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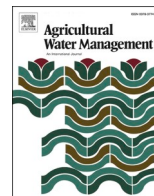
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Irrigation of rangeland soils with coal seam water - A lysimeter study on soil physico-chemical properties

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ABSTRACT

Groundwater extracted from coal seams may be a resource for irrigation of land in areas with low rainfall, but the effect of this water on soil properties needs to be established. A lysimeter study was conducted using intact soil cores (0.75 m diameter, 1.4 m deep) of four different soil types (Sodic Vertisol, Calcic Solonetz, Haplic Solonetz and Xanthic Lixisol) from southern Queensland, Australia, to study changes in soil physical and chemical properties under accelerated rates of irrigation with coal seam (CS) water (electrical conductivity (EC_w) of 3 dS/m, pH of 8.8, and a sodium adsorption ratio (SAR) of 100). Cores were also alternately irrigated with deionised water to simulate rainfall, and either lucerne (*Medicago sativa* L) or Rhodes grass (*Chloris gayana* Kunth.) where grown in the lysimeters. The soil surface was treated with stoichiometric rates of elemental sulfur (1.4 t/ha) and gypsum (2.5 t/ha) prior to every 450 mm CS water irrigation to minimise changes in SAR and pH. Three of the soils (Vertisol, both Solonetz) had low leaching fractions ($\leq 0.1\%$) due to their clay texture and were initially saline in the subsoil (EC_{se} 1.4–4.4 dS/m). Irrigation with CS water resulted in a gradual increase in salt content (EC) and SAR throughout the soil profile, but pH was not increased due to surface-applied elemental sulfur. The Lixisol had a higher hydraulic conductivity and leaching fraction (6.7%) due to its loamy texture – in this soil, accumulated salts could be leached and no increase in salinity or pH were measured. Despite an increase in SAR for this loamy soil, no structural degradation was observed, and it could be sustainably irrigated with up to 3200 mm CS water (with cumulative irrigation volume of 5400 mm). Hence, leaching fractions rather than soil chemistry are good indicators to identify soils suitable for irrigation with CS water that is saline, alkaline, and sodic.

1. Introduction

To increase agricultural production in regions with low and unreliable rainfall requires new approaches to improve productivity and increase food security. Irrigation of crops and pastures may increase production, but the low availability and poor quality of groundwater may limit opportunities for irrigation. Recently, coal seam (CS) gas (syn. coalbed methane) exploration has led to the increased availability of groundwater extracted from coal seams (18500 ML in 2013 (IESC 2014)). This water is variously referred to as CS-associated or co-produced water, or also referred to as CS water (DERM, 2000; Johnston et al.,

2008; Mendhe et al., 2017; Meng et al., 2014; NSW-EPA, 2015; Rice and Nuccio, 2000). Since the coal seams are located in sedimentary rock units, the presence of elevated salt and alkalinity in the CS water is commonly observed (Hamawand et al., 2013; Millar et al., 2016; Navi et al., 2015) which requires careful consideration of its risks and challenges for use as an irrigation resource (DERM, 2000; Majee et al., 2018). It has been proposed that CS water can be used for crop irrigation, supplementation of aquifers and potable water resources, depending on the quality of the CS water (Davies et al., 2015; Echchel et al., 2020; Millar et al., 2016).

The CS water for irrigation of agricultural lands can be treated by

Abbreviations: CEC, cation exchange capacity; CS, coal seam; DI, deionised; EC, electrical conductivity; EC_{se}, Electrical Conductivity of saturated paste; ESP, exchangeable sodium percentage; K_{sat}, saturated hydraulic conductivity; PAWC, plant available water content; SAR, sodium adsorption ratio.

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reverse-osmosis to remove salt and other impurities, but requires vast amounts of energy and produces a highly saline waste stream (brine) that needs to be managed (Davies et al., 2015; Echchel et al., 2020; Millar et al., 2016; Nghiem et al., 2011; Rebello et al., 2017). Alternatively, the CS water can be treated by dosing with acid to lower the alkalinity and blending with water of better quality (Bern et al., 2013; Hamawand et al., 2013; Johnston et al., 2008, 2013; Millar et al., 2016). An alternative approach uses surface applied amendments of sulfur and gypsum to offset the alkalinity and sodicity of the CS water during irrigation (Ganjegunte et al., 2008; Hamawand et al., 2013; Jakubowski et al., 2014; Johnston et al., 2008; McKenna et al., 2019) and limited field studies of this approach have been conducted (Bennett et al., 2016; Ganjegunte et al., 2008; Johnston et al., 2008). The alkalinity of CS water may potentially increase soil pH (Johnston et al., 2013), causing nutrient imbalances by precipitation of micronutrients as carbonates and by increasing negative charges on clay minerals, leading to dispersion (Ali et al., 2019). Soil alkalisation can be overcome by applying elemental sulfur (Ganjegunte et al., 2008). The sulfur will be oxidised by soil microbes (fungi and bacteria) to sulfuric acid which neutralises the alkalinity from the water (Germida and Janzen, 1993; McKenna et al., 2019). The elevated Na concentration in CS water can lead to sodicity in soils (increasing the exchangeable sodium percentage (ESP)) and increasing the sodium adsorption ratio (SAR) of the pore water (soil solution) (Bauder et al., 2008; Johnston et al., 2008; Shaw et al., 1994). Elevated sodicity can cause instability of soil aggregates, eventually causing crusting and hardsetting of the soil surface, and development of dense soil layers which may impair water movement in the soil (Curtin et al., 1995; Page et al., 2018; Qadir et al., 2007; Shaw et al., 1994). Application of gypsum releases calcium (Ca) ions which counteract some of the detrimental effects of sodium (Na) and helps maintain aggregate stability (McKenna et al., 2019; Niaz et al., 2022; Shainberg et al., 1989). The maintenance of soil structural stability is important for the long-term sustainability of irrigated soil since it enables the removal of accumulated Na ions and salts by leaching (either by overirrigation or during periods of high rainfall) (Ganjegunte et al., 2008; Jakubowski et al., 2014; Shaw et al., 1994; van de Craats et al., 2020).

In inland areas of Australia, rain-fed intensive agriculture is not possible, but grazing of sheep and cattle on native and improved pastures is widely practiced (Hunt et al., 2014). For this purpose, Rhodes grass (*Chloris gayana* Kunth) and lucerne (*Medicago sativa* L.) are frequently planted (O'Sullivan, 2013) and irrigation greatly improves pasture growth during periods of low rainfall. Soils in inland areas of Eastern Australia are often naturally saline and sodic, especially in the subsoil (Page et al., 2018; Shaw et al., 1994) and the use of salt-tolerant species for pastures is common in these areas (Deifel et al., 2006; Giles et al., 2014; Wehr et al., 2016).

The development of the CS gas industry in Australia in recent years has resulted in interest using CS water as a source of irrigation water in pasture production (Bennett et al., 2016; Hamawand et al., 2013; Pachas et al., 2016). This beneficial re-use of CS water is supported by governmental regulation, but requires that the following conditions are met under the Queensland Government “end of waste code” (DES, 2019):

1. soil structure, stability and productive capacity is maintained;
2. toxic effects do not occur;
3. a genuine benefit to the resource user through maintained or improved yields; and
4. no risk of serious or material environmental harm.

Therefore, it needs to be determined what effect CS irrigation has on soil properties, and how the risk of environmental harm can be minimised to meet legislated requirements. Lysimeters were used to investigate the effects of CS water irrigation under realistic field conditions. Unlike laboratory studies, which use disturbed and repacked soil, intact

soil cores give much different results since the soil structure and macropores are least disturbed. Also, the use of lysimeters permits a more detailed study of changes in solution chemistry than would be possible in field trials. This study applied volumes of CS water (32 ML/ha, 3200 mm) that enable projection of soil properties under long-term field irrigation. Current field irrigation with CS water in Queensland, Australia typically applies between 1 and 6 ML/ha per year.

The aim of this research was to investigate the effect of CS water irrigation on four soils from Queensland (Australia) which are representative of soils used for irrigation with CS water. The soils were collected as large intact cores from the field, grown with a vegetation cover of Rhodes grass or lucerne, and irrigated with a cumulative volume of 5400 mm (of which 3200 mm was CS water) over two years. Changes in soil chemistry, infiltration rate, and leaching fractions were investigated during the irrigation trial.

2. Materials and methods

The CS water was a composite groundwater sample from various CS gas wells in the Injune area (Queensland, Australia) and had a pH of 8.8, electrical conductivity (EC) of ~3 dS/m, SAR of ~100, contained 36 mM Na (36 meq/L Na), and with a total alkalinity (as CaCO₃ equivalent) of 8.0 mM (800 mg/L). A full analysis of the water is shown in [Suppl Table S1](#). The same batch of water was used for the entire experiment. A total of 12 intact soil cores were collected from four sites in southern Queensland identified as having potential for future irrigation development, with three replicate cores per site. These soils have been selected due to their proximity to coal seam water storage ponds and irrigation infrastructure. The climate at the sites is warm (mean minimum to maximum temperature 11.9–27.7°C) with a mean annual rainfall of 617 mm (Station 43015, Bureau of Meteorology) (http://www.bom.gov.au/climate/averages/tables/cw_043015.shtml). The soils at these locations were either non-saline or saline-sodic, varied in texture from sandy loam to heavy clay ([Table 1](#) and [Table 2](#)), and were classified as Xanthic Lixisol, Calcic Solonetz, Haplic Solonetz and Sodic Vertisol according to the FAO-World Reference Base Classification

Table 1

Characteristics of the four soils used in this study classified according to the FAO-World Reference Base (FAO-WRB). Values are means of three cores ± standard deviation.

Soil	Sodic Vertisol	Haplic Solonetz	Xanthic Lixisol	Calcic Solonetz
Colour	brown	brown	yellow	brown
PAWC (mm/1400 mm)	169 ± 15	170 ± 27	100 ± 5	160 ± 16
Ksat (mm/min)	1.1 ± 1.0	0.3 ± 0.1	2.5 ± 1.4	0.3 ± 0.2
	Topsoil layer (15, 30 cm depth)			
Texture (wet bolus)	Medium clay	Heavy clay, silty	Sandy loam	Medium clay, coarse sandy
CEC (cmol _c /kg)	26 ± 6	26 ± 6	3 ± 0	24 ± 4
vWC at -0.1 bar	60 %	46 %	20 %	35 %
vWC at -15 bar	29 %	30 %	12 %	24 %
	Subsoil layer (90, 105 cm depth)			
Texture	Medium-heavy clay	Light-medium clay, silty	Sandy clay loam	Medium-heavy clay
CEC (cmol _c /kg)	32 ± 2	30 ± 3	3 ± 0	21 ± 7
vWC at -0.1 bar	60 %	41 %	27 %	40 %
vWC at -15 bar	28 %	29 %	18 %	22 %

Abbreviations: PAWC (plant available water content), Ksat (saturated hydraulic conductivity), vWC (volumetric water content) and CEC (cation exchange capacity)

Table 2

Solid phase chemistry of soils before irrigation (0 mm) and after 1700 mm and 3400 mm cumulative irrigation with coal seam (CS) and deionised (DI) water. Values are means $\pm$ standard deviation of 4–6 determinations. Topsoil refers to the 15 and 30 cm sampling layers, and subsoil to the 90 and 105 cm layers.

