CSIRO PUBLISHING
www.publish.csiro.au/journals/sr *Soil Research*, 2011, **49**, 424–438

Deep drainage rates of Grey Vertosols depend on land use in semi-arid subtropical regions of Queensland, Australia

D. M. Silburn[A,F], *P. E. Tolmie*[A], *A. J. W. Biggs*[B,C], *J. P. M. Whish*[D], *and V. French*[E]

[A]Agricultural Production Systems Research Unit, Department of Environment and Resource Management, PO Box 318, Toowoomba, Qld 4350, Australia.
[B]Department of Environment and Resource Management, PO Box 318, Toowoomba, Qld 4350, Australia.
[C]The University of Queensland, School of Land, Crop and Food Sciences, St Lucia, Qld 4072, Australia.
[D]Agricultural Production Systems Research Unit, CSIRO, PO Box 318, Toowoomba, Qld 4350, Australia.
[E]Formerly: Primary Industries and Fisheries, Department of Employment, Economic Development and Innovation, PO Box 61, Miles, Qld 4415, Australia.
[F]Corresponding author. Email: mark.silburn@derm.qld.gov.au

Abstract. Changes in land use can affect the soil water balance and mobilise primary salinity. This paper examines changes in soil chloride (Cl) and deep drainage under pasture and annual cropping on five gilgaied Grey Vertosols in southern inland Queensland, Australia, comparing them to remnant native vegetation. Transient soil Cl mass-balance (CMB) was used for crop and pasture sites, as it is suitable for determining the long-term, low rates of drainage since clearing some 40–50 years ago. Steady-state CMB was used for native vegetation.

Large masses of salts and Cl were stored under native vegetation (31–103 t/ha of Cl to 3.2 m), and deep drainage was low (0.10–0.27 mm/year). The Cl profiles were generally of a normal shape for matrix flow (e.g. no bypass flow). Soil Cl was lost under cropping (average 65% lost to 1.4 m) and pasture (32%) compared with native vegetation. This lost Cl was not stored within the top 4–5 m of soil, indicating movement of water below 4–5 m. Deep drainage averaged 10 mm/year under cropping for both gilgai mounds and depressions (range 2.7–25 mm/year), and 3.3 and 5.1 mm/year under pasture for mounds and depressions, respectively. Subsoil (depth 1.5–4+ m) was generally dry under native vegetation and wetter under cropping and pasture. Deep drainage over the last 40–50 years was stored in the unsaturated zone (to deeper than 4+ m), indicating a long time lag between land-use change and groundwater response. Steady-state CMB greatly underestimated drainage for crop and pasture sites.

Additional keywords: dryland salinity, gilgai, native vegetation, Queensland, steady-state mass-balance, tillage, transient mass-balance, Vertosol.

Introduction

The salinity hazard map for the Queensland Murray–Darling Basin, Australia, was released in July 2002 (NRM 2002). It illustrated inherent salinity hazard, based on a combination of the presence of salt, recharge potential, and discharge potential. A large part of the former Tara Shire in southern Queensland (now part of Dalby Regional Council) was indicated as high hazard, prompting two pro-active farmer groups to seek more information about salinity in their area.

A key driver for the conversion of a high salinity hazard to a salinity risk is an increase in deep drainage (potential groundwater recharge) with change in land use from native vegetation to cropping or grazing (Scanlon *et al*. 2007; Silburn *et al*. 2008, 2009; Robinson *et al*. 2010). The farmer groups were comfortable with crop modelling presented to them as part of a previous project (Hochman 2006) but were sceptical about drainage estimates from the modelling. However, they still saw deep drainage as an issue, particularly with publicity concerning salinity at the time.

The questions were: do Grey Vertosols drain significantly in this semi-arid subtropical environment; are current land-use practices affecting drainage, and if so are they mobilising the stored salt; and finally, if salt is being mobilised where is it going?

