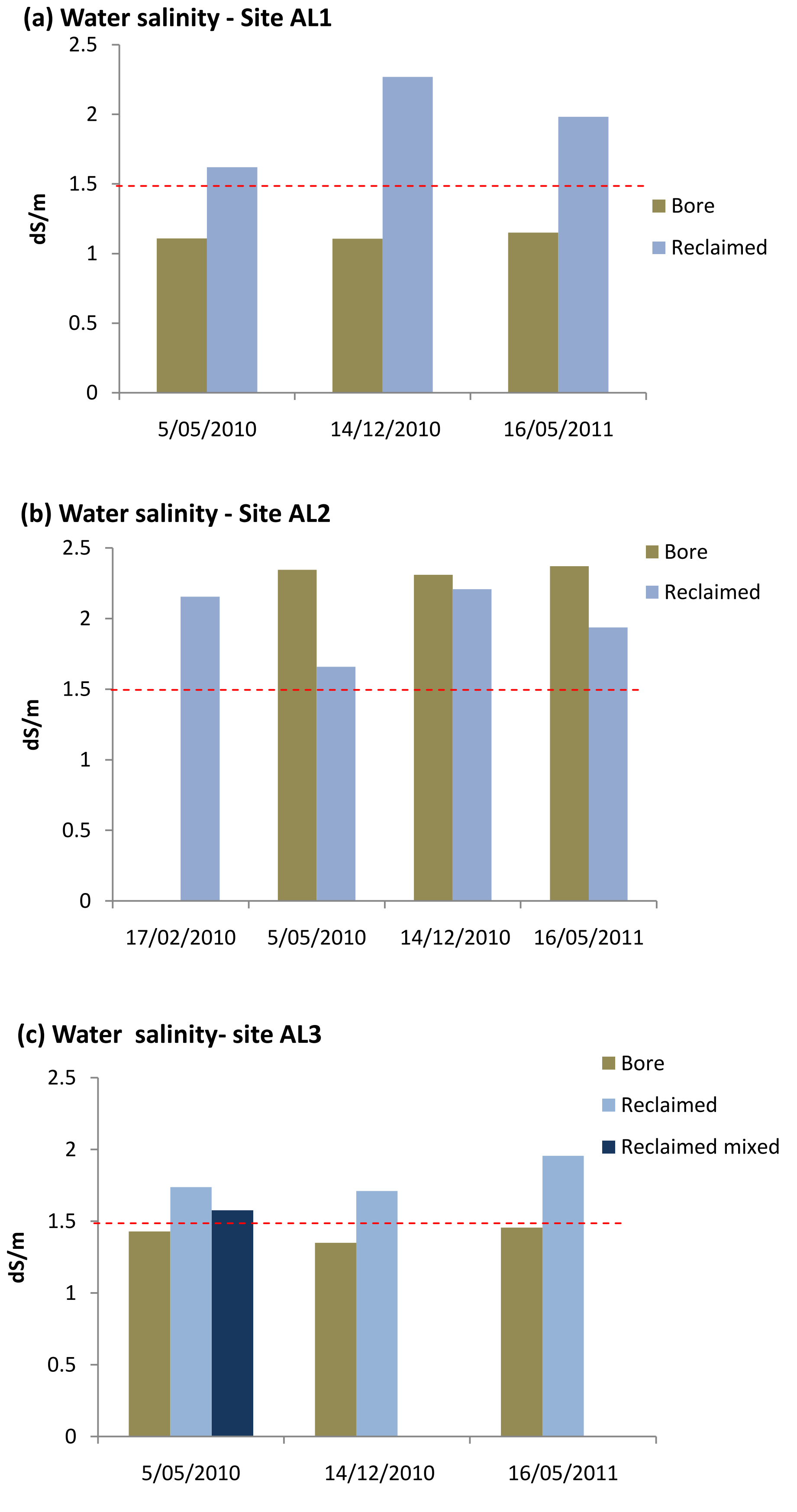
4.2.1.2 Salinity – Electrical Conductivity and Total Dissolved Salts

Electrical conductivity (EC_{se}; units dS/m) showed the levels of reclaimed irrigation water were higher than the salinity tolerance of almonds (EC_{se} 1.5 dS/m) at all sites. This indicates the quality of reclaimed water is deemed unsuitable for irrigation of almonds.

At site AL1, reclaimed water was consistently more saline than bore water (Figure 5a) and fluctuated through the year ranging from 1.62 to 2.27 dS/m. At 1.1 dS/m, the bore water EC_{se} values were within the acceptable range for irrigating almond trees consistent the season.

At site AL2, both bore and reclaimed irrigation water were saline ranging from 1.65 to 2.37 dS/m (Figure 5b). Bore water was more saline than reclaimed water at all sampling times. The results confirmed that the underground water used at this site was more saline than at other properties in the region.

Figure 5. Irrigation water salinity (dS/m) in one year (2010/2011) at three almond sites: (a) AL1, (b) AL2 and (c) AL3. The rootzone soil salinity (EC_{se}) for almond production is 1.5 dS/m.



At site AL3, reclaimed irrigation water was more saline than bore water, with EC_{se} values of 1.74 to 1.95 dS/m above the acceptable limits for irrigating almonds. Analysis of a shandied mix of reclaimed and bore showed this practice reduced the saline properties of reclaimed water slightly from 1.74 to 1.57 dS/m (Figure 5c), however it was still higher than the threshold concentration. The benefit of shandying water is dependent on the salinity levels of the respective water sources e.g. less saline bore water such as found in site AL1 would provide more benefit from this practice.

The unacceptably high salinity of the reclaimed water is further demonstrated in Figure 6 which shows water salinity as Total Dissolved Solids (TDS) sampled on a regular basis from July 2009 to May 2011 and suggests that the only period when salinity may have been acceptable was during late autumn and winter i.e, outside the normal irrigation season.

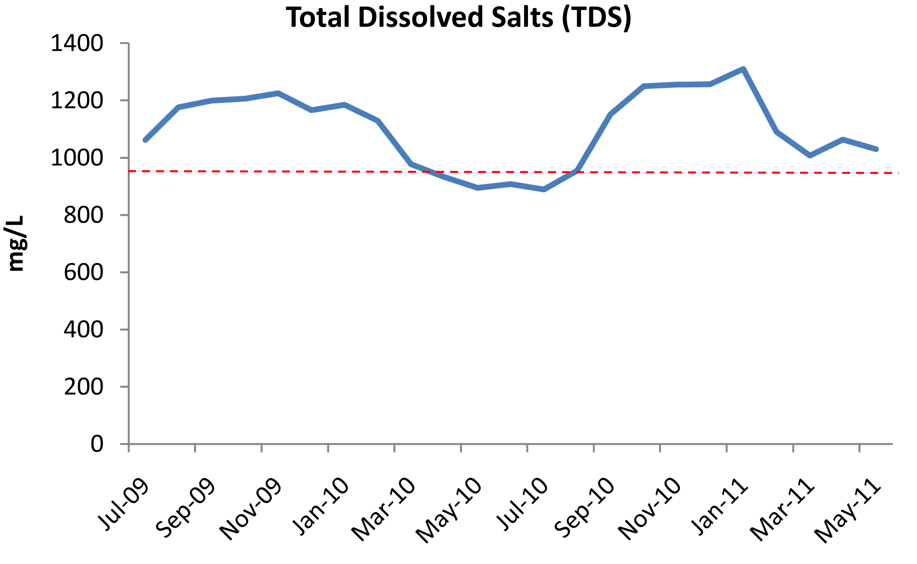


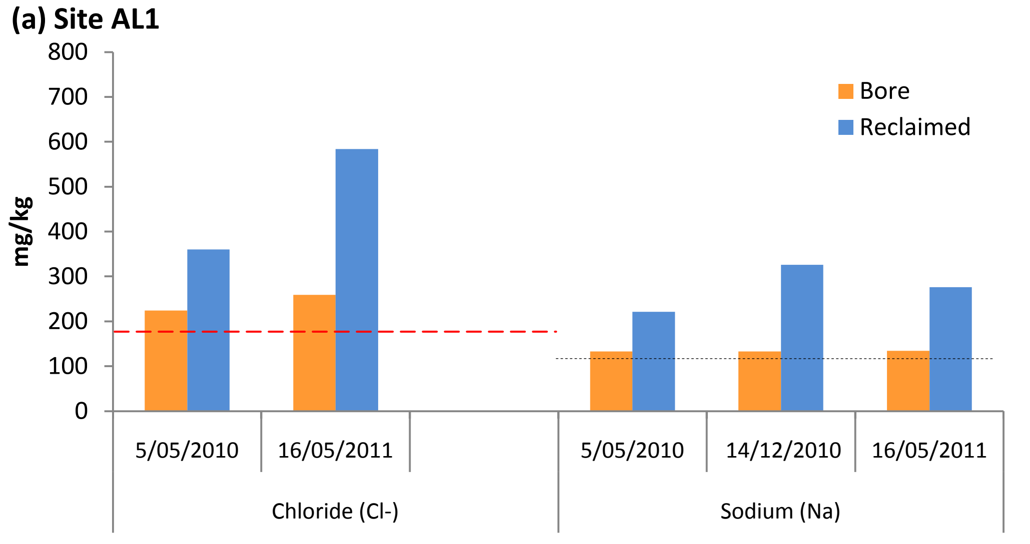
Figure 6. Total dissolved salts (TDS) of reclaimed water at the Bolivar wastewater treatment plant and the acceptable threshold level for almond production before foliar damage occurs (980 mg/L).