Soil	Volume (mm)	EC 1:5 (dS/m)		ECse (dS/m)		Ca ex (cmol (c) /kg)		ESP		pH (1:5 water)	
		Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
Sodic	0	0.3 $\pm$ 0.1	0.7 $\pm$ 0.1	1.9	4.4	12.0 $\pm$ 0.0	9.5 $\pm$ 0.7	8 $\pm$ 4	22 $\pm$ 2	7.1 $\pm$ 0.5	7.3 $\pm$ 0.8
Vertisol	1700	0.8 $\pm$ 0.1	0.9 $\pm$ 0.0	5.1	5.8	8.4 $\pm$ 1.4	4.9 $\pm$ 0.6	18 $\pm$ 3	23 $\pm$ 1	7.2 $\pm$ 0.6	5.0 $\pm$ 0.7
	3400	2.0 $\pm$ 0.1	0.9 $\pm$ 0.1	12.8	5.8	9.9 $\pm$ 1.6	6.6 $\pm$ 0.2	41 $\pm$ 8	26 $\pm$ 2	7.9 $\pm$ 0.6	5.6 $\pm$ 1.3
Haplic	0	0.2 $\pm$ 0.1	0.2 $\pm$ 0.1	1.4	1.4	12.9 $\pm$ 3.8	10.2 $\pm$ 1.2	5 $\pm$ 3	13 $\pm$ 2	7.3 $\pm$ 0.7	8.0 $\pm$ 0.3
Solonetz	1700	0.9 $\pm$ 0.1	1.3 $\pm$ 0.0	6.1	8.8	11.4 $\pm$ 0.8	9.3 $\pm$ 0.6	16 $\pm$ 3	19 $\pm$ 2	6.7 $\pm$ 0.6	7.9 $\pm$ 0.2
	3400	2.0 $\pm$ 0.2	1.1 $\pm$ 0.0	13.6	7.5	11.5 $\pm$ 2.9	12.1 $\pm$ 2.0	33 $\pm$ 14	18 $\pm$ 2	7.4 $\pm$ 0.1	8.0 $\pm$ 0.3
Xanthic	0	0.1 $\pm$ 0.0	0.1 $\pm$ 0.0	1.0	1.0	0.6 $\pm$ 0.0	0.0 $\pm$ 0.0	3 $\pm$ 0	11 $\pm$ 3	4.2 $\pm$ 0.1	6.4 $\pm$ 0.4
Lixisol	1700	0.2 $\pm$ 0.0	0.3 $\pm$ 0.0	2.3	3.5	0.1 $\pm$ 0.1	0.1 $\pm$ 0.0	81 $\pm$ 9	22 $\pm$ 10	5.7 $\pm$ 0.0	5.4 $\pm$ 0.1
	3400	0.3 $\pm$ 0.2	0.7 $\pm$ 0.2	3.5	8.2	0.4 $\pm$ 0.3	0.4 $\pm$ 0.1	90 $\pm$ 3	36 $\pm$ 7	7.0 $\pm$ 1.1	5.7 $\pm$ 0.1
Calcic	0	0.3 $\pm$ 0.2	0.6 $\pm$ 0.5	2.1	4.2	11.2 $\pm$ 3.2	7.6 $\pm$ 5.7	5 $\pm$ 5	12 $\pm$ 7	8.0 $\pm$ 1.0	8.7 $\pm$ 0.4
Solonetz	1700	0.7 $\pm$ 0.1	0.6 $\pm$ 0.0	4.9	4.2	10.3 $\pm$ 0.0	3.7 $\pm$ 0.8	15 $\pm$ 6	25 $\pm$ 1	8.4 $\pm$ 0.3	7.9 $\pm$ 1.2
	3400	1.5 $\pm$ 0.2	0.7 $\pm$ 0.1	10.5	4.9	11.5 $\pm$ 2.6	5.6 $\pm$ 2.5	28 $\pm$ 13	24 $\pm$ 2	7.9 $\pm$ 0.2	7.7 $\pm$ 1.3

EC: electrical conductivity, measured in 1:5 soil water suspension (EC 1:5) or saturated paste (ECse). Ca ex: exchangeable Ca. ESP: exchangeable sodium percentage.

(FAO-WRB, 2015). In the Australian Soil Classification, these soils correspond to a Yellow Kandosol, Red Dermosol, Brown Dermosol and Red Vertosol, respectively (Isbell and National Committee on Soil and Terrain, 2021).

2.1. Lysimeters

The steel cores of the lysimeters had a diameter of 75 cm and a height of 140 cm, with a tapered cutting lip to facilitate insertion and retrieval. They were inserted by a hydraulic ram into the soil to a depth of approx. 130 cm, excavated and transported to Brisbane (Queensland). The bottoms of the steel cores were sealed with steel caps to prevent loss of soil and to aid the collection of drainage water after installing drainage pipes. The volume of drainage water collected every week was determined with a measuring cylinder. The cores were insulated with 5 cm

thick polystyrene foam and reflective foil to minimise temperature fluctuations in the soil cores. Rainout shelters made from polycarbonate sheeting were placed 60–70 cm above the soil cores to avoid rainfall affecting the results, whilst still allowing air circulation (Fig. 1). The lysimeter cores were placed on a concrete pad at The University of Queensland, St Lucia (Latitude and Longitude: $-27.5, 153.0$). The air temperature during the trial ranged from 16.4 to 26.7°C (mean minimum and maximum) (Station 040913, Bureau of Meteorology, <http://www.bom.gov.au/climate/data/>). The experiment consisted of these four soil types, each with three replicates, yielding a total of 12 experimental units.

2.2. Soil pore water sampling

Soil pore water samples were collected with 25 cm long

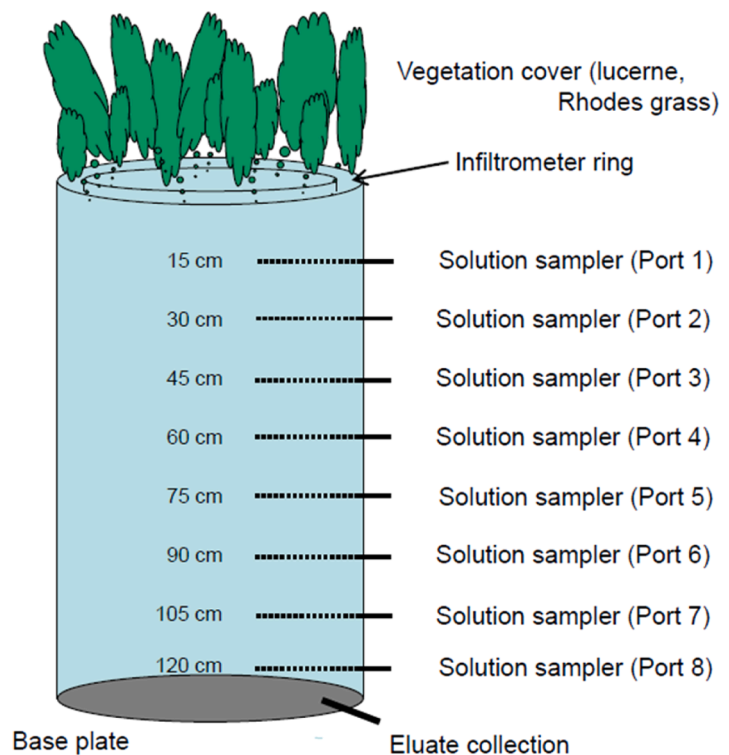


Fig. 1. Photo of a soil core with Rhodes grass after irrigation with 3200 mm coal seam (CS) water and 2200 mm deionised (DI) water (left), and the schematic layout (right) of the soil core.

polyacrylonitrile hollow fibre samplers (Pall Microza) (Menzies and Guppy, 2000). At depths of 15, 30, 45, 60, 75, 90, 105 and 120 cm, small holes were drilled through the steel wall of the lysimeters and a thin diameter steel wire (the same size as the hollow fibre sampler) pushed horizontally into the soil to make a channel for the sampler. The sampler was carefully inserted into the channel and sealed into place with silicone adhesive around the steel wall. After approx. every 100 mm of irrigation, a 20 mL syringe was attached to the hollow fibre sampler with silicon tubing and vacuum was applied to the fibre sampler by pulling the syringe plunger to ~15 mL and holding the plunger in place with a plastic spacer. After ~6–24 h, sufficient soil pore water (~5–10 mL) was collected in the syringe. The soil pore water samples were refrigerated for up to a week prior to chemical analysis.

Soil pore water was analysed for pH and EC using an electronic pH and EC meter (TPS, Brisbane, Australia), and the elemental composition of the solution (Na, Ca, Mg, and S) was determined by inductively coupled plasma-optical emission spectroscopy (ICP-OES). The measured Na, Ca and Mg concentrations were used to calculate the SAR of the soil pore water. The ionic composition of the soil pore water was also used to model the speciation of ions and predict potential precipitation of salts using PHREEQC v. 3 (Parkhurst and Appelo, 2013).

2.3. Soil sampling

Soil samples were obtained three times during the trial, viz. prior to CS water irrigation (baseline), after 1700 mm cumulative irrigation (consisting of 900 mm CS and 800 mm deionised (DI) water, see later) and after 3400 mm cumulative irrigation (2500 mm CS and 900 mm DI). The baseline samples were collected in the field at the time of lysimeter collection, and for the 1700 mm and 3400 mm collections, a 2.5 cm hole was drilled into the sidewall of the lysimeter, the soil extracted with a 30 cm long spiral drill bit and the hole backfilled with expanding polyurethane foam to minimise future disruption to water flow. Due to the destructive nature of soil sampling, it was only performed three times during the trial.

The plant available water content (PAWC) was determined by pressure plate apparatus between –0.1 kPa and –1500 kPa and summed up for the different soil layers. The saturated hydraulic conductivity (K_{sat}) $\pm$ standard deviation was determined by double ring infiltrometer prior to the start of the trial when columns were fully wet-up. For the topsoil and subsoil layers, texture was determined by the wet bolus method and the cation exchange capacity (CEC) of the soil was determined after prewashing the soil with 60 % ethanol and summing the charges of Ca^{2+} , Mg^{2+} , Na^{+} , K^{+} and Al^{3+} ions extracted with 1 M alcoholic ammonium acetate at pH 8.5 (Sumner and Miller, 1996).