Deep drainage can be determined by direct measurement (lysimetry), soil physics methods, measured (drainage by difference) or modelled soil water balance, groundwater level analysis, or using tracers such as chloride (Cl) in the soil or groundwater (Walker *et al*. 2002; Zhang and Walker 2002). Most of these methods were considered unsuitable for determining long-term average deep drainage in the study area in the time available. For instance, lysimetry, soil physics, and measured water balance require measurements over a period of years, a task which is more difficult in areas such

10.1071/SR10216 1838-675X/11/050424

as southern inland Queensland where drainage is episodic due to high rainfall variability (Yee Yet and Silburn 2003). Groundwater analysis was not suitable for the study area, as there are few monitoring bores and water level records are restricted to the last few years. Sub-artesian groundwater in the area is highly saline and of low yield, and typically does not respond to rainfall (Biggs *et al*. 2005). Recharge estimation using groundwater chemical or tracer methods would only yield estimates of the pre-clearing situation (Cartwright *et al*. 2007).

In contrast, soil Cl mass-balance (CMB) can estimate long-term drainage for the period (decades) since land clearing (Tolmie *et al*. 2003, 2011; Silburn *et al*. 2009). Steady-state CMB (USSL 1954) will give an estimate of deep drainage under pre-clearing land use. However, use of steady-state CMB for sites after a change in land use and deep drainage will give erroneous estimates of deep drainage (Thorburn *et al*. 1991; Silburn *et al*. 2009). Transient CMB (Rose *et al*. 1979; Walker *et al*. 1991) on soil Cl profiles from paired sites with pre-clearing and current land use (crop or pasture) provides an estimate of drainage since the change in land use. As the soils in the study area typically have high salinity and Cl concentrations in the subsoil, they are ideal for Cl studies; the Cl tracer method cannot be used where soil Cl is low. The transient CMB of Rose *et al.* (1979) is applicable where soil Cl is sampled within and somewhat below the depth of the root-zone, whereas the Cl front displacement method of Walker *et al*. (1991) is suitable where the unsaturated zone can be sampled to below the depth of displacement of the chloride and newly added soil water after a change in land use (e.g. tens of metres). The latter method generally requires drilling, and obtaining replicate cores is expensive, whereas for the former method samples can be obtained using soil sampling equipment (available to us), and replicate cores can be obtained with minimal expense.

Transient soil CMB has been successfully applied to Vertosols in the Queensland Murray–Darling Basin (Tolmie *et al*. 2011) and the Fitzroy Basin, Queensland (Radford *et al.* 2009; Silburn *et al*. 2009). Deep drainage rates obtained were reasonably similar to estimates from soil water balance modelling (Owens *et al*. 2004; Whish *et al*. 2006; Huth *et al.* 2010). Soil water balance modelling has also been used in and around the study area and is reported elsewhere (Yee Yet and Silburn 2003; Whish *et al*. 2006; Silburn *et al*. 2007; Robinson *et al*. 2010). However, without independent estimates of deep drainage such as those provided by transient CMB, there is a high level of uncertainty with modelled estimates. Deep drainage is the smallest component of the water balance in semi-arid environments, and any error in the other, larger water balance terms will lead to large errors in deep drainage.

The effects of gilgai microrelief, which is common in the study area (Van Dijk 1985; Maher 1996), on soil water balance and chemistry are also of interest. Gilgai is surface microrelief associated with soils containing shrink–swell clay and consists of mounds and depressions showing varying degrees of order (McDonald *et al*. 1990). In theory, crops and pastures growing in gilgai mounds should extract less water, as mounds typically have greater soil chemical and physical limitations to plant growth. On the other hand, being convex (and often surface crusting), there is a likelihood that they shed water, and thus infiltration (and therefore potential water for deep drainage) is less. However, water lies in depressions after rain, often for weeks, which may increase deep drainage compared with mounds.