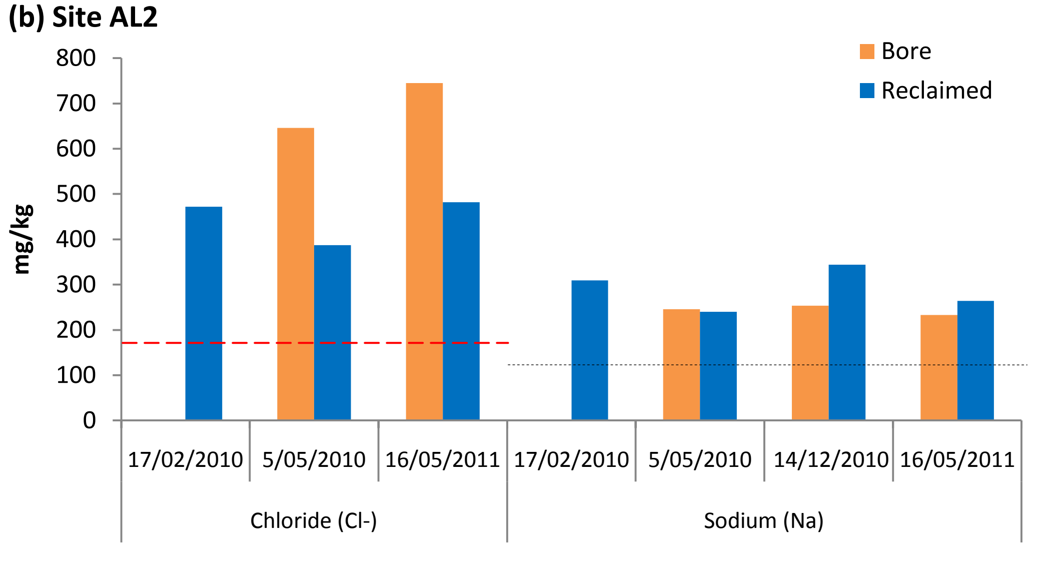
In comparison, many vegetables are able to tolerate a higher level of salinity than almond crops. At the vegetable sites, cabbage crops were planted and have a threshold of 1.8 dS/m (Table 1). Similarly, other crops generally planted at these sites such as cauliflower and broccoli have a much higher threshold (2.5 and 2.8 dS/m respectively). EC_{se} values were 1.59 and 1.77 dS/m for reclaimed and bore water, respectively which was within the acceptable range for vegetable production.

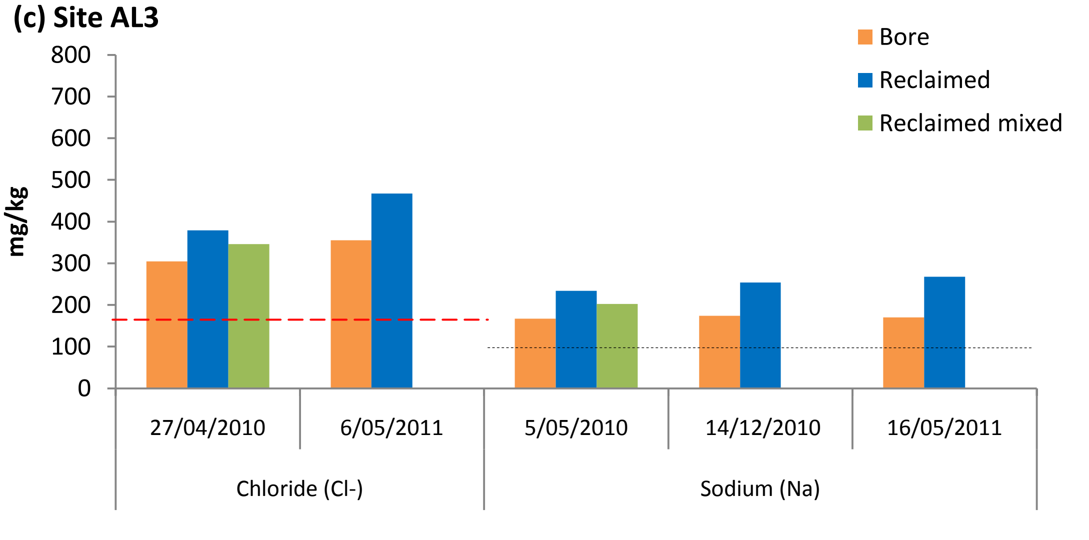
4.2.1.3 Salinity - Chloride and sodium

When dissolved in water, salts such as sodium chloride separate into ions (Nicholas, 2004). Sodium is not an essential element and the use of rootstocks is used to select those plants that can limit the uptake of sodium by the roots. Comparatively, chloride is an essential plant micro-nutrient although high concentrations can lead to toxicity. Almonds are susceptible to foliar injury at chloride concentrations >178 mg/L and sodium concentrations >114 mg/L (Stevens, 2009).

Figure 7. Chloride and sodium concentration (mg/kg) in irrigation water used at sites: (a) AL1, (b) AL2 and (c) AL3. Foliar injury in plants can occur if chloride concentration is >178 mg/L (----) and sodium concentration is >114 mg/L (-----).







All irrigation water used in the Northern Adelaide Plains had levels of chloride and sodium above the concentrations at which injury could occur. At site AL1 reclaimed water consistently had higher levels of chloride (360 – 583 mg/kg) and sodium (221 – 276 mg/kg) than bore water (224 - 258 mg/kg and 133-134 mg/kg respectively) (Figure 7a).

At site AL2, bore water had excessive chloride concentrations (645 – 744 mg/kg) and reclaimed water (387 – 481 mg/kg) (Figure 7b). Almonds are generally more susceptible to chloride toxicity and salt tolerant varieties have been planted at this site to combat the problem. Sodium levels were moderately high, however there was little difference between bore and reclaimed irrigation water.

At site AL3, reclaimed water had high levels of chloride (379 – 466 mg/kg) and sodium (234 -268 mg/kg) (Figure 7c). The practice of "shandying" irrigation waters only slightly reduced the chloride concentration. Chloride and sodium levels in all water sources were above those where foliar damage could occur.

Unlike perennials, vegetables are not specifically sensitive to sodium and chloride toxicity. Brassica are tolerant to chloride levels >700 mg/L and sodium concentrations of >460 mg/L (Stevens, 2009). At VEG1 reclaimed site, chloride concentrations were 380 mg/kg and at VEG2 bore water chloride was 422 mg/kg. Sodium concentrations were similar for both water sources (235 and 228 mg/kg for reclaimed and bore, respectively).

4.2.1.4 Sodicity

High chloride and sodium concentrations were confirmed in water analysis from the Bolivar wastewater treatment plant (Table 6). Reclaimed water can contain relatively large concentrations of sodium compared to other cations like calcium and magnesium, leading to a high sodium adsorption ratio (SAR).

The SAR of irrigation water can be used to predict its potential impact on soil structure (see Sodicity section 4.2.2.4). The acceptable SAR of irrigation water depends on the soil type and salinity of the water. For medium to heavy clay soils, similar to sites AL1 and AL3, SAR of irrigation water should not exceed 5 (Stevens, 2009). The SAR of reclaimed water used in the Northern Adelaide Plains ranged from 7.2 to 8.8 (Table 6) and at this level has the potential to cause soils to become sodic and degrade soil structure. Data from Bolivar wastewater treatment plant collected over time shows chloride and sodium concentrations peak in late spring – summer and decline during the winter months (Figure 8). Similarly, Ca and Mg are highest in the growing season (see Appendix II).

Table 6. Chloride and sodium concentration (mg/L) and sodium adsorption ratio (SAR) of reclaimed water at the Bolivar Wastewater Treatment Plant.

	Chloride	**Sodium**	**SAR**
April 2010	352	231	7.2
November 2010	503	346	8.8
April 2011	406	282	7.6

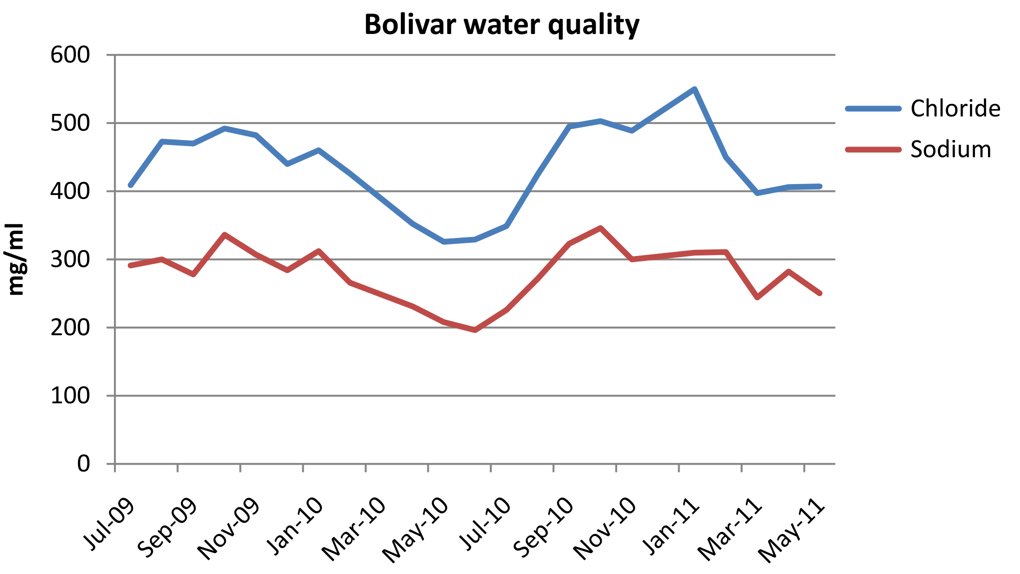


Figure 8. Trends in the concentration of chloride and sodium (mg/L) of reclaimed water at Bolivar wastewater treatment plant, July 2009 – May 2011.

4.2.1.5 Calcium

Water that contains high levels of dissolved calcium or magnesium salts, or both, is described as being 'hard'. Water is considered hard when the total amount of $CaCO_3$ concentration is greater than 150 mg/L. High calcium concentrations can cause blockages in drip irrigation systems.

All irrigation waters except bore water at site AL2 were moderately soft, with calcium levels below 70 mg/L. At site AL2, calcium levels in the bore water ranged from 170 – 183 mg/L, considerably higher than reclaimed water (Figure 9). Bore water used at site AL2 may cause calcium and magnesium from soil and water to precipitate as insoluble carbonates. This can increase soil sodicity.