Electrical conductivity (EC) and pH was measured in 1:5 soil:water suspension. The EC of saturated paste (EC_{se}) was calculated by multiplying the EC1:5 with experimentally determined conversion factors, viz. 6.4 for the Sodic Vertisol, 6.8 for the Haplic Solonetz, 11.7 for the Xanthic Lixisol, and 7.0 for the Calcic Solonetz.

2.4. Irrigation regime

Prior to the start of the irrigation trial, lysimeters were sown with lucerne (*Medicago sativa* cv. L91) seeds. The lysimeters were watered with DI water until seedlings were established (~6 weeks). This lucerne cultivar was selected as it is comparatively salt tolerant and hence routinely grown in Queensland where CS water is used for irrigation. The surface soil was amended by sprinkling with ~2.5 t/ha gypsum (agricultural grade) and ~1.4 t/ha sulfur (sublimed grade) at the start of the irrigation trial and then after every 450 mm CS water application. Specifically, these application rates were calculated based on the SAR of the CS water, with the aim to lower SAR to 20 and to completely offset the total alkalinity of the CS water (assuming complete oxidation of the sulfur) for 450 mm CS water. Hence, the ameliorant application rate is the same of the four soils since the CS water applied was the same. While

sulfur oxidation is a slow process, the increase in alkalinity in the soil is also a slow process, hence surface application of sulfur after 450 mm CS water application was sufficient to prevent alkalisation of the soil. During irrigation, lysimeters were watered with 20 mm CS or DI water every 2–5 d (whenever the soil surface dried off, irrigation was 2–3 time/week in summer and 1–2 times/week in winter). The soil water content at which the solution samples were collected was ranging between saturation and field capacity (~0 to –10 kPa).

Each irrigation event was 20 mm, and soils were alternately irrigated in blocks of 100–320 mm (in individual applications of 20 mm each) of CS and DI water (to simulate expected rainfall patterns) (up to 1700 mm cumulative irrigation), followed by 1000 mm CS water only (to simulate drought with no rainfall diluting the salinity in soil) (Fig. 2). After the cores dried down, solid phase samples were collected (see above). Thereafter, irrigation was continued on only three soil types (Calcic Solonetz, Sodic Vertisol, and Xanthic Lixisol). The lucerne was sprayed out with glyphosate herbicide, and Rhodes grass (*Chloris gayana*) cv. Topcut sown, followed by irrigation with 1000 mm DI water (to simulate extensive rainfall leaching) followed by irrigation with alternating 300 mm CS and DI water irrigations until a total cumulative volume of 5400 mm water was applied to the cores (Fig. 2).

The CS water and DI water irrigation regime is also shown in Figs. 2–6 next to the x-axes as horizontal lines coloured in red (for CS water) and blue (for DI water).

2.5. Determination of infiltration rate

The infiltration rate was determined after inserting a stainless-steel ring (60 cm diameter) into the soil surface to a depth of 10 cm. These rings were kept in place for the entire duration of the trial to minimise disturbance of the soil surface. Irrigation water was added to the inner and outer ring and the time taken for water to infiltrate in the inner ring determined with a float, ruler and stopwatch (Eijkelkamp Soil and Water, The Netherlands: Double ring infiltrometer operating instructions). Infiltration was measured prior to seeding after soils were completely wetted up (thus infiltration rate corresponds to saturated hydraulic conductivity), and after every 100 mm of irrigation with CS or DI water. We measured infiltration rate rather than saturated hydraulic conductivity. The infiltration rate is expected to be greater than the saturated hydraulic conductivity, but since soil water content in the lysimeters did not fluctuate widely (soil was irrigated whenever the topsoil dried off, followed by infiltration measurements), the measured infiltration rate was considered to reflect changes in water transmission in soil rather than changes in soil water content.

2.6. Statistical analysis

Three replicate cores were used per soil type, with pore water samples collected at 15 and 30 cm (“topsoil”) and 90 and 105 cm depth (“subsoil”). Hence, each data point is the mean of up to six values for the “topsoil” (two depths (15 and 30 cm) $\times$ three replicate cores) and “subsoil” (two depths (90 and 105 cm) $\times$ three replicate cores) solution samples. Sometimes, insufficient solution samples were obtained, resulting in fewer observations contributing to the mean value. Soil pore water data for intermediate soil layers are not reported for sake of brevity. The 120 cm depth sample was not collected since this depth was located in decomposing bedrock in some lysimeters which made installation of solution samplers impossible.

A best-fit third order polynomial line was chosen using SigmaPlot v14, solely with the intent to better visualise trends in soil pore water chemistry with irrigation volume.

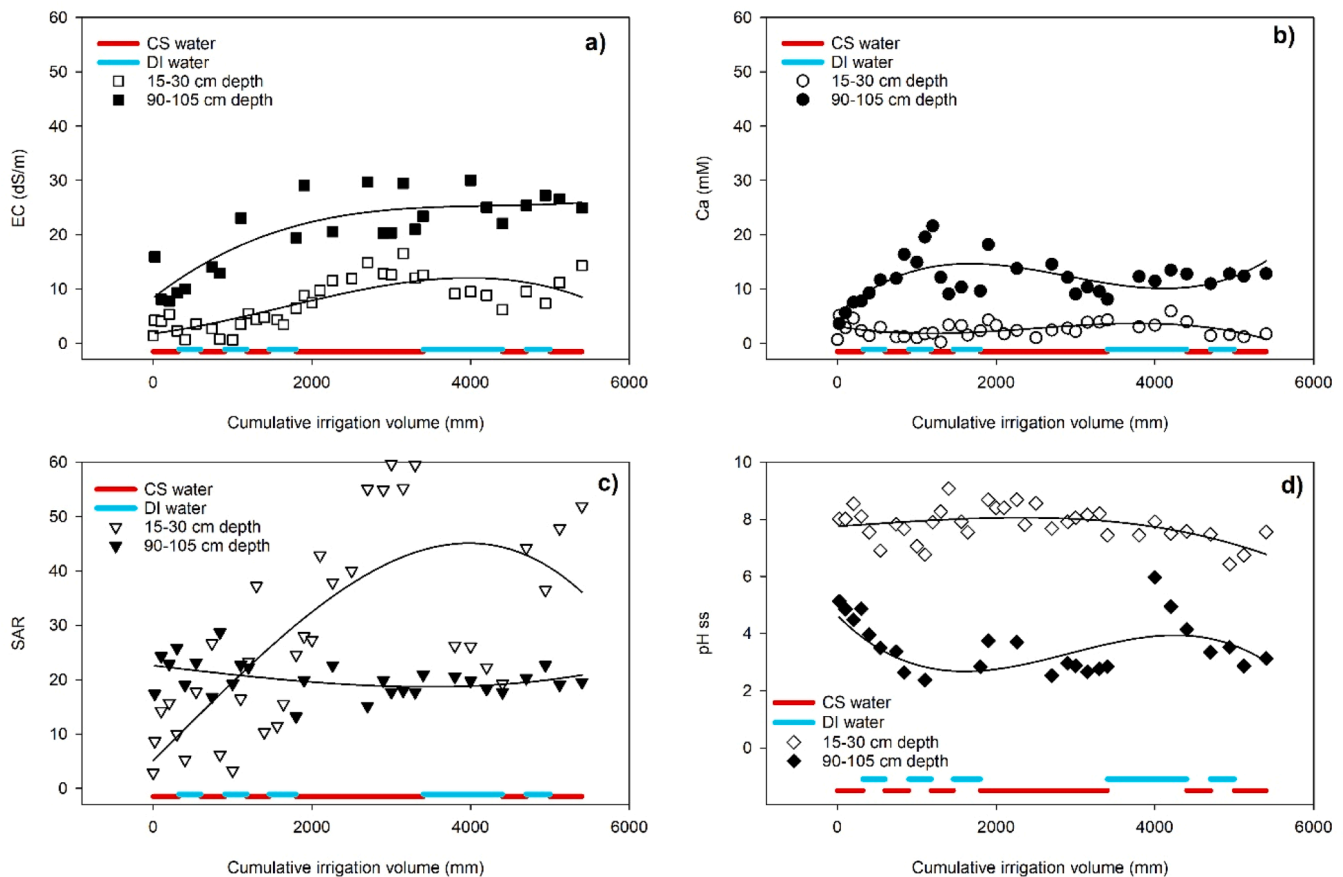


Fig. 2. Soil pore water chemistry of the Sodic Vertisol soil cores at two depths (15–30 cm and 90–105 cm) as a function of irrigation volume. Each data point is the average of three replicate cores and the two depths (15–30 cm, or 90–105 cm). Volumes of coal seam (CS) water (red lines) and deionised (DI) water (blue lines) are shown as horizontal lines above the x-axis. a) Changes in EC (dS/m), (b) changes in Ca (mM), (c) changes in SAR, (d) changes in S (mM), and (e) solution pH. The lines represent the best-fit third order polynomial (SigmaPlot v 14) and are shown solely for the purpose of highlighting trends in pore water chemistry.

3. Results

3.1. Changes in soil pore water chemistry

The EC in the soil pore water of the topsoil (15 and 30 cm depth) of all soils increased with volume of CS water to 10–20 dS/m (Figs. 2a–5a). During irrigation with 1000 mm DI water (i.e. between 3400 and 4400 mm cumulative irrigation), the EC in the topsoil gradually decreased but did not return to initial values. Changes in subsoil (90–105 cm depth) EC differed between soils: soils that were initially saline either increased in salinity (from 10 dS/m to ~25 dS/m in the Sodic Vertisol, Fig. 2a) or showed no change in EC in the subsoil with increasing irrigation [Haplic Solonetz: average EC 27 dS/m (Fig. 3a), Calcic Solonetz: average EC 15 dS/m (Fig. 5a)]. In the non-saline Xanthic Lixisol, the EC in the subsoil pore water increased from 1 to 20 dS/m but it was noted that the accumulated salt could be leached during DI water irrigation, resulting in a decrease in EC to ~5 dS/m (Fig. 4a). It was noteworthy that DI water irrigation did not lower the EC in the subsoil of the Calcic Solonetz or the Sodic Vertisol (the Haplic Solonetz was not leached) because no drainage occurred in these three soils.

The soil pore water Ca concentration in the topsoil increased from ~2–5 mM to 6 mM in the Sodic Vertisol (Fig. 2b), to ~17 mM in the Haplic Solonetz (Fig. 3b), and to ~20 mM in the Calcic Solonetz (Fig. 5b). The increase in solution Ca was less in the Xanthic Lixisol (~8 mM) (Fig. 4b). After DI water irrigation, the topsoil Ca decreased to ~10 mM in the Sodic Vertisol and Calcic Solonetz (Figs. 2b and 5b), whilst in the Xanthic Lixisol the Ca concentration decreased to ~4 mM

(Fig. 4b). The subsoil pore water Ca concentration was not affected by irrigation volume in the Haplic Solonetz (~30 mM) (Fig. 3b), Xanthic Lixisol (~2 mM) (Fig. 4b) and Calcic Solonetz (~5 mM) (Fig. 5b), whilst in the subsoil of the Sodic Vertisol, the solution Ca concentration increased from ~5 mM to ~15 mM after CS irrigation (Fig. 2b).