This paper will show that despite soils being heavy clays (sodic Grey Vertosols) in a semi-arid, subtropical environment, episodic deep drainage does occur and drainage rates are significantly influenced by land use. However, deep drainage over the last 40–50 years is currently stored in the unsaturated zone below the root-zone, indicating a long time lag between land use change and groundwater response.

Materials and methods

Study area

The study area is in southern inland Queensland (Fig. 1). It experiences a subtropical climate and summer-dominant rainfall. It includes portions of the Condamine–Balonne and Moonie catchments, to the north and south, respectively. Mean annual rainfall is 616 mm at Tara, using the SILO Patched Point Dataset (Jeffrey *et al*. 2001). The landscape is dominated by residual plains of Quaternary alluvia, surrounded by undulating plains to rises of Jurassic to Cretaceous sediments. The latter are primarily labile and argillaceous, but are often deeply weathered (to depths of up to 30 m). The Condamine sites are on younger alluvia of the Condamine River and have less well-developed, smaller gilgai than at Moonie sites, which are on older alluvia. Soils of the area were mapped at a regional scale by Maher (1996) and the suggested provenance of the residual plains was discussed by Van Dijk (1985).

Hydrogeology, catchment scale salinity trends, and land-use history are described by Biggs *et al*. (2005). Pre-European vegetation was dominated by brigalow (*Acacia harpophylla*) open woodland. Extensive clearing only commenced following the eradication of prickly pear in the early 1930s. Mechanisation in the 1950s led to increased development for cropping.

The dominant soils under brigalow in the area are sodic to strongly sodic Grey Vertosols with weak to very strong gilgai microrelief (Maher 1996). These Vertosols are often characterised by a strong pH inversion. The upper profile (generally <1 m depth) is strongly alkaline, and often contains free calcium carbonate as small concretions or soft segregations, with low to moderate salinity (measured as electrical conductivity (EC) and Cl). The lower profile is often strongly acid, gypseous, and high in Cl. The boundary between the two zones is typically abrupt. It has generally been assumed that the point of change corresponds to the long-term wetting front (depth of leaching) in these soils.

Morphology varies between mound and depression, particularly in areas with large gilgai (vertical interval >0.25 m, horizontal interval ~5 m). The surface of the mounds is typically lighter in texture, is crusting, possesses carbonate concretions, and has sparser ground cover. Surface soils in depressions are typically heavier in texture, self-mulching/strongly cracking, well-vegetated in pastures, and have better fertility. Calcium carbonate is generally absent.

Field sites

Sites with natural woodland, long-term pasture and long-term cropping in close proximity and on the same soil type were