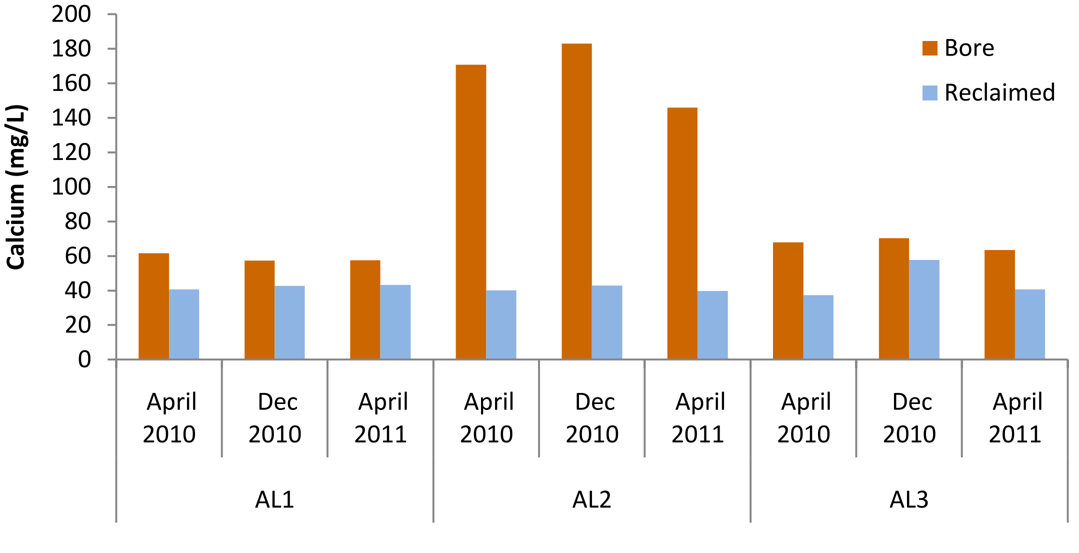


Figure 9. Calcium concentration (mg/L) of irrigation water used at three almond production sites (AL1, AL2 and AL3).

4.2.2 Soil chemistry

4.2.2.1 Soil $pH_{(water)}$

Soil pH $_{(water)}$ is a reliable measurement of pH where soils are alkaline as opposed to pH $_{(CaCl)}$ (Thomas, 2009). At site AL1, irrigated soils were consistently alkaline at all sampling times, with all pH values above 7.9. Under bore irrigation, the top soil became more alkaline during the year, increasing from pH 7.9 in April 2010 to 8.7 in April 2011 (Figure 10a). Calcium nitrate was applied through the irrigation system prior to sampling in April 2011 but Micke (1996) suggests calcium nitrate has little effect on soil pH. Under reclaimed water, soils were moderately alkaline (pH > 8.6) down the profile following a drought season in 2010 and there was no significant change during the season even after winter rain. High pH values may be correlated to soil salinity (EC_{se} 8 dS/m) as observed in April 2010.

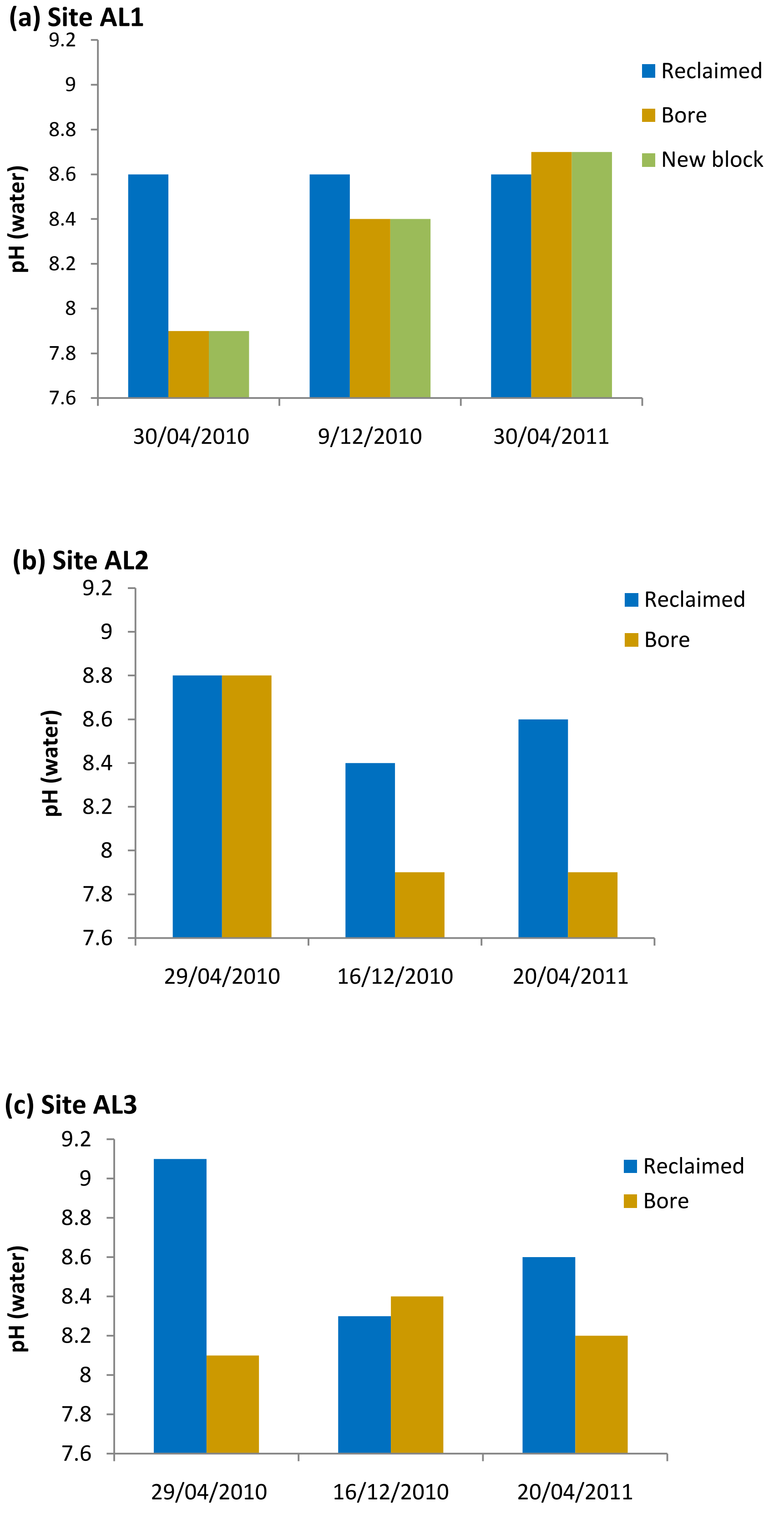
The new block at site AL1 became more alkaline following the application of reclaimed water. Initially the top soil in the new block was similar to the bore irrigated soil (pH 7.9). Following planting of new trees, the addition of gypsum and application of reclaimed water in October 2010, the soil pH increased to 8.4. The C horizon was found to be excessively alkaline (pH 9.0) following the application of reclaimed water for irrigation.

At site AL2, there was no initial difference in pH between reclaimed and bore irrigated soils (Figure 10b). There was a distinct reduction in pH following the use of saline bore water over time.

Initially strongly alkaline soils (pH 9.1) were observed under reclaimed water at site AL3 (Figure 10c). pH values declined significantly following winter rains and there was little difference between soils irrigated by bore or reclaimed water. Use of reclaimed water during the growing season however increased alkalinity of the soil again compared to soils irrigated with bore water.

In general there was a tendency for soils to be moderately-strongly alkaline under both bore and reclaimed irrigation, particularly deep the soil profile. Soils were more alkaline deeper in the profile (pH 8.7 – 9.0) at levels detrimental to plant growth and can be associated with an accumulation of sodium. Given the change from neutral pH to alkaline in undisturbed soil (new block), it is suggested application of irrigation water influenced soil properties. Although acidification has a great impact on nutrient availability and water uptake, alkaline soils can adversely affect plant growth by highlighting zinc, iron, manganese and copper deficiencies in the soil (Thomas, 2009). At most sites, soils irrigated with reclaimed water were more alkaline than soils irrigated with bore water.

Figure 10. Soil pH (water) in the A horizon irrigated by reclaimed or bore water (a) site AL1 including a new block established in July 2010 and irrigated with reclaimed water in October 2010, (b) site AL2 and (c) site AL3.



4.2.2.2 Salinity

Initial EC_{se} values in April 2010 indicated high salinity under both reclaimed and bore irrigation water at site AL1 (Figure 11a) even though reclaimed water was used for the first time in 2009/2010. There was a high accumulation of salts in all soil horizons which would impact root uptake of nutrients and water and cause salt toxicity.

Soils at site AL1 are sodic and application of saline irrigation water can have a stabilising effect on soil structure. Sodic soils are likely to be less dispersive when irrigated with saline water than rainfall (Stevens, 2009). The dramatic reduction in EC_{se} from autumn to early summer in 2010 (Figure 11b), e.g. 8 dS/m decrease to 1.8 dS/m, would have a detrimental effect on soil structure resulting in soil dispersal.

Analysis of soil from the new block indicated soil at site AL1 was not naturally saline (Figure 11a). The application of reclaimed water increased salinity (0.81 to 2.18 dS/m) to above the salinity threshold for almond production only 5 months after orchard establishment (Figure 11c). This highlights the effect of using poor quality irrigation water on soil properties even in good rainfall conditions.

Adequate winter rainfall typically leaches salts through the soil profile, however at site AL2 there was a minimal reduction in soil salinity across the year. Following the use of saline bore water, EC_{se} was > 2 in most soil horizons (Figure 12a) and was relatively unchanged at sampling later in the year (Figure 12b). Rainfall during the season assisted in the reduction of salts in the sandy loam A horizon, however salts accumulated deeper in the soil profile (predominantly clay, Figure 12c). Saline bore water used at AL2 maintained salts in the system and is not suitable for irrigation.

Although not as saline as bore water, reclaimed water used at AL2 maintained soil salinity at unacceptably high levels regardless of rainfall.

Saline soils are prevalent at site AL3 regardless of irrigation type. Soil salinity was high under reclaimed water, particularly in Horizon B and C (Figure 13a). Even after good winter rainfall in the region, salt concentration remained at higher than desired levels for almond production (Figure 13b). Salts were concentrated in the soil into the next year (Figure 13 c). Although initial sampling indicated low soil salinity under bore irrigation water (EC_{se} <1.5), salts accumulated later in the season and remained constant (Figure 13b and 13c).