The SAR in the topsoil pore water was approximately 5–10 at the start of the irrigation, but this increased with CS water irrigation to ca. SAR 40 in the Haplic Solonetz (Fig. 3c) and SAR 30 in Calcic Solonetz (Fig. 5c), to SAR 60 in the Sodic Vertisol (Fig. 2c), and to SAR 100 in the Xanthic Lixisol (Fig. 4c). During DI water leaching irrigation, the SAR in the pore water decreased, but did not return to initial values. The SAR in the subsoil pore water of the Vertisol and the two Solonetz did not change with CS or DI water irrigation and fluctuated around SAR 20 (Panel c, Figs. 2–5). In the Xanthic Lixisol, the subsoil SAR increased from 1 at the start of irrigation to SAR 40 with 5400 mm cumulative irrigation (Fig. 4c) and did not decrease during DI water irrigation. (The haplic Solonetz was not irrigated further).

The soil pore water pH in the topsoil was relatively constant for the four soils (~pH 7–8) (Figs. 2d–5d) and decreased only insignificantly during DI water irrigation. The subsoil pore water pH showed greater fluctuations (pH 4–8) with irrigation volume, but very low values (pH 2.5–3) measured in some instances in the Sodic Vertisols, Haplic Solonetz and Xanthic Lixisol are likely an artefact of iron redox reactions (explained later).

3.2. Changes in soil solid phase chemistry

The soil solid phase was sampled prior to irrigation, after 1700 mm

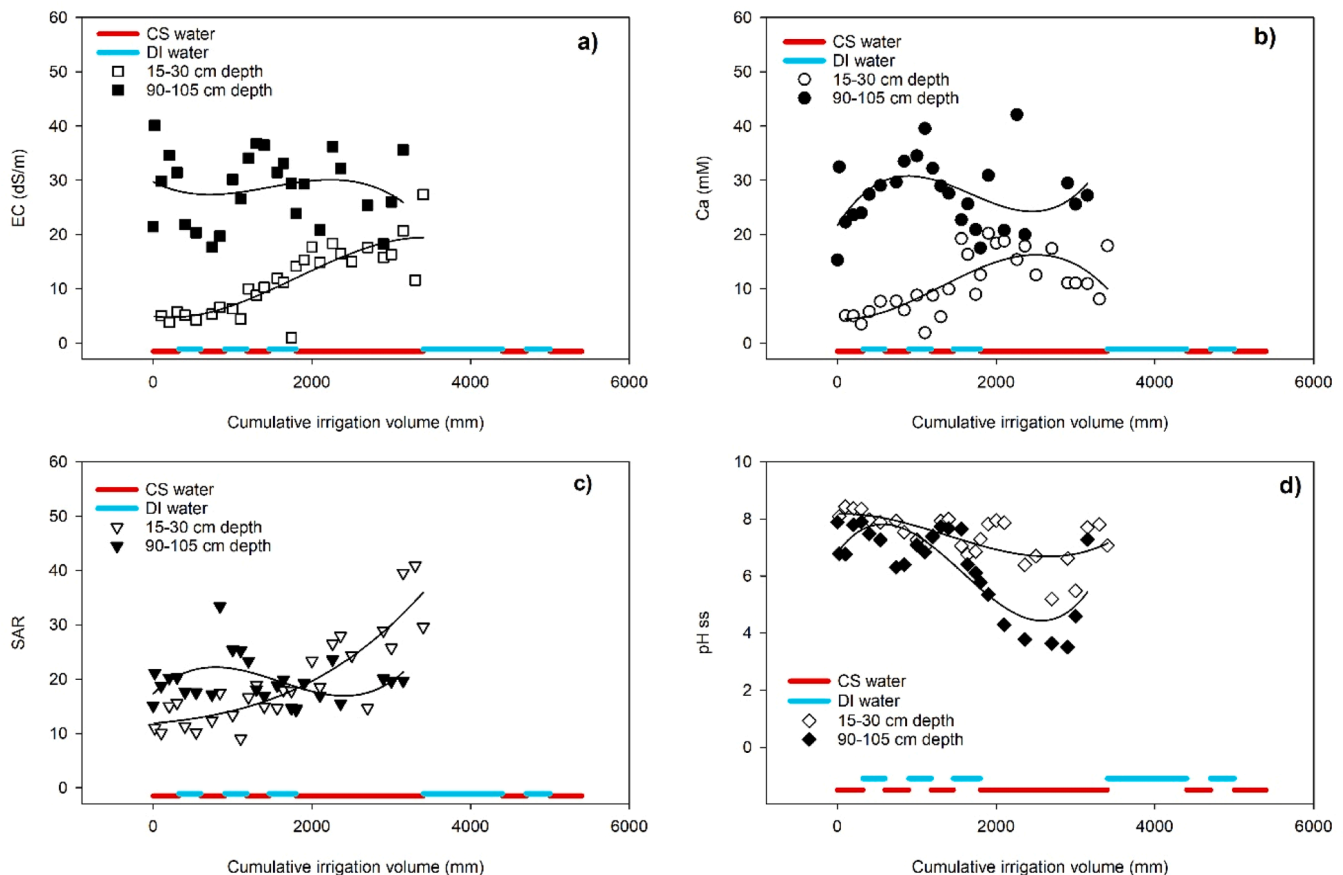


Fig. 3. Soil pore water chemistry of the Haplic Solonetz soil cores at two depths (15–30 cm and 90–105 cm) as a function of irrigation volume. Each data point is the average of three replicate cores and the two depths (15–30 cm or 90–105 cm). Volumes of coal seam (CS) water (red lines) and deionised (DI) water (blue lines) are shown as horizontal lines above the x-axis. a) Changes in EC (dS/m), (b) changes in Ca (mM), (c) changes in SAR, (d) changes in S (mM), and (e) solution pH. The lines represent the best-fit third order polynomial (SigmaPlot v14) and are shown solely for the purpose of highlighting trends in pore water chemistry.

cumulative irrigation, and after 3400 mm cumulative irrigation. With increasing irrigation, the EC_{se} in the topsoil increased to 10.5–13.6 dS/m in the Vertisol and Solonetz, but increased to 3.5 dS/m in the Lixisol. In the subsoil, the EC_{se} increased in the Haplic Solonetz and Xanthic Lixisol, but not in the Sodic Vertisol or Calcic Solonetz (Table 2). The Xanthic Lixisol had the lowest EC_{se} in topsoil (3.5 dS/m) after 3400 mm cumulative irrigation.

The exchangeable Ca^{2+} concentration increased in the topsoil of the Sodic Vertisol, Haplic Solonetz and Calcic Solonetz to 10–12 cmol(c)/kg. However, the exchangeable Ca^{2+} concentration in Xanthic Lixisol topsoil only reached 0.4 cmol(c)/kg (Table 2). In the subsoil, Ca^{2+} increased to 5.6–12 cmol(c)/kg in the three clay soils, but the permeable Xanthic Lixisol only reached 0.4 cmol(c)/kg/ (Table 2).

The ESP in the topsoil ranged between 3 and 8 prior to irrigation and increased to 28–41 in the clay soils (Sodic Vertisol, Haplic and Calcic Solonetz) or ESP 90 in the loamy Xanthic Lixisol (Table 2). The subsoil ESP ranged from 11 to 22 prior to irrigation and increased to 18–36 after 3400 mm cumulative irrigation (Table 2). Soils with an ESP > 5 are considered sodic in Australia (Northcote and Skene, 1972).

The pH fluctuated with irrigation volume and showed no consistent trend. The topsoil pH of the Sodic Vertisol, Haplic and Calcic Solonetz ranged between 7.1 and 8.0 before and after irrigation. In the subsoil, the pH ranged between 7.3 and 8.0 before irrigation and decreased slightly to between pH 5.6 and 7.7 after irrigation with 3400 mm. The topsoil pH of the Xanthic Lixisol, the topsoil pH was strongly acidic (pH 4.2) before irrigation and increased to pH 7.0 after irrigation, while the subsoil pH fluctuated between 5.7 and 6.4 (Table 2).

3.3. Infiltration rates and leaching fractions

The water infiltration rate of the cores fluctuated over time and was highly variable (Fig. 6). In the Sodic Vertisol, Haplic Solonetz and Xanthic Lixisol, irrigation with up to 3400 mm (during which time lucerne was being grown) appeared to increase the infiltration rate to 2–4 mm/min. After 3400 mm irrigation, lucerne was replaced by Rhodes grass and further irrigation caused a decrease in infiltration rate in the Xanthic Lixisol and Sodic Vertisol (the Haplic Solonetz was not irrigated further) to 0.03–0.6 mm/min (Fig. 6). In contrast, infiltration rate in the Calcic Solonetz gradually decreased with irrigation rate irrespective of the vegetation cover, but data were highly variable.

The leaching fractions were greatest in the Xanthic Lixisol, ranging between 3 % and 12 % (Table 3). The other soils had very low leaching fractions, ranging from ~0.1 % (Sodic Vertisol, Haplic Solonetz) to 0.8 % (Calcic Solonetz) (Table 3). Similar to the infiltration rates, the leaching fractions fluctuated over time, but showed no consistent trend with CS or DI water irrigation, nor was there a relationship between infiltration rate and leaching fraction (compare Fig. 6 and Table 3).