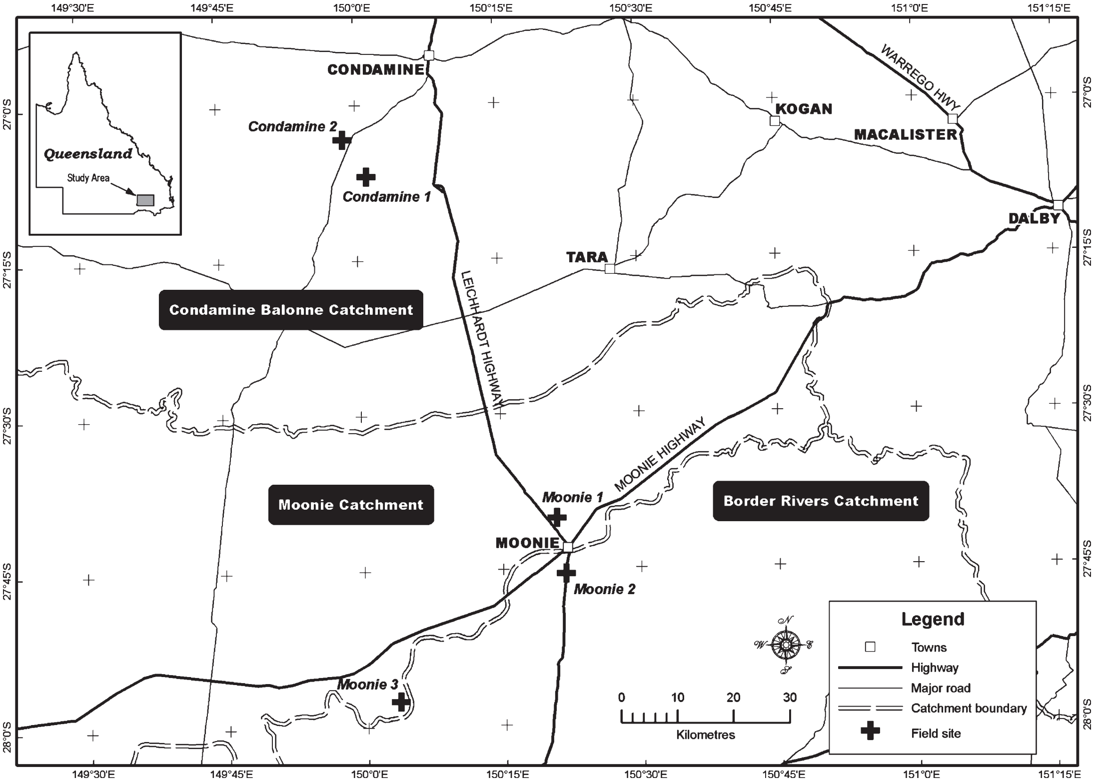

Fig. 1. Location of the study area and sampling sites.

sought. Five sites were selected, each with all land uses, three in the Moonie catchment and two in the Condamine, all roughly 100 km apart by road (Table 1, Fig. 1). The native vegetation was brigalow and belah (*Casuarina cristata*) and clearing took place ~35–50 years ago. Sites were geolocated and soil morphology was described. Soils at all sites were Grey Vertosols (Isbell 1996). No pasture site was available at the Moonie 1 site.

Data collection

A hydraulic soil coring rig was used to take 50-mm-diameter soil cores to a depth of ~4 m, for chemical analysis and soil water content. The sampling protocol was designed to account for variability associated with gilgai. Therefore, three adjacent pairs of mounds/depressions were identified for each land use at each site. Each mound or depression was sampled separately by taking three cores within each and bulking (giving a total of one replicate, comprising three bulked cores for each of the three mounds or depressions) for chemical analysis; these were duplicated for measurement of soil water content (air-dry and field). The three mounds and three depressions gave a total of six sampled points per paddock. Morphology was described according to the national standard (McDonald *et al.* 1990). Frequent in-field morphology comparisons were made between the cores to ensure minimal morphological difference.

As these soils have a very abrupt chemical change, generally around 0.7–0.9 m, cores were separated into 0.1-m increments to 1.5 m depth in order not to blur this boundary more than necessary. Below this, 0.3-m increments were used for the rest of the profile (i.e. 21–26 increments per core, depending on length). To contain costs, alternate increments were analysed. All samples were archived.

Soil samples were analysed by Department of Environment and Resource Management (DERM) laboratories for pH (method 4A1), $EC_{1:5}$ (method 3A1) and Cl (method 5A2) on a 1 : 5 soil : water extract, and particle size analysis, exchangeable cations, and cation exchange capacity (CEC) using the methods of Rayment and Higginson (1992). Only EC and Cl data are presented here. All Cl concentrations (mg/kg) were calculated on an oven-dry (OD) basis before drainage (mm/year), and mass of Cl (t/ha) was determined. One mound at Condamine 1, native vegetation area (described as 'red mound, different from other mounds'), had considerably more Cl than other profiles at Condamine 1; this profile was considered unusual and the data were excluded from further analysis. Soil water content data are not available for the Moonie 2 site.