The results indicate salts are added to the soil from the irrigation water. Salts are concentrated in the soil by evaporation of water from the surface and by the tree which will remove the water but absorb little of the salt. At two sites, good winter and seasonal rainfall was not useful to leach salts out of the system and did not reduce soil salinity at sites where long term irrigation was used.

However at site AL1, salts were leach down the profile following winter rains. Soil type and soil dispersion may have assisted salt movement through the profile. Additionally the water table is variable across the region and it is possible a rise in the water table at the other sites may have carried salts up into the profile. Although salts can be moved down the soil profile, almonds are deep rooted and salts could still be within reach of the rootzone, especially in clay subsoils. Application of excessive irrigation could carry salt back up into the rootzone further exacerbating the problem of soil salinity.

Unusual episodic rainfall events during the growing season (e.g. >80 mm/day in January 2011) did not assist leaching of salts as efficient leaching is only achieved when the fresh water has a long transit time through the profile to interact with clay and dissolve salt.

Figure 11. Soil salinity (EC_{se} dS/m) down a soil profile (Horizon A – C) across one year at site AL1 under trees irrigated by bore or reclaimed water compared to a new block (irrigated October 2010 with reclaimed water). The critical EC_{se} value for almonds above which yield loss occurs is 1.5 dS/m.

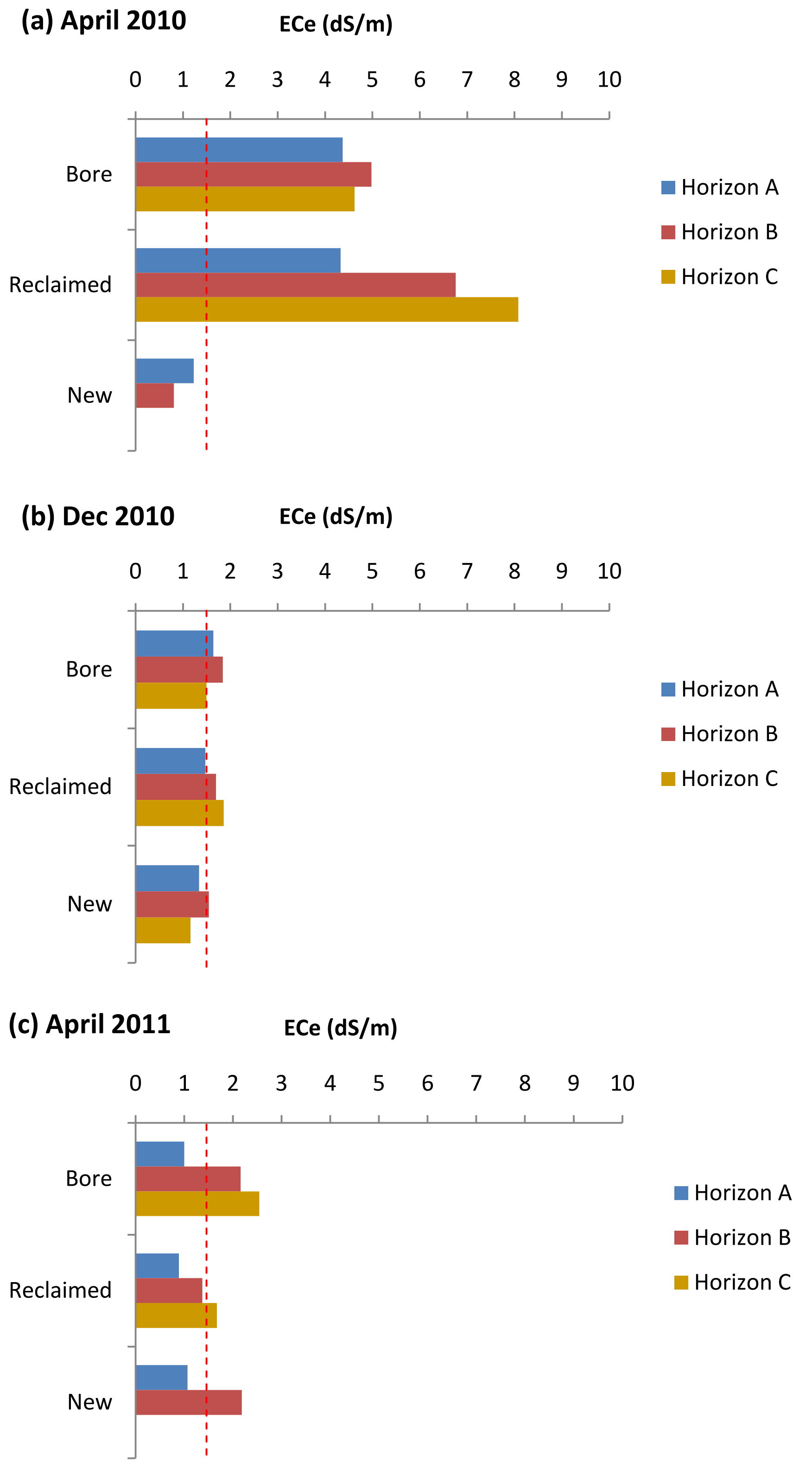


Figure 12. Soil salinity (EC_{se} dS/m) down a soil profile (Horizon A – C) across one year (2010/2011) at site AL2 under trees irrigated by bore or reclaimed water. The critical EC_{se} value for almonds above which yield loss occurs is 1.5 dS/m.

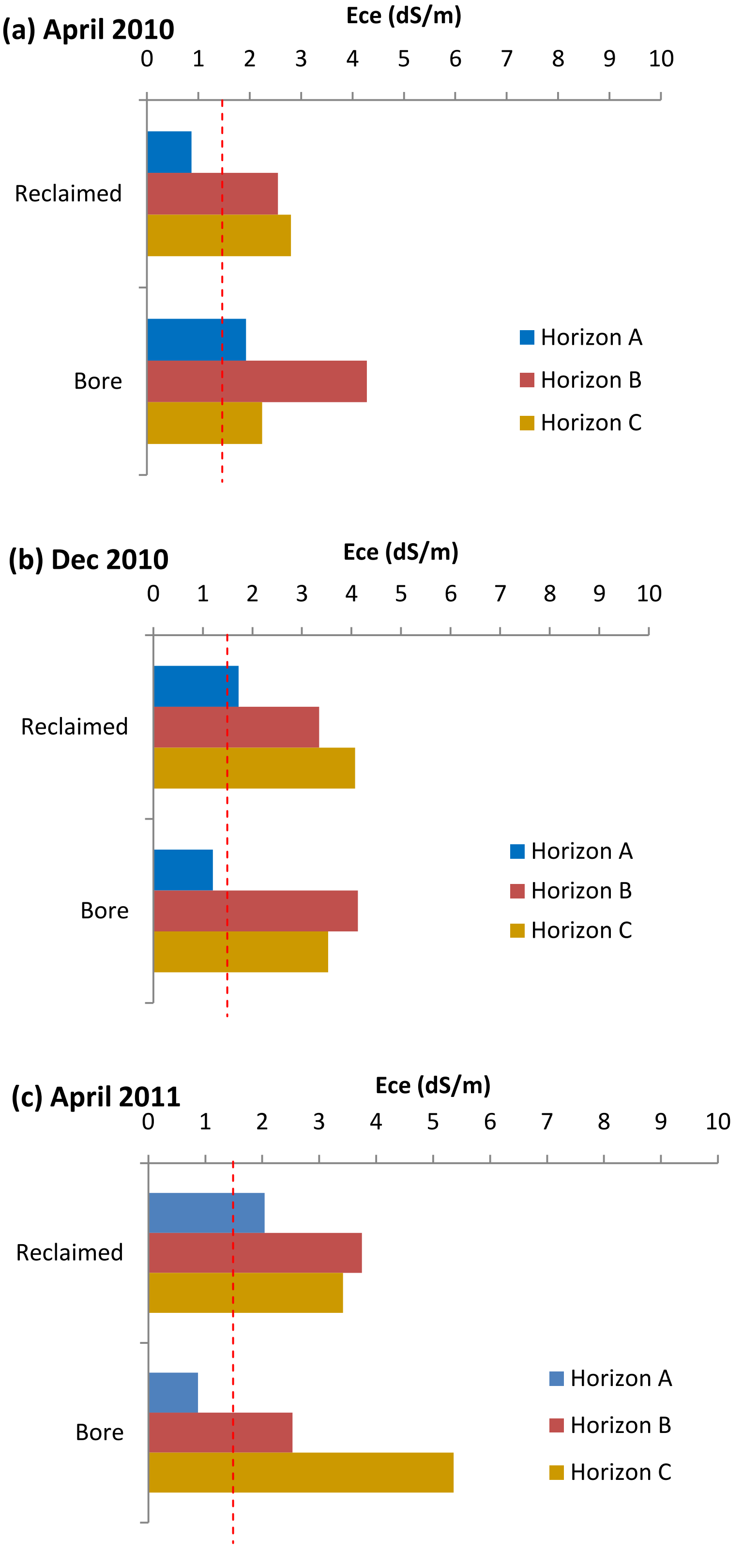
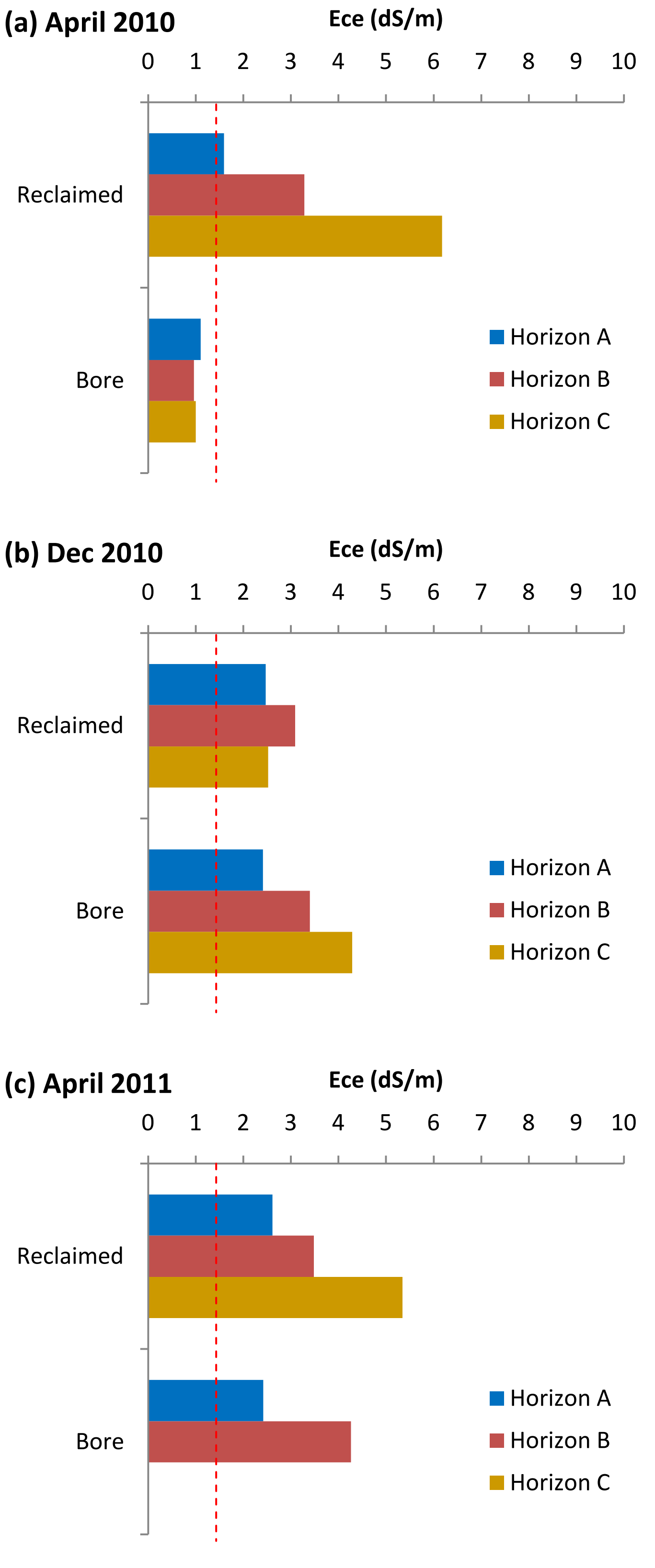