4. Discussion

During the initial 3400 mm irrigation (which included 2500 mm CS water), the EC in the topsoil pore water increased 3- to 7-fold due to the addition of salts within the CS water together with the surface application of gypsum and sulfur. The increase in EC is caused by salinity of the CS water and the added gypsum (saturated gypsum solution has an $EC \sim 2.2$ dS/m) (Oster and Frenkel, 1980). As a result of plant water

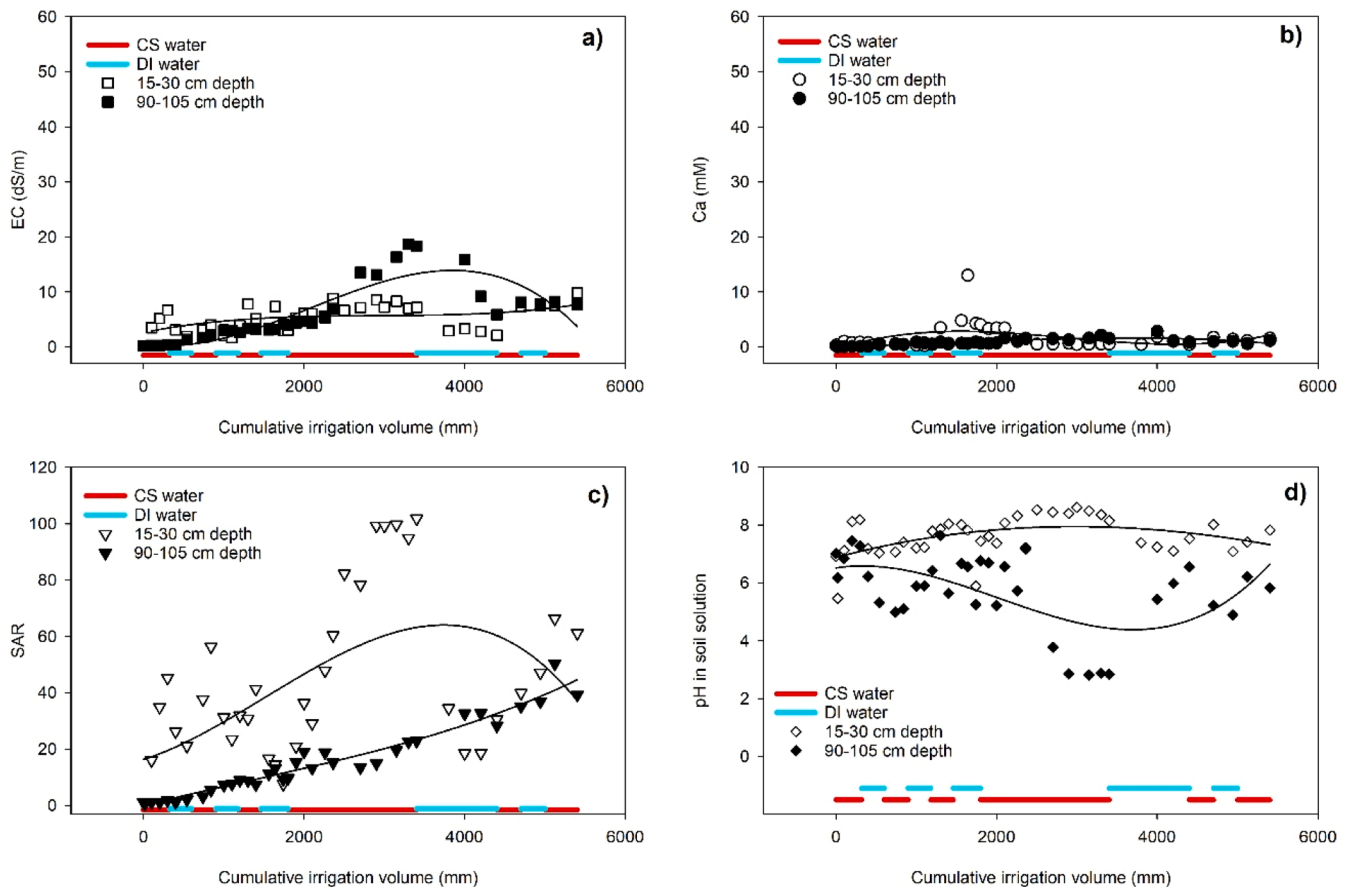


Fig. 4. Soil pore water chemistry of the Xanthic Lixisol soil cores at two depths (15–30 cm and 90–105 cm) as a function of irrigation volume. Each data point is the average of three replicate cores and the two depths (15–30 cm or 90–105 cm). Volumes of coal seam (CS) water (red lines) and deionised (DI) water (blue lines) are shown as horizontal lines above the x-axis. a) Changes in EC (dS/m), (b) changes in Ca (mM), (c) changes in SAR, (d) changes in S (mM), and e solution pH. The lines represent the best-fit third order polynomial (SigmaPlot v 14) and are shown solely for the purpose of highlighting trends in pore water chemistry.

extraction together with continued CS water irrigation, the EC gradually increased given that the added salt remained within the soil. The Haplic and Calcic Solonetz were initially saline soils (114–165 mol Na per core) and the addition of CS water added another 33 mol Na. It is common for soils in low-rainfall regions of Australia with low hydraulic conductivity to be saline and sodic (Shaw et al., 1994). The soil $EC_{1:5}$ (Table 2) mirrored the trends in soil pore water EC, and the EC_{se} (estimated from $EC_{1:5}$) being below 14 dS/m after 3400 mm irrigation in the Sodic Vertisol, Haplic, and Calcic Solonetz. The EC_{se} in the Sodic Vertisol was greater than the EC measured in a comparable study by Bennet et al. (2016) (~4 dS/m) given that their study used only a low volume of CS water (272 mm). These levels of EC in the Vertisol and Solonetz may affect salt sensitive pasture species but the Rhodes grass cultivar used here was salt tolerant, with 50 % growth reduction at EC_{se} thresholds of >20 dS/m (Giles et al., 2014; Russell, 1976; Taleisnik et al., 1997). Furthermore, Rhodes grass seed germination is only slightly inhibited in saline and alkaline solution (Wehr et al., 2016). Hence, natural recruitment of seedlings is not likely to be impaired in the field during and after CS water irrigation. While Rhodes grass was not affected by the salinity, lucerne root growth into the subsoil layer may have become impaired since its salinity tolerance is lower, with a 50 % reduction in growth at EC_{se} 6–8 dS/m (Bhardwaj et al., 2010; Giles et al., 2014; Russell, 1976).

Following the initial 3400 mm irrigation, soils were leached with 1000 mm DI water (from 3400 mm to 4400 mm cumulative irrigation volume). During this period of irrigation with 1000 mm DI water, the EC in the topsoil decreased but did not return to the initial values, hence volumes of DI water >1000 mm are needed to remove the accumulated

salts in the topsoil. Furthermore, sufficient hydraulic conductivity (and leaching fraction) is required to leach the salt from the topsoil to the subsoil, with Ganjgunte et al. (2008) and Echchel et al. (2019) stating that lighter textured soils such as sandy clay loams are more suited for irrigation with CS water since salt accumulation is less in these soils.

This is confirmed by our results showing that the Calcic Solonetz and Sodic Vertisol, which had low hydraulic conductivity (Table 1) and low leaching fractions (Table 3), showed minimal changes in subsoil pore water EC, since salt could not be effectively removed from the surface soil layers. In contrast, the sandy loam Xanthic Lixisol showed a decrease in subsoil salinity during DI water irrigation, due to its high infiltration rate (Table 1) and leaching fraction (Table 3). The DI water irrigation decreased the EC in the Xanthic Lixisol subsoil only slightly. Thus it would require several years of rainfall to leach the applied salt from the soil profile. Deep drainage may mobilise the native and applied salt to a shallow aquifer and this risk needs to be assessed during the feasibility study of CS water irrigation systems.

The Xanthic Lixisol would not be subject to soil salinity risk and could be irrigated with >3000 mm CS water since the leaching fraction was high enough to prevent a large increase in EC. Hence, plant growth was not decreased in the Xanthic Lixisol (Fig. 1) and this soil appeared to be most suitable for irrigation with CS water. When leaching salt from the topsoil (i.e. lowering the EC), it is important to supply Ca^{2+} to maintain structural stability of soil aggregates. Lowering the EC will increase soil dispersion risk and this needs to be mitigated by the application of gypsum, which maintains the soil pore water EC at ~2.2 dS/m and releases Ca^{2+} ions (Oster and Frenkel, 1980). Hence, the soil surface application of gypsum is required to maintain the topsoil

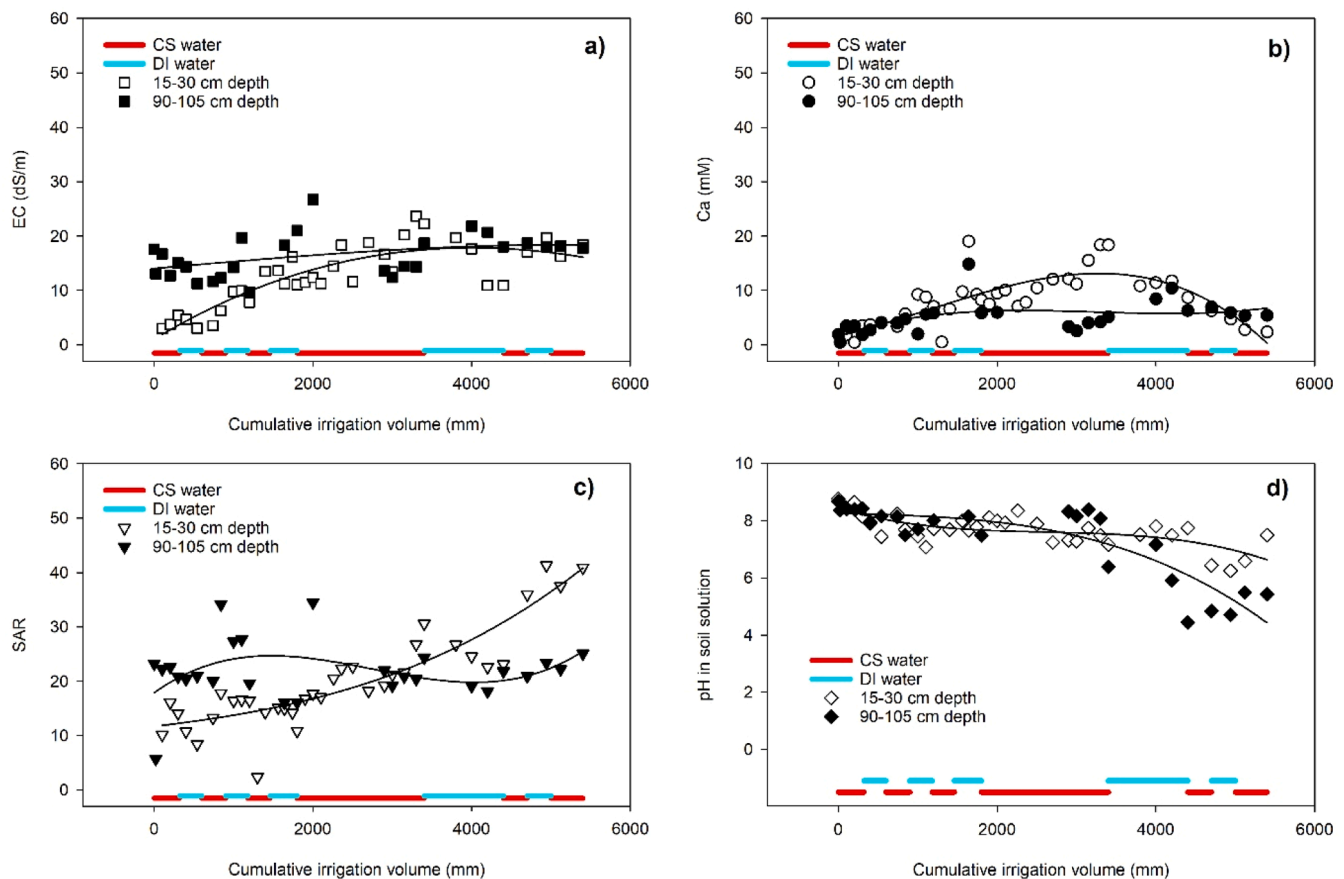


Fig. 5. Soil pore water chemistry of the Calcic Solonetz soil cores at two depths (15–30 cm and 90–105 cm) as a function of irrigation volume. Each data point is the average of three replicate cores and the two depths (15–30 cm or 90–105 cm). Volumes of coal seam (CS) water (red lines) and deionised (DI) water (blue lines) are shown as horizontal lines above the x-axis. a) Changes in EC (dS/m), (b) changes in Ca (mM), (c) changes in SAR, (d) changes in S (mM), and (e) solution pH. The lines represent the best-fit third order polynomial (SigmaPot v14) and are shown solely for the purpose of highlighting trends in pore water chemistry.

structure and water infiltration when irrigated with CS water.