Deep coring to 8 m

On seeing the preliminary results, the farmers asked the obvious question: *where is the lost Cl and water going*? Therefore, an initial investigation was made with deeper cores collected at one location (Moonie 1). Soil cores (43 mm diameter) were taken to a depth of ~8 m in the native vegetation and cropped site mounds using a Geoprobe. Morphology was described and measurements were made of soil water content, matric potential

Table 1. Summary of information on field sites

Location is for native vegetation, mound rep 1, using Geocentric Datum of Australia (GDA 94). Maximum sampling depth is different from maximum reporting depth which, for ease of comparison between treatments, was set at 3.2 m, i.e. the shortest maximum. Underlined years indicate when land clearing occurred which were used to calculate 'years since clearing'

Site	Location (lat. S, long. E)	Clearing history	Years of new land use	Land uses	Max. sampling depth (m)	Cl in rain[A] (mg/L)
Moonie 1	–27.66984, 150.34912	Native vegetation: Brigalow regrowth. Crop: 1930s ringbarked; native pasture (probably Queensland blue grass) grazed; some brigalow, belah, and box suckers; 1967 cleared and ploughed for cultivation	36	Native veg., crop	3.2 (native veg.), 4.5 (crop)	1.77
Moonie 2	–27.75926, 150.36346	Native vegetation: Brigalow regrowth. Crop and pasture: 1930s ringbarked; native pasture (probably Queensland blue grass) grazed; some brigalow, belah, and box suckers. Crop: 1966–67 pulled; 1971 stick-raked offsets and prepared for wheat; deep ripped. Pasture: no raking and no ploughing	3636	Native veg., crop, pasture	3.9 (all)	1.77
Moonie 3	–27.96013, 150.05988	Native vegetation: Brigalow regrowth. Crop: 1934–35 ringbarked with ~80% clearance of brigalow and belah; 1968 pulled, ~60% recovered by brigalow and belah; 1974 raked and ploughed. Pasture: same as cropping paddock to 1976; 1976 pulled and raked; 1981 prepared and planted to wheat (poor crop, undersown with medic); 1982 wheat (poor crop); 1983 planted to purple pigeon grass; 1983–2004 grazed by cattle	2929	Native veg., crop, pasture	4.8 (all)	1.59
Condamine 1	–27.11622, 150.01868	Native vegetation: Brigalow, never cleared. Crop: 1955 pulled and burnt; native pasture (probably Queensland blue grass) grazed by cattle, lightly suckered and suckers kept under control with occasional fire; 1970 stick-raked and ploughed for cultivation, no levelling despite large gilgai. Pasture: cleared 1967, cropped for a couple of years, pasture since early 1970s (buffel and medic); some minor cultivation but mainly buffel pasture; no levelling at all	3340	Native veg., crop, pasture	3.9 (native veg.), 4.8 (pasture, crop)	1.62
Condamine 2	–27.05563, 149.97714	Native vegetation: Brigalow, never cleared. Crop: 1957 cleared. Pasture: 1957 cleared; 1958 not cultivated; natural spread of buffel grass and medic	4646	Native veg., crop, pasture	3.9 (all)	1.60

[A] Biggs (2006).

(using a psychrometer), $EC_{1:5}$, Cl, and pH. The deeper cores taken with the Geoprobe expanded during extraction; thus, the measured matric potential was greater (drier) than the actual *in situ* matric potential for moister samples; the error would be minimal for dry soil. However, the data still provide a useful relative measure of the water status, because the contrast between the native vegetation and cropped cores was so large.

Chloride balance

Deep drainage under native vegetation was determined using steady-state CMB (USSL 1954). Transient CMB (Rose *et al.* 1979; Thorburn *et al.* 1990, 1991) was used to calculate deep drainage under cleared sites by comparing data from the crop and pasture sites with data from the native vegetation sites. The Cl profiles from native vegetation are assumed to represent the profile for the paired crop or pasture site at the time of initial development. Soil sampling at the Brigalow Catchment Study over two decades showed no change in Cl under native vegetation over time (Silburn *et al.* 2009).