Figure 13. Soil salinity (EC_{se} dS/m) down a soil profile (Horizon A –C) across one year (2010/2011) at site AL3 under trees irrigated by bore or reclaimed water. The critical EC_{se} value for almonds above which yield loss occurs is 1.5 dS/m.



4.2.2.3 Chloride

At site AL1, high concentrations of chloride (317 – 1000 mg/kg) were evident in soils in April 2010 irrigated by both reclaimed and bore water (Figure 14a). The highest concentration (1000 mg/kg) accumulated in the C horizon under reclaimed water irrigation. Winter rainfalls leached salts downward and in reclaimed irrigated soils, reduced chloride concentrations by up to 94% by December 2010. By April 2011 however, applications of bore water in the growing season increased chloride levels in the B and C horizons to 185 and 161 mg/kg respectively.

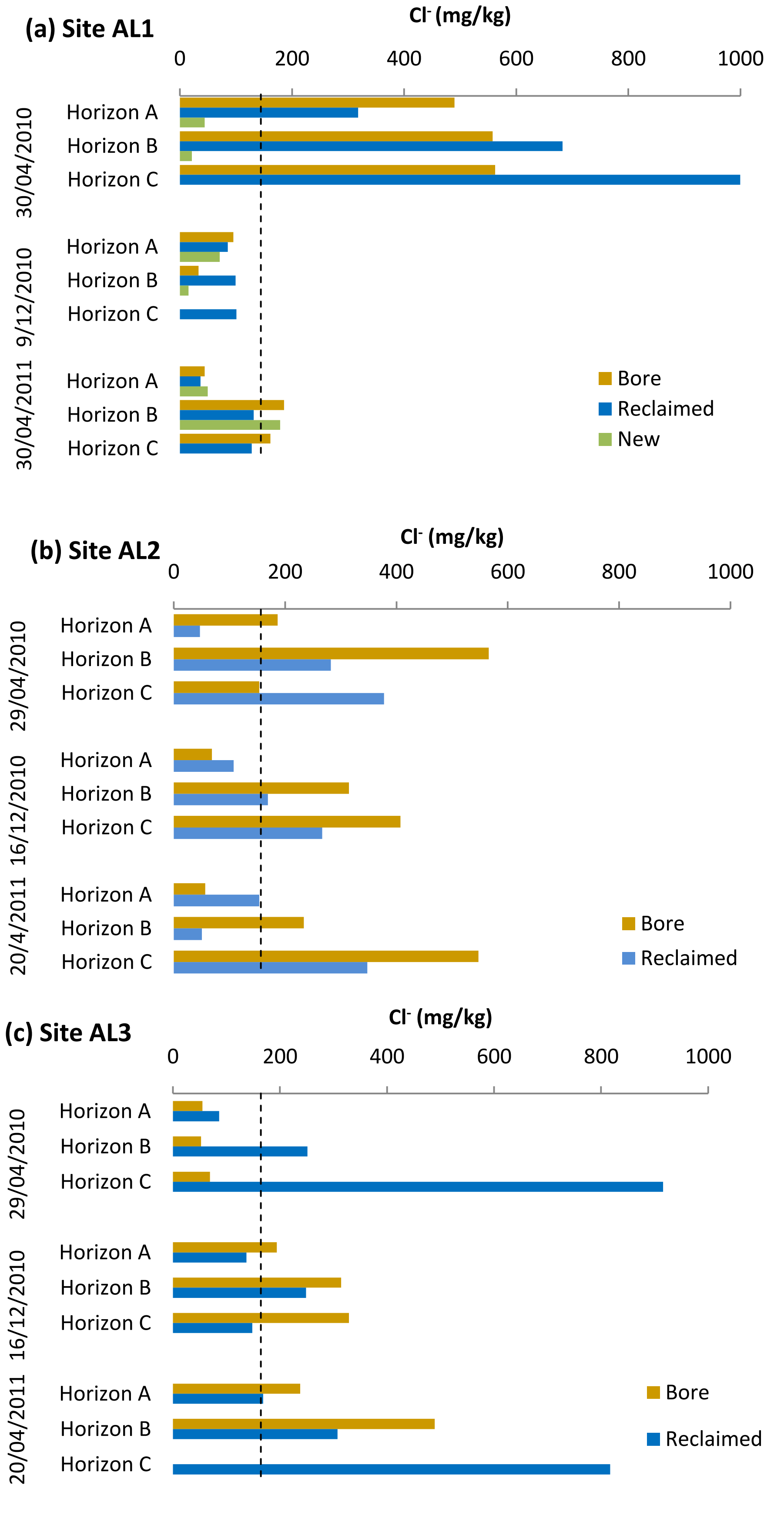
In the new block at site AL1, chloride levels were very low in the April 2010 sampling, with less that 45 mg/Kg in the A horizon (Figure 14a). However after a year of irrigation with reclaimed water, even with the good winter rains, chloride levels in the B horizon had increased above the critical value. Chloride levels only increased in the new block once reclaimed irrigation water was applied.

At site AL2, soils irrigated with bore water generally had higher chloride concentrations than those irrigated with reclaimed water. Following good winter rainfall, chloride was moved down the profile which resulted in an accumulation in the C horizon to excessive levels (Figure 14b). Chloride concentration was marginally reduced in the A horizon, but overall, chloride concentration was high at site AL2.

Chloride concentration was significantly influenced by irrigation water type at AL3 in April 2011 (Figure 14c). Chloride concentration was greatest (915 mg/kg) in heavy clay of the C horizon in soils irrigated with reclaimed water in April 2010. While this was reduced following the winter rains, by April 2011 it had increased again to 816 mg/kg. In comparison, soil chloride levels in soils under bore water were quite low in April 2010 (55 – 69 mg/kg). Chloride concentrations in bore irrigated soils however increased over time (up to 489 mg/kg).

While the chloride levels over time were variable, there was a trend at most sites for chloride to accumulate in the C horizon. Even with the good winter rains reducing the levels in some sites, this was not sustained over time and indicates the need for flushing to reduce accumulation of salts.

Figure 14. Chloride concentration (mg/kg) in soils from three almond sites (a) site AL1 including a new block established in July 2010 and irrigated with reclaimed water in October 2010, (b) site AL2 and (c) site AL3. The critical chloride value for almonds before foliar damage occurs is 178 mg/kg .



4.2.2.4 Sodicity

When sodic soils are irrigated with poor quality irrigation water, they become increasingly degraded. The sodicity of a soil is determined by the sodium adsorption ratio (SAR), i.e. the relative concentration of sodium to calcium and magnesium in the soil. From the first analytic soil test, SAR values of soil horizons A- C were calculated using concentration of soluble ions in the saturation extract ($_e$)(Table 7). Soils are deemed sodic if SAR_e >6 (Nicholas, 2004).

Table 7. Sodium adsorption ratio (SAR_e) at almond (AL) or vegetable (VEG) production sites under irrigation with either bore or reclaimed water in April 2010.

Site	**Bore**	**Reclaimed**
AL1[#]	2.5 – 3.0	4.8 – 7.7
AL2	3.0 – 4.9	2.3 – 4.0
AL3	1.3 – 1.6	3.6 – 8.4
VEG	1.7 – 2.0	3.1 – 3.9

[#] New block SAR_e ranged from 0.7 – 2.8 prior to establishment and irrigation

Except in site AL2 with saline bore water, the highest SAR_e values were observed in soils irrigated with reclaimed water (Table 7), indicating they were sodic and susceptible to structural degradation when wet. Soils at site AL1 were also strongly sodic in the lower horizons (separate horizon data not presented). In comparison, SAR_e indicated soils at the same properties irrigated with bore water were generally stable. Soils in the new block were not sodic (data not presented).

Soils at site AL2 had lower clay content than other soils and although saline bore water was used to irrigate almond trees, soils were non-sodic. It would be valuable to monitor sodicity at site AL2 as sodium in saline irrigation water may gradually displace calcium.

Sodicity was generally not a concern at the vegetable production sites, however SAR_e was higher in soils irrigated with reclaimed water. Soils used for vegetable production are continuously tilled and treated with a range of soil amendments such as manure and fertilisers that maintain soil structure and hence reduce potential salinity and sodicity impacts.