The increase in SAR in the topsoil pore water, or ESP in the soil solid phase, was due to the addition of Na from the CS water. The high SAR values of the pore water lead to high ESP values on the soil exchange sites and can cause soil structural problems, especially if the pore water EC is low (Klopp and Bleam, 2021; Stavi et al., 2021). However, the dissolution of surface-applied gypsum and the dissolution of unidentified Mg-containing clay minerals (data not shown) in the soil counteracted some of the effect of applied Na^+ on SAR. Despite increasing SAR in the pore water and ESP in the solid phase of the Xanthic Lixisol, the infiltration rates did not decrease significantly and there was no relationship between infiltration rate and leaching fraction (compare Fig. 6 and Table 3). An increase in SAR to ~60 after 3600 mm CS water irrigation was also reported by McKenna et al. (2019) on a similar soil, but no effect of SAR on infiltration was reported in that study.

Although 1000 mm of DI water irrigation was not sufficient to return the SAR to initial levels, it decreased topsoil pore water SAR by over 60 % in the Sodic Vertisol and Xanthic Lixisol. In the subsoils of the two Solonetz, the pore water SAR did not change, likely due to low water movement (low leaching fraction), resulting in limited movement of Na^+ , Ca^{2+} or Mg^{2+} ions. This was likely caused by the soil structure enabling water (and thus Ca^{2+}) infiltration: the Sodic Vertisol has 2:1 clay minerals causing shrink-swelling, and the Lixisol has sandy texture, whereas the Solonetz subsoils are dominated by 1:1 clays that do not shrink and swell. While it is desirable to limit the increase in SAR by gypsum application, an increase in SAR does not always result in structural degradation of soil. The Xanthic Lixisol was not disturbed, and supported a dense sward of salt-tolerant Rhodes grass that may have

contributed root exudates to soil organic matter which can stabilise the soil particles (Niaz et al., 2022). Hence, even with SAR ~100 and ESP 90 %, the soil maintained hydraulic infiltration and leaching fractions, and did not show soil dispersion.

Solubility of gypsum strongly increases in saline solutions as a consequence of the Debye-Hückel law and at least 15 mM Ca^{2+} and SO_4^{2-} would be expected in pore water without added salt (Li and Duan, 2011; Tanji, 1969). The pore water Ca^{2+} concentration in the topsoil of the Haplic and Calcic Solonetz gradually increased to ~15 mM, but in the Sodic Vertisol and Xanthic Lixisol, it did not reach 15 mM Ca^{2+} in solution as predicted from the solubility of gypsum. It needs to be stressed that the gypsum application rate was based on the CS irrigation water application, not on the gypsum requirement of the soil. Speciation modelling using PHREEQCi with the “Phreeqc” or “minteq” databases and using the pore water composition as input parameters showed that no precipitation of Ca^{2+} as gypsum or calcite/lime was occurring in the soils. The increasing concentration of Ca held on exchange sites in the topsoil (Table 3) suggests that topsoil pore water Ca concentration is likely controlled by ion adsorption and offset by leaching of Ca into the subsoil. In soils with a high leaching fraction (Xanthic Lixisol) or preferential flow paths in the topsoil (e.g. cracks) (Sodic Vertisol), the topsoil Ca concentration remained low, likely because the Ca is leached into the subsoil. The pore water Ca concentration in the Sodic Vertisol (4–6 mM) was similar to the concentration reported by Bennett et al. (2016) for a field trial on the same soil.

In the subsoil pore water of the Calcic Solonetz, Ca concentration was low (~5–7 mM) likely due to limited movement of Ca from the topsoil layer, and adsorption of Ca in the subsoil. In Sodic Vertisol and Haplic

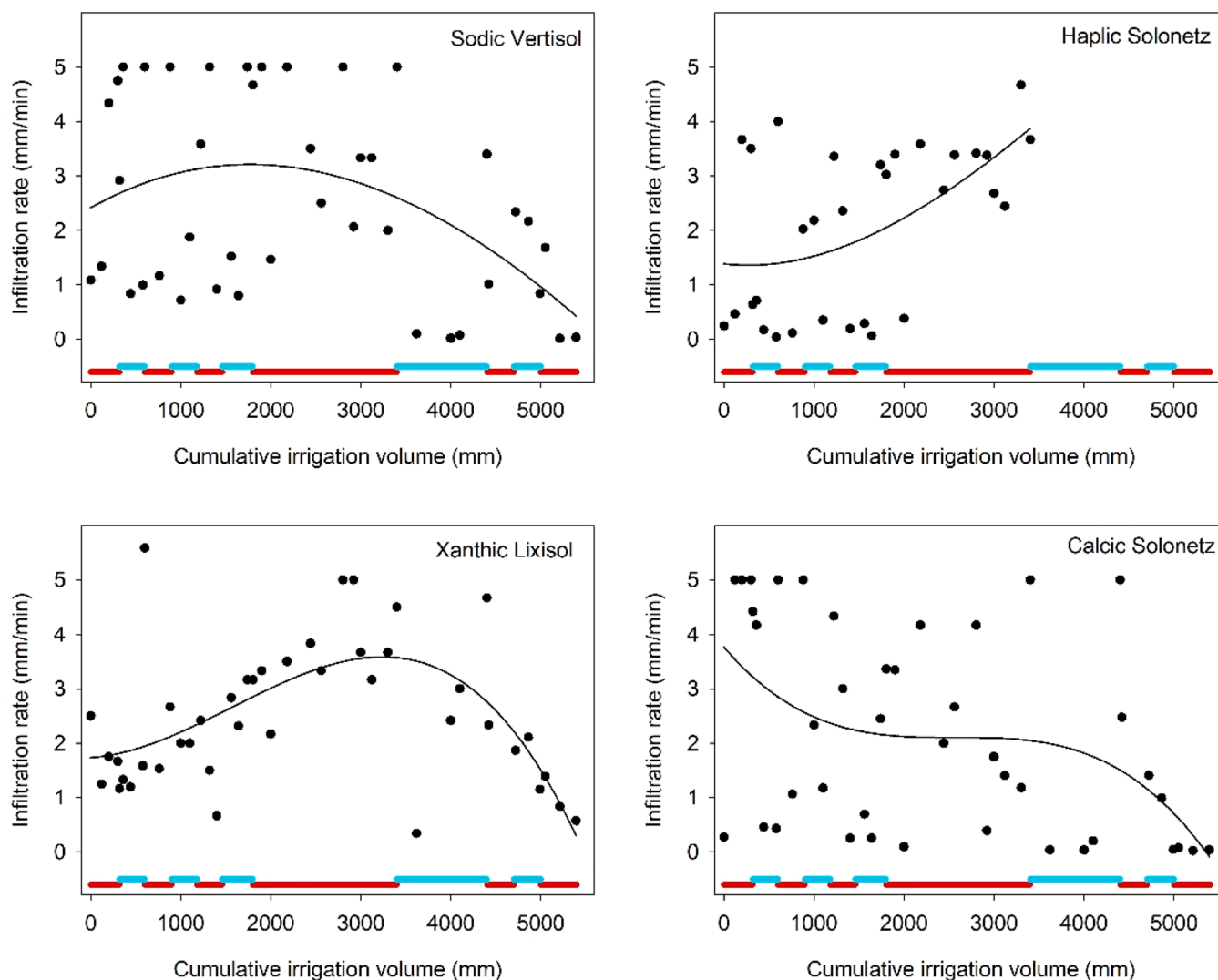


Fig. 6. Changes in water infiltration rates (mm/min) as a function of irrigation volume. Each data point is the average of three replicate cores. Volumes of coal seam (CS) water (red lines) and deionised (DI) water (blue lines) are shown as horizontal lines above the x-axis. The lines represent the best-fit third order polynomial (SigmaPlot v14) and are shown solely for the purpose of highlighting trends in infiltration.

Table 3

Leaching fractions of the four soils after increasing volumes of coal seam (CS) and deionised (DI) water were applied. Values are means $\pm$ standard deviation of three replicate cores.

Cumulative volume (mm)	Vol CS+ DI (mm)	Sodic Vertisol	Haplic Solonetz	Xanthic Lixisol	Calcic Solonetz
1800	900+900	0.0 $\pm$ 0.0 %	0.1 $\pm$ 0.1 %	6.7 $\pm$ 4.9 %	0.0 $\pm$ 0.1 %
3400	2500+900	0.0 $\pm$ 0.0 %	0.2 $\pm$ 0.3 %	3.1 $\pm$ 0.7 %	0.2 $\pm$ 0.4 %
4400	2500+1900	0.3 $\pm$ 0.3 %	-	12.0 $\pm$ 5.5 %	0.8 $\pm$ 1.0 %
5400	3200+2200	0.2 $\pm$ 0.3 %	-	5.8 $\pm$ 2.6 %	0.6 $\pm$ 0.5 %

Solonetz subsoil, the pore water Ca reached a plateau after ~ 1000 mm cumulative irrigation but the subsoil Ca concentration in the Vertisol was around 15–20 mM (as expected from the gypsum solubility) whereas the Solonetz reached a concentration of 30–40 mM. This suggests that the Ca concentration in the subsoil of the Solonetz is controlled by the extent of Ca movement into the subsoil, and limited adsorption. The increase in subsoil Ca even in soils with low LF indicates

that redistribution of Ca due to water extraction by plant roots is sufficient to move Ca to a depth of ~ 100 cm with 1000 mm of irrigation, which helped minimise changes in SAR in the subsoil pore water.