4.2.2.5 Organic Carbon

In general, almond production sites had very low organic carbon in the A horizon, with soils in AL1 and AL2 around 0.4 – 0.45% (Figure 15). Ideally, organic carbon Soil organic carbon <0.4 % indicates soils are severely degraded and 0.4 – 0.59% have very poor structural properties (see Table 2). The exception was site AL3, with carbon levels over 1%. There were no significant differences in carbon between bore or reclaimed water, with the exception of the April 2010 measurements in AL3, where carbon was much higher (1.8%) under bore water than reclaimed (1.1%).

The new block at site AL1 also had low organic carbon (0.71%) although it was marginally better than soils under almond production at the same site.

Site AL3 soils are generally alkaline clay loam over heavy clay soils with moderate organic carbon. There is a correlation between soil organic carbon and microbial biomass where both were higher at AL3 in irrigated soils (see section 4.2.3.1).

Vegetable production has regular inputs of organic fertilisers with crop rotations which contribute to organic carbon. Soils under vegetable crops irrigated with reclaimed water had 1.27% organic carbon in the A horizon compared to 0.89 % under bore irrigation.

In general, changes in soil organic carbon are slow. Soil organic carbon is influenced by the input of the type and amount of plant residues which can be limited by water availability (Liddicoat et al., 2010). Soil analysis in this study showed soil organic carbon declined significantly with soil depth even though deep-rooted perennial plants can improve soil organic carbon in deeper soil layers (>10 cm). Furthermore, use of saline irrigation water may have a detrimental effect by causing structural degradation (eg. sodicity) which in turn reduces microbial activity and organic carbon.

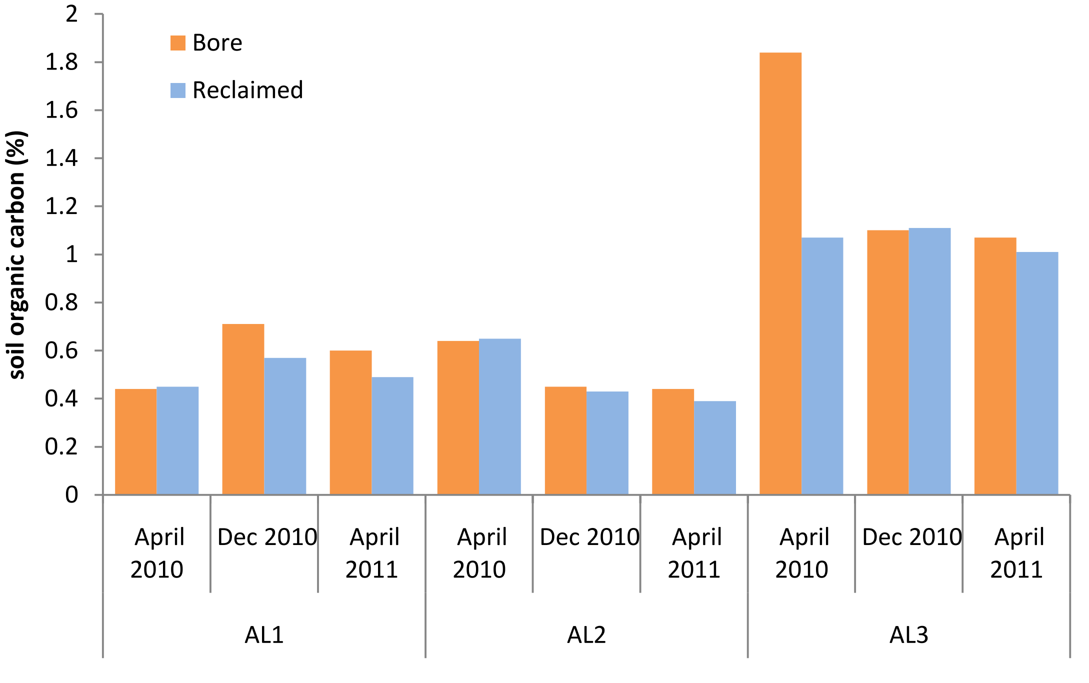


Figure 15. Soil organic carbon in the A Horizon at three almond production sites (AL1, AL2 and AL3) irrigated by bore or reclaimed water.

4.2.2.6 Nutrients

Soil analysis generally does not give a good indication of likely plant nutritional status however is useful to detect potential soil problems and effect of soil management.

Reclaimed irrigation water can contribute additional nutrients to the soil. Bolivar wastewater treatment plant water analysis showed a high concentration of nitrate in April 2010 (18.9 mg/L) however levels were quite variable throughout the season ranging from 6.6 – 19.5 mg/L (see Appendix II).

Nitrate nitrogen was higher in reclaimed water than bore water at sites AL1 and AL2 (Appendix III). Although nitrate was higher in reclaimed water, there was no distinct difference in soil nitrate between bore and reclaimed water irrigated soils. Soils watered with reclaimed water did not display higher nitrate levels than bore (data not shown).

Phosphorous concentration in Bolivar wastewater treatment plant reclaimed water was low in 2011 compared to 2010 and potassium was relatively consistent (Appendix II). This did not appear to influence soil nutrient properties.

There were no distinguishable differences between irrigation water source (reclaimed or bore) and nutrient status of the soil. In general, site AL1 soils had low nitrate and high potassium levels. Phosphorous was generally low, although levels for reclaimed horizon A were high. The new block had the highest nitrate levels (34 mg/L) and adequate nutrients prior to orchard establishment.

In general, site AL2 soils had low nitrate, and high potassium. However phosphorous concentration was variable during the sampling period and fluctuated between 4 – 90 mg/kg. Even though phosphorous was higher in soils irrigated by bore water than reclaimed water (e.g. 89 vs 45 mg/kg P), bore water was consistently lower in phosphorous than reclaimed water (<0.05 and <1.05 respectively). There was no difference in nutrient status of reclaimed and bore irrigated soils.

There was a correlation between high potassium in water and high potassium in soil at site AL3 (Table 8). Reclaimed water was higher in potassium than bore water. Soils irrigated with reclaimed water had higher concentration of potassium than bore. Grower fertilizer data would support these observations.

Under vegetable production, there was little difference in soil nutrients following irrigation with reclaimed or bore water in April 2010. At VEG1 reclaimed, levels of nitrate and phosphorous were variable, decreasing in fertility from Horizon A to C. However, potassium levels were high (839 mg/kg). Bore irrigation (VEG2) soils were higher in nitrate and phosphorous than reclaimed water. Potassium was also high, but more likely a result of fertiliser use.

Table 8. Comparison of potassium in irrigation water (mg/L) and in soil (mg/kg) treated with irrigated water at site AL3.

	Potassium (K)		
	April 2010	Dec 2010	April 2011
Reclaimed water	34.9	23.9	36.6
Bore water	8.4	8.6	8.6
Reclaimed soil	529	516	476
Bore soil	144	243	356

4.2.3 Soil biology

4.2.3.1 Microbial activity

The microbial biomass was below the desired level of 25 ugC/g for all soils except under reclaimed water at AL3 and the new block at AL1 (Figure 16). Many sites were also below the critical level of 10 ugC/g, which is considered too low for microbial populations to perform soil functions effectively (CSBP Plant and Soil Laboratories, WA).

At site AL1, the new block showed the highest level of microbial biomass, with 27 ugC/g. Soil microbial biomass can be used as a predictor of change in soil organic matter; the greater the plant biomass input, the greater the increase in microbial biomass (Dalal, 1998). This was obvious at the new block where initial samples were collected when weeds and grasses were on the soil surface. In comparison, establishment of the orchard involved cultivation and the removal of plant substrates which drastically reduced soil biological activity detected in December 2010 (Figure 16).

The soil biological activity of soil under bore water at site AL1 was significantly higher than for reclaimed, with 20 and 5 ugC/g respectively. There was a decrease in soil biological activity in early summer to below 4 ugC/g in all three soils, yet moisture content was satisfactory at this time. At all times, the microbial biomass in soil under reclaimed water at AL1 was below the critical level of 10 ugC/g. Fertilisers were applied in May-July, with monthly applications of potassium nitrate and urea from September yet soil biological activity was not influenced by the addition of nutrients. Soils were bacterial dominant for soils under reclaimed and the new block, but populations were small. The ratio of fungi to bacteria was generally 1:1 under bore water which is considered to be within an ideal range (data not presented). Fungal-bacterial ratio is not influenced by seasonal changes and generally a ratio of 0.50-1.50 is considered ideal for nutrient cycling and residue breakdown.

The biological performances of soil at AL2 were very poor. There was no notable difference between bore or reclaimed irrigated soils until April 2011, where the soil microbial biomass under reclaimed water increased to 8 ug C/g (Figure 16). The soil biological activity for both sites was below the critical level of 10 ugC/g in both April and December 2010. The fungal-bacterial ratios for both sites were also low (data not presented) and although the amount of fungi and bacteria changed during the season, the level of activity was too low to have any considerable meaning. Irrigation water had little effect on the composition of fungi and bacteria.

At site AL3, the soil biological activity was similar for reclaimed and bore water irrigated soils in 2010, with the biological activity for reclaimed (24 ugC/g) slightly higher than bore (19 ugC/g). However soil biological activity under reclaimed water after harvest in 2011 was very high at 46 ugC/g, and biologically, soils were better than bore (12 ugC/g). The fungal-bacterial ratios for both sites were low, indicating a bacterial dominant system (data not presented). This implies less plant material was available for decomposition by fungi.

Vegetable production sites had good levels of soil biological activity. Based on microbial activity alone, reclaimed was the better of the two soils with a total active microbial biomass (TAMB) of 29 ugC/g, compared to bore with a TAMB of 17 ugC/g (data not shown). The fungal-bacterial ratio (FBR) of both vegetable sites was within ideal range. Vegetable production is highly intensive involving high rotation and tillage coupled with high inputs (e.g. organic fertiliser) which stimulate soil microbial activity.

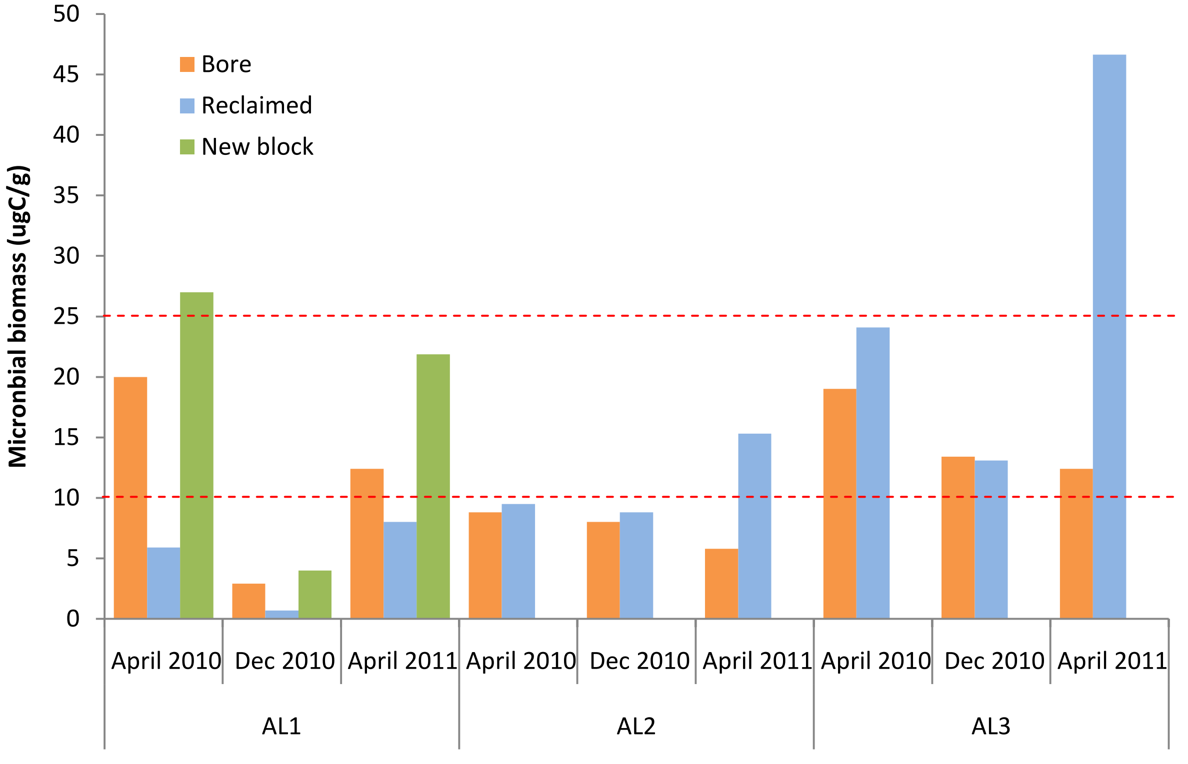


Figure 16. Total microbial biomass (ugC/g) at three almond production sites (AL1, AL2 and AL3) irrigated by bore or reclaimed water. Microbial activity <10 ugC/g is unsatisfactory and the desired range for microbial activity is >25 ugC/g.

4.2.3.2 Nematodes

Almond sites were assessed for the presence and abundance of nematodes. High levels of plant parasitic nematodes were detected in most soils, except site AL1 reclaimed water (Table 9). The highest risk of nematode damage to almonds was at site AL3 bore water due to the presence of root-knot and dagger nematodes. There were no consistent trends in abundance of plant parasitic nematodes in soils irrigated with reclaimed or bore water.

Generally, soils from almond production sites were relatively low in free-living (beneficial) nematodes, which is typical of agricultural soils (Dr Greg Walker, SARDI). It is difficult to determine a desirable level of nematodes as they are highly influenced by seasonal and soil conditions. Nematode abundance and community structure provides information on differences between soil management practices and provides a good indication of soil disturbance. Soils under bore irrigation water were particularly deficient of free-living nematodes, with all sites having higher levels with reclaimed water.

Site AL1 bore had the highest population levels of beneficial free-living nematodes (Figure 17). Site AL1 bore and reclaimed soil samples had the highest population levels of free-living nematodes and the lowest population levels of plant parasitic nematodes compared to other sites.

In comparison, the AL1 new block soils had a different community structure from the other soils, with a higher proportion of plant parasites than fungal and bacterial feeders. It is possible this could be related to more recent cropping on this block, and/or community structure could change over the life of the almond crop. The use of reclaimed water was not detrimental to nematode communities.

Table 9. Number of plant parasitic nematodes detected in soil under reclaimed or bore irrigation at three almond production sites in April 2011, including a new block established in July 2010 and irrigated with reclaimed water in October 2010.

		Number of plant parasitic nematodes per 200 g dry weight of soil *			
Site	**Water source**	**Root-knot**	**Lesion**	**Spiral**	**Others**
AL1	New	—	139	—	566 Pin
					32 Stunt
	Bore	—	—	109	45 Stunt
	Reclaimed	—	—	—	62 Stunt
AL2	Bore	—	254	—	46 Ring
					61 Stubby-root
	Reclaimed	—	36	6	296 Ring
					113 Stubby-root
					2 Stunt
AL3	Bore	70	6	369	5 Dagger
					3 Stubby-root
					47 Stunt
	Reclaimed	—	—	144	144 Ring
					587 Pin
					17 Stunt

* Nematode key: root-knot=*Meloidogyne*; lesion=*Pratylenchus*; dagger=*Xiphinema*; stubby-root=*Paratrichodorus*; ring=*Criconemoides*; spiral=*Scutellonema/Helicotylenchus*; pin=*Paratylenchus* s.l.; stunt=*Tylenchorhynchus* s.l.

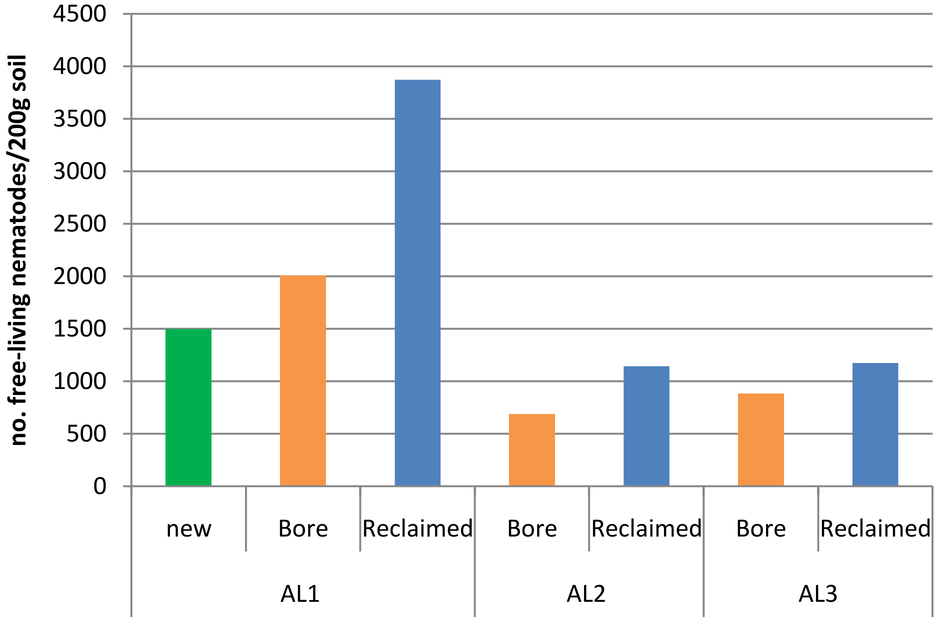


Figure 17. Number of free-living nematodes detected in soil samples under reclaimed or bore irrigation at three almond production sites (AL1, AL2 and AL3) in April 2011, including a new block established in July 2010 and irrigated with reclaimed water in October 2010.

4.3 Conclusion

There are considerable issues with the quality of irrigation water used for almond production in the Northern Adelaide Plains. The study found that long term use of reclaimed water and saline bore water is not viable for almond crop production. In comparison, water was suitable for irrigating a range of vegetable crops and preliminary findings indicated little difference between soil properties under reclaimed or bore water. For this reason, soil properties were monitored under almond production during the 2010/2011 growing season.

The use of reclaimed water is vital for the viability of the horticultural industry in years of drought and low water availability however continued use at its current quality will increase soil salinity.

This project has shown that saline irrigation waters used long term for almond production has affected chemical and physical soil properties. Good winter rainfall is ideal to leach accumulated salts downward, but this had little effect on salts accumulated in soil after long term irrigation with saline water. Typically growers are required to use leaching irrigation to remove salts, but this is unadvisable when the quality of irrigation water is not suitable for leaching requirements.

The practice of shandying reclaimed water to reduce the salt load will not be viable given the salinity of bore water in the region. Salts are present far in excess for plant requirements. In some cases, bore water is too saline and hard for irrigation purposes.

The use of salt tolerant rootstocks provide a means to manage salinity for current almond production but the role of rootstocks is limited if soil salinity increases. Excessive salts can cause salt toxicity, prevent uptake of nutrients, reduce the plant’s ability to extract water from saline soil and have negative impact on soil structure.

The problem of soil salinity is escalated by the soil type in the region. In heavy-textured soils such as clays, where internal drainage is poor, water moves downward more slowly. Salts tend to accumulate in the rootzone longer, and are likely to harm plants more than in well-drained soils. It was shown that there is a benefit of low water salinity in some heavy clay soils where salinity helps flocculate clay particles, thus improving soil structure. However the increased use of poor quality saline irrigation water will not improve soil structure but rather hinder crop production. Improving organic matter content, addition of gypsum and maintaining cover crops in the midrow may alleviate the problem.

Production practices to manage soil salinity, such as use of gypsum, do not combat the long term effect of using poor water quality on soil health. The effect of salts on chemical, physical and biological soil properties can take years to recover and, in some cases, may be irreversible. Sodic soils irrigated with poor quality water will become increasingly degraded. Crusting, waterlogging, hard setting and compaction will increase, creating an even worse environment for plant growth.

With increasing pressure on water availability and predicted low rainfall conditions in Australia, an increase in reclaimed water salinity will continue. If reclaimed water was non-saline and within the range of crop tolerance, appropriate volumes of reclaimed water as a leaching source would assist management of rootzone salinity. As it stands, bore water and reclaimed water available to the Northern Adelaide Plains is unsuitable for irrigation of almonds.