In the Xanthic Lixisol, topsoil and subsoil pore water concentration of Ca^{2+} did not reach values predicted by gypsum solubility, and this can be attributed to movement of dissolved gypsum with irrigation water since the soil was reasonably permeable and the soil had a low CEC, leading to poor retention of cations in the soil. This is also confirmed by the low exchangeable Ca^{2+} in the Xanthic Lixisol subsoil (0.4 $\text{cmol}_{\text{C}}/\text{kg}$) (Table 2). Thus, the Ca^{2+} from gypsum is leached from the Lixisol soil and the low Ca^{2+} concentration in pore water led to an increase of SAR, despite the frequent addition of gypsum at rates calculated to maintain a low SAR. This may be due to the dissolution of gypsum being slower than the rate of Na addition in CS water.

In Sodic Vertisol, the topsoil pore water pH and soil pH remained relatively constant ($\sim \text{pH } 8$), indicating that the calculated S amendment application rate based on CS water composition was correct. This finding is supported by Bennet et al. (2016) who found no changes in topsoil pH in a field irrigation trial using the same soil, but their study only applied 272 mm CS water. While the subsoil pore water pH decreased from $\sim \text{pH } 5$ to $\text{pH } 3$, this is likely due to redox processes involving Fe minerals (goethite and hematite) and does not reflect the true pH of a soil-water

suspension. Indeed, the solid phase pH varied between pH 7.3 and 5.0, suggesting that the low pH values in pore water were due to the redox reactions. It is likely that the Fe^{III} minerals (e.g. goethite or hematite) in the water-saturated anoxic subsoil become reduced to soluble Fe^{II} ions which are then extracted by pore water samplers. The Fe^{II} ions are then re-oxidised to Fe^{III} ions in the sample collection syringe and the Fe^{III} ions hydrolyse to $\text{Fe}(\text{OH})_3$ and release protons which lower the pore water pH to $\sim$ pH 3. Once the subsoil was sufficiently drained and became oxic again, the pore water pH increased again. Indeed, the solid phase samples collected from the subsoils of all soils did not show these extreme pH fluctuations, with pH values ranging from pH 5.0–8.7 (Table 2).

In the Xanthic Lixisol, topsoil was strongly acidic (pH 4.2, Table 2) and likely inhibitory to plant growth. Irrigation with CS water increased to topsoil pH to pH 5.7 after 1700 mm irrigation, thereby overcoming Al-toxicity. In a study using repacked cores with a soil similar to the Xanthic Lixisol, McKenna et al. (2019) also observed a pH increase after irrigation with 3600 mm CS water and this was attributed to the low CEC of the soil. In the Calcic Solonetz, the pH was strongly alkaline in the topsoil (pH 8.0) and subsoil (pH 8.7) (Table 2), which could lead to trace element and phosphorus immobilisation. Surface application of S and irrigation with CS water lowered the pH and made the soil more amenable to plant growth. The results for the four soils show that rate of sulfur addition, calculated from the alkalinity of the CS water was sufficient to minimise soil pH changes.

The hydraulic conductivity of the soils was highly variable due to combined effects of clay swelling, formation and stabilisation of aggregates due to root exudates, infill of pores due to root proliferation, and generation of macropores due to root decay (Lucas et al., 2022). In the Calcic Solonetz, water infiltration decreased over time, in Haplic Solonetz it increased over time and in the Sodic Vertisol and Xanthic Lixisol, the infiltration increased followed by a decrease (Fig. 6). In a short-term irrigation trial with 272 mm CS water, little effect of CS on hydraulic conductivity of the Sodic Vertisol was observed (Bennett et al., 2016). The infiltration rates did not reflect the leaching fractions (compare Fig. 6 to Table 3) likely due to multiple factors controlling leaching fractions, e.g. plant water uptake. In order to achieve leaching, more water needs to be applied than is being lost by evapotranspiration. It appears that lucerne (grown up to 3400 mm cumulative irrigation) increased infiltration rate and it has been suggested that the strong taproot in lucerne aids in penetration of water into clay layers in soils (Meek et al., 1992; Rasse et al., 2000). Once lucerne was replaced with Rhodes grass, the infiltration rate decreased and this is potentially due to the dense and fibrous nature of Rhodes grass roots that may have resulted in macropore infill (Bodner et al., 2014). Mitchell et al. (1995) have stated that lucerne produces stable macropores, resulting in high infiltration rates, whereas wheat (also a member of the Poaceae) does not produce stable macropores. Similarly, Zong et al. (2022) observed that cotton roots increased soil porosity and improves leaching on saline sodic soils. Only the Xanthic Lixisol had sufficiently high leaching fractions to allow leaching of accumulated salt and would allow for long-term sustainable irrigation with CS water and recovery of the soil during irrigation with DI water (e.g. rainfall). This result confirms observations by Echchelhel et al. (2019) that sandy soils with good drainage are less prone to salinisation.

5. Conclusions

In conclusion, changes in pore water chemistry are not a good predictor of long-term suitability for irrigation with CS water. The soil with the highest hydraulic conductivity (Xanthic Lixisol) had only limited salt accumulation and was suited for irrigation with up to 5400 mm (equivalent to 3200 mm CS water), while pasture growth was increased. Although the Xanthic Lixisol had low CEC and showed the largest increase in SAR ($\sim$ 100) and ESP ($\sim$ 80), it maintained its leaching fraction (3–12 %). This suggests that the leaching fraction is the most suitable indicator of soils suited for saline and CS water irrigation, rather than

the SAR of the water or the ESP of the soil. Soils with low hydraulic conductivity result in salt accumulation due to the low leaching fraction and these soils may require more careful management for CS water irrigation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Johannes Bernhard Wehr reports financial support was provided by Santos GLNG Pty Ltd. Peter Martin Kopittke reports financial support was provided by Santos GLNG Pty Ltd. Peter Martin Kopittke reports a relationship with Santos GLNG Pty Ltd that includes: consulting or advisory. Johannes Bernhard Wehr reports a relationship with Santos GLNG Pty Ltd that includes: consulting or advisory. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.109135.

Data Availability

Data will be made available on request.

References

- Ali, A., Biggs, A.J.W., Marchuk, A., Bennett, J.M., 2019. Effect of Irrigation Water pH on Saturated Hydraulic Conductivity and Electrokinetic Properties of Acidic, Neutral, and Alkaline Soils. *Soil Sci. Soc. Am. J.* 83 (6), 1672–1682. <https://doi.org/10.2136/sssaj2019.04.0123>.
- Bauder, J.W., Hershberger, K.R., Browning, L.S., 2008. Soil solution and exchange complex response to repeated wetting-drying with modestly saline-sodic water. *Irrig. Sci.* 26 (2), 121–130. <https://doi.org/10.1007/s00271-007-0078-8>.
- Bennett, J.M., Marchuk, A., Raine, S.R., Dalzell, S.A., Macfarlane, D.C., 2016. Managing land application of coal seam water: A field study of land amendment irrigation using saline-sodic and alkaline water on a Red Vertisol. *J. Environ. Manag.* 184, 178–185. <https://doi.org/10.1016/j.jenvman.2016.09.078>.
- Bern, C.R., Breit, G.N., Healy, R.W., Zupancic, J.W., Hammack, R., 2013. Deep subsurface drip irrigation using coal-bed sodic water: Part I. Water and solute movement. *Agric. Wat. Manag.* 118, 122–134. <https://doi.org/10.1016/j.agwat.2012.11.014>.
- Bhardwaj, S., Sharma, N., Srivastava, P., Shukla, G., 2010. Salt tolerance assessment in Alfalfa (*Medicago sativa*) ecotypes. *Bot. Res. J.* 3, 1–6. <https://doi.org/10.3923/brj.2010.1.6>.
- Bodner, G., Leitner, D., Kaul, H.-P., 2014. Coarse and fine root plants affect pores size distributions differently. *Plant Soil* 380, 133–151. <https://doi.org/10.1007/s11104-014-2079-8>.
- Curtin, D., Steppuhn, H., Mermut, A.R., Selles, F., 1995. Sodicity in irrigated soils in Saskatchewan: chemistry and structural stability. *Can. J. Soil Sci.* 75, 177–185. <https://doi.org/10.4141/cjss95-025>.
- Davies, P.J., Gore, D.B., Khan, S.J., 2015. Managing produced water from coal seam gas projects: implications for an emerging industry in Australia. *Environ. Sci. Pollut. Res.* 22, 10981–11000. <https://doi.org/10.1007/s11356-015-4254-8>.
- van de Craats, D., van der Zee, S.E.M., Sui, C., van Asten, P.J.A., Cornelissen, P., Leijnse, A., 2020. Soil sodicity originating from marginal groundwater. *Vadose Zone J.* 19 (1), e20010. <https://doi.org/10.1002/vzj2.20010>.
- Deifel, K.S., Kopittke, P.M., Menzies, N.W., 2006. Growth response of various perennial grasses to increasing salinity. *J. Plant Nutr.* 29 (9), 1573–1584. <https://doi.org/10.1080/01904160600848870>.
- DERM, 2000. Environmental Protection (Waste Management) Regulation. Guideline for approval of coal seam gas water for beneficial use. Dept. Environment and Resource Management, Queensland Government, Brisbane.
- DES, 2019. End of waste code. Irrigation of associated water (including coal seam water). Dept of Environment and Science. Queensland Government, Brisbane, p. 18.
- Echchelhel, A., Hess, T., Sakrabani, R., de Paz, J.M., Visconti, F., 2019. Assessing the environmental sustainability of irrigation with oil and gas produced water in