5 Recommendations

This project highlights salinity is a problem in underground bore water and reclaimed water used for irrigation purposes in the Northern Adelaide Plains.

Reducing salinity in reclaimed water could be undertaken by changing the processes in reclamation, or identifying and removing the source of the salinity. The Virginia Pipeline Scheme is providing essential water to the region, but reducing the salt load will ensure sustainable long term agricultural production.

The Bolivar wastewater treatment plant complies with high standards in water treatment however treated water appears more saline than in other areas (e.g. SA Water Christies Beach wastewater treatment plant). The potential source of salt accumulation requires investigation. Various processes, such as reverse osmosis, deionisation and electrodialysis, are commercially available to remove more than 90% of the salts from saline water (Yiasoumi, 2005). Success of the use of reclaimed water relies heavily on the on-going minimisation of environmental risks associated with salt-loading with irrigation (Laurenson, et al. 2010).

In 2001, a reclaimed water user manual was distributed to growers contracted to use reclaimed water (Kelly et al. 2001). Revision of the manual to include the findings of research projects conducted in the region (Laurenson, et al. 2010; Harvey and Strudwick, 2009; Marks and Boon, 2005; Stevens et al. 2003; Dowley, 2001) will assist grower understanding of the implications of using saline irrigation water for crop production. On-going management of soil health and crop quality is integral to the long term use of saline irrigation water.

5.1.1 Recommendations for soil management

With poor quality of irrigation water, tailored soil management strategies are required to minimise the high risk of soil salinity, sodicity and associated soil structural decline. Soil management may include:

Monitoring soil salinity on a regular basis
Standard soil sampling procedures should be followed to obtain a representative sample from different soil types or from specific problem areas on the property. The use of salt solute samplers provides an opportunity to monitor soil salt movement over time. Samples should be taken from different depths in the root-zone, e.g. 25, 50, 75 and 100 cm where possible for perennial crops. In drip irrigated orchards soil samples should be taken at the same distance from a dripper. Samples should be taken on a regular basis at the beginning and end of the growing season, eg. in late Spring and again in Autumn. Trends should be followed over time to ensure that soil salinity is not building up and that leaching practices are effective (Biswas and Bourne, 2005). Soil salinity is more accurately measured by electrical conductivity, preferably the laboratory saturation extraction method (EC_{se}).

Applying gypsum to the soil or irrigation water
Gypsum can be applied to correct soil structural problems caused by high exchangeable sodium and lack of soluble calcium in the soil. The response of gypsum application will depend on salinity and sodicity. As gypsum is insoluble it will need either irrigation of rainfall to move it though the soil profile; consider ripping it in at depth. Gypsum is a salt and will contribute to soil salinity unless there is effective leaching.

Leaching salts

Although access to good quality water is limited, the irrigation plan should include measures to prevent the build up of salts in the rootzone. If EC is > 0.5 dS/m, additional irrigation water will be required to move the salts away from the rootzone. This should coincide with water analysis and monitoring of salt concentration of irrigation water to undertake leaching when salt concentration is at its lowest. Preliminary investigations in drip irrigated vineyards indicates that the most efficient time to leach is late winter-early spring when the soil should be wet from winter rains and that several small leaching irrigations are more effective than a single large event. The salinity of the reclaimed water may be low enough in late winter to do some leaching provided it does not contribute to waterlogging which may impede almond growth and root uptake of nutrients.

Determining nutrient levels for fertiliser recommendations

Soil and petiole analysis will assist decisions on fertiliser applications and correct use will prevent the addition of additional salts into the soil.

Balanced irrigation scheduling

Scheduling is a key factor in long term sustainability of the orchard. Plant water use is determined by crop water use and evaporation. Excessive irrigation and application of fertilisers in addition to watering requirements is wasteful and may cause water logging. Frequent light irrigations are likely to leave salts concentrated in the rootzone.

Minimising complete soil drying

If soil dries out completely, the salinity of the remaining soil water tends to increase and the effects of salinity will be more severe.

Improving organic matter

Organic matter enhances soil structure, drainage and nutrient holding capacity of the soil. The addition of soil amendments (e.g. compost) may be restrictive due to the requirement for a clean orchard floor however it may be possible to rip organic matter into the top soil without causing excessive tree root damage. Timely application of suitable organic amendments after harvest will decompose and leave minimal residues for the following season. Soil organic matter can also be improved by the use of cover crops and leaf litter in the midrow.

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7 Technology transfer

This report details the findings of soil and water analysis in a one-year study conducted between March 2010 and May 2011. Given the analysis of some data was received in late May, this is the first publication of the work.

With approval of the Virginia Irrigation Association (VIA), the findings of this study will be presented to growers in the region and published in a relevant industry journal for dissemination of the findings. The findings and recommendations will made available to SA water authorities responsible for the Bolivar wastewater treatment plant which provides reclaimed water to the Northern Adelaide Plains.

The impact of irrigation on soil health and almond productivity will be of concern to the National Almond Board of Australia.

8 Main outcomes

The aim of this project was to provide growers and industry personnel with a greater understanding of soil health and crop sustainability following irrigation with either reclaimed water or underground bore water.

The findings substantiate that the long term use of poor quality reclaimed water and saline bore water is not viable for almond crop production. The results highlight further work is needed to develop management strategies to prevent soil structural degradation and decline in soil health when using poor quality irrigation water on clay soils in the Northern Adelaide Plains.

The findings will assist growers to understand the implications of using reclaimed water and saline bore water for irrigation purposes and assist in the development of appropriate soil management programs to control salinity and its effect on soil properties.

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Appendix I

Methods for soil chemical analysis:

- Soil pH (water) (Method 4A1, Rayment and Higginson, 1992)
- Soil pH (calcium chloride) (Method 4B2, Rayment and Higginson, 1992)
- Organic Carbon (Walkley and Black, 1934)
- Nitrate-nitrogen – 2M KCl extraction (Searle, 1984)
- Ammonium-nitrogen – 2M KCl extraction (Searle, 1984)
- Extractable Phosphorus – Colwell method (Method 9B1, Rayment and Higginson, 1992)
- Extractable Potassium – Colwell method (Method 9B1, Rayment and Higginson, 1992)
- Extractable Sulfur – 0.25M KCl extraction (Blair *et al*., 1991)
- Exchangeable Cations (Ca, Mg, Na, K) – 0.1M $BaCl_2$/ 0.1M NH4Cl extraction (Method 15E1, Rayment and Higginson, 1992)
- DTPA Extractable Trace Elements (Cu, Zn, Mn, Fe) (Method 12A1, Rayment and Higginson, 1992)
- Extractable Boron – Hot 0.01M CaCl2 extraction (Method 12C1, Rayment and Higginson, 1992)
- Extractable Aluminium – 0.01M CaCl2 extraction (Bromfield, 1987)
- Electrical Conductivity – 1:5 soil:water extract (Method 3A1, Rayment and Higginson,1992)
- Electrical Conductivity – saturated paste extract (Method 2D1, Rayment and Higginson,1992)
- Soluble Chloride (Method 5A2 – Rayment and Higginson, 1992)

Appendix II

Bolivar dissolved air flotation/filtration (DAFF) plant water analysis (units mg/L).

	Daff plant product water (monthly average)										
Year	**month**	**pH**	**TDS (calc. from conductivity)**	**Nitrate**	**Total P**	**Sodium**	**Chloride**	**SAR**	**Calcium**	**Magnesium**	**Potassium**
2009	July	7.1	1061.5	11.9	0.9	291.0	409.0	8.4	37.2	32.4	38.8
	August	7.0	1176.4	13.3	0.7	300.0	473.0	8.3	37.5	37.3	31.0
	Septembei	6.9	1199.1	13.7	0.7	278.0	470.0	7.8	37.8	35.0	33.3
	October	6.9	1206.1	12.9	1.0	336.0	492.0	8.8	43.2	41.3	37.6
	November	6.9	1225.1	6.6	1.1	307.0	482.0	8.4	38.5	37.7	36.4
	December	7.0	1166.3	7.3	0.8	284.0	440.0	8.1	37.6	33.5	37.6
2010	January	7.0	1185.0	9.5	0.6	312.0	460.0	8.4	42.0	37.6	37.1
	February	6.9	1129.1	12.4	0.4	265.5	426.0	7.5	40.7	32.1	38.6
	March	6.8	977.3	16.7							
	April	6.7	932.1	18.9	1.1	231.0	352.0	7.2	35.0	26.8	37.6
	May	6.8	894.4	19.5	1.4	208.0	326.0	6.7	32.3	25.2	33.7
	June	6.8	908.4	18.0	0.6	196.0	329.0	6.3	33.0	23.9	33.9
	July	6.9	888.9	17.2	1.2	226.0	349.0	7.0	33.2	27.4	33.3
	August	6.8	955.3	15.3							
	Septembei	6.9	1151.7	13.7	1.1	272.0	425.0	7.7	38.2	35.0	30.9
	October	6.9	1249.2	14.7	1.8	323.0	495.0	8.9	37.1	38.7	37.5
	November	6.9	1255.1	12.1	1.2	346.0	503.0	8.8	45.1	43.9	42.2
	December	6.8	1256.4	11.2	0.4	300.0	489.0	7.8	47.4	39.5	38.1
2011	January	6.8	1310.3	10.5	0.5	310.0	550.0	7.6	50.2	45.4	41.1
	February	6.7	1090.1	7.0	0.2	311.0	450.0	8.4	42.8	37.9	40.7
	March	6.7	1007.1	9.0	0.1	244.0	397.0	7.2	39.2	29.6	35.3
	April	6.8	1062.9	13.2	0.3	282.0	406.0	7.6	44.7	35.7	39.8
	May	6.8	1029.7	15.0	0.6	250.0	407.0	7.1	42.7	32.0	37.2

Appendix III

Nitrate nitrogen (mg/L) in irrigation water at almond production sites AL1 and AL2 (2010/2011).

Site	Date	Nitrate nitrogen (mg/L)	
		Bore	**Reclaimed**
AL1	April 2010	< 0.10	17.21
	Dec 2011	0.1	11.96
	April 2011	<0.10	13.6
AL2	April 2010	1.57	19.33
	Dec 2011	4.58	13.48
	April 2011	0.16	16.43