- drylands. *Agric. Wat. Manag.* 223, 105694. <https://doi.org/10.1016/j.agwat.2019.105694>.
- Echchel, A., Hess, T., Sakrabani, R., 2020. Agro-environmental sustainability and financial cost of reusing gasfield-produced water for agricultural irrigation. *Agric. Wat. Manag.* 227, 105860. <https://doi.org/10.1016/j.agwat.2019.105860>.
- FAO-WRB, 2015. *World reference base for soil resources 2014*. FAO, Rome.
- Ganjegunte, G.K., King, L.A., Vance, G.F., 2008. Cumulative soil chemistry changes from land application of saline-sodic waters. *J. Environ. Qual.* 37 (5), S128–S138. <https://doi.org/10.2134/jeq2007.0424>.
- Germida, J.J., Janzen, H.H., 1993. Factors affecting the oxidation of elemental sulfur in soils. *Fertil. Res.* 35, 101–114. <https://doi.org/10.1007/BF00750224>.
- Giles, H.E., Lambrides, C., Dalzell, S.A., Macfarlane, D.C., Shelton, H.M., 2014. The growth response of tropical and subtropical forage species to increasing salinity. *Trop. Grassl.* 2, 57–59. [https://doi.org/10.17138/TGFT\(2\)57-59](https://doi.org/10.17138/TGFT(2)57-59).
- Hamawand, I., Yusaf, T., Hamawand, S.G., 2013. Coal seam gas and associated water: a review paper. *Renew. Sustain. Energy Rev.* 22, 550–560. <https://doi.org/10.1016/j.rser.2013.02.030>.
- Hunt, L.P., McIvor, J.G., Grice, A.C., Bray, S.G., 2014. Principles and guidelines for managing cattle grazing in the grazing lands of northern Australia: stocking rates, pasture resting, prescribed fire, paddock size and water points – a review. *Rangel. J.* 36 (2), 105–119. <https://doi.org/10.1071/RJ13070>.
- IESC, 2014. Coal seam gas extraction and co-produced water. In: Australian Government, DoE. (Ed.), *Indep. Expert Sci. Comm. Coal Seam. Gas. Large Coal Min. Dev.*, Canberra ACT 5.
- Isbell, R.F., National Committee on Soil and Terrain, 2021. *The Australian Soil Classification*. CSIRO Publishing, Melbourne, p. 181.
- Jakubowski, R., Haws, N., Ellerbroek, D., Murtagh, J., Macfarlane, D., 2014. Development of a Management Tool to Support the Beneficial Use of Treated Coal Seam Gas Water for Irrigation in Eastern Australia. *Mine Water Environ.* 33 (2), 133–145. <https://doi.org/10.1007/s10230-013-0246-4>.
- Johnston, C.R., Vance, G.F., Ganjigunte, G.K., 2008. Irrigation with coalbed natural gas co-produced water. *Agric. Wat. Manag.* 95 (11), 1243–1252. <https://doi.org/10.1016/j.agwat.2008.04.015>.
- Johnston, C.R., Vance, G.F., Ganjigunte, G.K., 2013. Soil property changes following irrigation with coalbed natural gas water: role of water treatments, soil amendments and land suitability. *Land Degrad. Dev.* 24 (4), 350–362. <https://doi.org/10.1002/ldr.1132>.
- Klopp, H., Bleam, W., 2021. The Effects of Soil Solution Electrical Conductivity and Sodium Adsorption Ratio on Soil Liquid Limit and Soil Strength. *Commun. Soil Sci. Plant Anal.* 52 (21), 2644–2653. <https://doi.org/10.1080/00103624.2021.1953060>.
- Li, J., Duan, Z., 2011. A thermodynamic model for the prediction of phase equilibria and speciation in the H₂O–CO₂–NaCl–CaCO₃–CaSO₄ system from 0 to 250°C, 1 to 1000 bar with NaCl concentrations up to halite saturation. *Geochim. Cosmochim. Acta* 75 (15), 4351–4376. <https://doi.org/10.1016/j.gca.2011.05.019>.
- Lucas, M., Nguyen, L.T.T., Guber, A., Kravchenko, A.N., 2022. Cover crop influence on pore size distribution and biopore dynamics: emerging root and soil faunal effects. *Front. Plant Sci.* 13, 928569. <https://doi.org/10.3389/fpls.2022.928569>.
- Majee, U., Chattopadhyay, G.N., Chaudhury, S., 2018. Qualitative assessment of coal bed methane produced water for developing safe disposal strategies. *Environ. Earth Sci.* 77 (15). <https://doi.org/10.1007/s12665-018-7736-4>.
- McKenna, B.A., Kopittke, P.M., MacFarlane, D.C., Dalzell, S., Menzies, N.W., 2019. Changes in soil chemistry after the application of gypsum and sulfur and irrigation with coal seam water. *Geoderma* 337, 782–791. <https://doi.org/10.1016/j.geoderma.2018.10.019>.
- Meek, B., Rechel, E., Carter, L., DeTar, W., Urie, A., 1992. Infiltration rate of a sandy loam soil: effects of traffic, tillage and plant roots. *Soil Sci. Soc. Am. J.* 56, 908–913. <https://doi.org/10.2136/sssaj1992.03615995005600030038x>.
- Mendhe, V.A., Mishra, S., Varma, A.K., Singh, A.P., 2017. Coalbed methane-produced water quality and its management options in Raniganj Basin, West Bengal, India. *Appl. Water Sci.* 7 (3), 1359–1367. <https://doi.org/10.1007/s13201-015-0326-7>.
- Meng, Y.J., Tang, D.Z., Xu, H., Li, Y., Gao, L.J., 2014. Coalbed methane produced water in China: status and environmental issues. *Environ. Sci. Pollut. Res.* 21 (11), 6964–6974. <https://doi.org/10.1007/s11356-014-2675-4>.
- Menzies, N., Guppy, C., 2000. In-situ soil solution extraction with polyacrylonitrile hollow-fibers. *Commun. Soil Sci. Plant Anal.* 31 (11–14), 1875–1886. <https://doi.org/10.1080/00103620009370544>.
- Millar, G.J., Couperthwaite, S.J., Moodliar, C.D., 2016. Strategies for the management and treatment of coal seam gas associated water. *Renew. Sustain. Energy Rev.* 57, 669–691. <https://doi.org/10.1016/j.rser.2015.12.087>.
- Mitchell, A.R., Ellsworth, T.R., Meek, B.D., 1995. Effect of root systems of preferential flow in swelling soil. *Commun. Soil Sci. Plant Anal.* 26, 2655–2666. <https://doi.org/10.1080/00103629509369475>.
- Navi, M., Skelly, C., Taulis, M., Nasiri, S., 2015. Coal seam gas water: potential hazards and exposure pathways in Queensland. *Int. J. Environ. Health Res.* 25 (2), 162–183. <https://doi.org/10.1080/09603123.2014.915018>.
- Nghiem, L.D., Ren, T., Aziz, N., Porter, I., Regmi, G., 2011. Treatment of coal seam gas produced water for beneficial use in Australia: A review of best practices. *Desalin. Water Treat.* 32 (1–3), 316–323. <https://doi.org/10.5004/dwt.2011.2716>.
- Niaz, S., Wehr, J.B., Dalal, R.C., Kopittke, P.M., Menzies, N.W., 2022. Organic amendments and gypsum reduce dispersion and increase aggregation of two sodic Vertisols. *Geoderma* 425. <https://doi.org/10.1016/j.geoderma.2022.116047>.
- Northcote, K.H., Skene, J.K.M., 1972. *Australian soils with saline and sodic properties*. CSIRO, Melbourne.
- NSW-EPA, 2015. *Produced water and coal seam gas*. NSW Government, Sydney.
- Oster, J.D., Frenkel, H., 1980. The chemistry and reclamation of sodic soils with gypsum and lime. *Soil Sci. Soc. Am. J.* 44, 41–45. <https://doi.org/10.2136/sssaj1980.03615995004400010010x>.
- O'Sullivan, D., 2013. In: Fisheries, F. Dept. Agriculture (Eds.), *Pasture management for South East Queensland*. Queensland Government, Brisbane, pp. 1–69.
- Pachas, A.N.A., Shelton, H.M., Lambrides, C.J., Dalzell, S.A., Macfarlane, D.C., Murtagh, G.J., 2016. Water use, root activity and deep drainage within a perennial legume-grass pasture: A case study in southern inland Queensland, Australia. *Trop. Grassl. -Forrages Trop.* 4 (3), 129–138. [https://doi.org/10.17138/tgft\(4\)129-138](https://doi.org/10.17138/tgft(4)129-138).
- Page, K.L., et al., 2018. Management of the major chemical soil constraints affecting yields in the grain growing region of Queensland and New South Wales, Australia - a review. *Soil Res.* 56 (8), 765–779. <https://doi.org/10.1071/sr18233>.
- Parkhurst, D.L. and Appelo, C.A.J., 2013. Description of input and examples for PHREEQC version 3: a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. 6-A43, Reston, VA. <https://doi.org/10.3133/tm6A43>.
- Qadir, M., Oster, J.D., Schubert, S., Noble, A.D., Sahrawat, K.L., 2007. Phytoremediation of sodic and saline-sodic soils. *Adv. Agron.* 96, 197–247. [https://doi.org/10.1016/S0065-2113\(07\)96006-X](https://doi.org/10.1016/S0065-2113(07)96006-X).
- Rasse, D.P., Smucker, A.J.M., Santos, D., 2000. Alfalfa root and shoot mulching effects on soil hydraulic properties and aggregation. *Soil Sci. Soc. Am. J.* 64, 725–731. <https://doi.org/10.2136/sssaj2000.642725x>.
- Rebello, C.A., Couperthwaite, S.J., Millar, G.J., Dawes, L.A., 2017. Coal seam water quality and the impact upon management strategies. *J. Pet. Sci. Eng.* 150, 323–333. <https://doi.org/10.1016/j.petrol.2016.12.022>.
- Rice, C.A., Nuccio, V., 2000. In: USGS (Ed.), *Water produced with coal-bed methane*. United States Geological Service, Denver, CO.
- Russell, J., 1976. Comparative salt tolerance of some tropical and temperate legumes and tropical grasses. *Aus. J. Exp. Agric.* 16 (78), 103–109. <https://doi.org/10.1071/EA9760103>.
- Shainberg, I., Sumner, M.E., Miller, W.P., Farina, M.P.W., Pavan, M.A., Fey, M.V., 1989. Use of gypsum in soil: a review. In: Stewart, B.A. (Ed.), *Advances in Soil Sciences*. Springer, New York, pp. 1–111. https://doi.org/10.1007/978-1-4612-3532-3_1.
- Shaw, R., Brebber, L., Ahern, C., Weinand, M., 1994. A review of sodicity and sodic soil behaviour in Queensland. *Aust. J. Soil Res.* 32, 143–172. <https://doi.org/10.1071/SR9940143>.
- Stavi, I., Thevs, N., Priori, S., 2021. Soil salinity and sodicity in drylands: a review of causes, effects, monitoring, and restoration measures. *Front. Environ. Sci.* 9, 712831. <https://doi.org/10.3389/fenvs.2021.712831>.
- Sumner, M.E., Miller, W.P., 1996. Cation Exchange Capacity and Exchange Coefficients. *Methods Soil Anal.* 1201–1229. <https://doi.org/10.2136/sssabookser5.3.c40>.
- Taleisnik, E., Peyrano, G., Arias, C., 1997. Response of *Chloris gayana* cultivars to salinity. 1. Germination and early vegetative growth. *Trop. Grassl.* 31, 232–240.
- Tanji, K., K., 1969. Solubility of gypsum in aqueous electrolytes as affected by ion association and ionic strengths up to 0.15M and at 25°C. *Environ. Sci. Technol.* 3, 656–661. <https://doi.org/10.1021/es60030a003>.
- Wehr, J.B., Kopittke, P.M., Dalzell, S.A., Menzies, N.W., 2016. Germination of leucaena and Rodes grass seeds in saline and alkaline conditions. *Seed Sci. Technol.* 44, 461–474. <https://doi.org/10.15258/sst.2016.44.3.06>.
- Zong, R., Han, Y., Tan, M., Zou, R., Wang, Z., 2022. Migration characteristics of soil salinity in saline-sodic cotton field with different reclamation time in non-irrigation season. *Agric. Wat. Manag.* 263, 107440. <https://doi.org/10.1016/j.agwat.2021.107440>.