Chloride mass-balance relies on the water-soluble nature of Cl and assumes complete mixing of Cl in the soil and water. Results from the transient analysis indicate the average deep drainage that has occurred since the land was cleared for farming or grazing. The transient CMB method is widely reported (Rose *et al.* 1979; Slavich and Yang 1990; Thorburn *et al.* 1990, 1991; Tolmie *et al.* 2003; Silburn *et al.* 2009) and is coded a Microsoft Excel spreadsheet used with Visual Basic (Tolmie *et al.* 2003), and will not be repeated here.

Data required for the analysis are Cl concentration for each soil layer (mg/kg OD), time between sampling (years), rainfall (mm/year), Cl concentration of rainfall (mg/L), drained upper limit (DUL) water content (g/g), and bulk density for each soil layer (kg/m^3). Bulk density is used to convert soil Cl concentrations to mass per unit area (kg/ha). The drainage calculation is not affected by bulk density. The DUL is used to calculate the average solute concentration in the leachate at a specified depth. Chloride concentration in rain (Table 1) was determined as a function of distance from the coast using equation 3 in Biggs (2006), and rainfall data were obtained from the SILO database (Jeffrey *et al.* 2001). The transient CMB is only slightly sensitive to the amount and Cl concentration of rainfall, while drainage calculated with the steady-state CMB is directly proportional to these values (Tolmie *et al.* 2003). Removal of Cl in harvested grain could alter the CMB of cropped sites but this is expected to be minor and have only a small influence on calculated deep drainage (Tolmie *et al.* 2011).

Bulk density and DUL were measured to 1.8 m at each cropped site using the method of Dalgliesh and Foale (1998), whereby the soil is wet, covered, and allowed to drain to DUL before sampling. Bulk density and DUL at 1.5–1.8 m were used for soil from 1.8 to 3.2 m. Deep drainage was calculated with both the steady-state and transient CMB for each sampling increment below the root-zone (1.4 m) to 3.2 m, and these results were averaged, as explained by Willis and Black (1996). This was done, firstly, because the root-zone is imprecise; and secondly, the deep drainage values calculated for each sampling increment are typically reasonably similar but this approach averages out small variations caused by variation in soil Cl in individual layers.

Time since clearing was determined from farmers' records and air photos. Detailed paddock histories of the farmers' cropping sequences, rainfall, and land management methods were collected to help interpret drainage results. These histories were also used as the basis for soil water balance modelling to further understand the sequence of drainage and to help identify suitable management strategies to profitably farm with reduced drainage (Whish *et al.* 2006).

Leachate Cl and EC

The mean Cl concentration (mg/L) of leachate below 1.4 m was calculated by dividing the total Cl loss by the total deep drainage below 1.4 m. The leachate EC is an estimate calculated from the Cl concentration by multiplying by 1.648 to determine concentration of NaCl, and dividing by 0.7, the ratio of total dissolved ions to EC for groundwater in the relict alluvia and underlying Griman Creek Formation (Biggs *et al.* 2005).

Results and discussion

Native vegetation: EC and Cl profiles and deep drainage

The shapes of soil EC and Cl profiles give an indication of drainage processes (Allison *et al.* 1994; SalCon 1997). In a 'normal' profile, Cl is low in the surface, increases to a maximum, and then remains more-or-less constant with depth. This shape is expected for water and salt drainage by matrix flow in a uniform soil with moderate-to-low permeability and subject to evapotranspiration (Raats 1974; SalCon 1997). A normal profile indicates that the site has not been subject to palaeoclimate variations, bypass flow or diffusion to a watertable (Allison *et al.* 1994) or influential changes in texture. The EC and Cl profiles had reasonably normal shapes in the native vegetation at Moonie 1 in depressions, at Moonie 2 in mounds and depressions (Fig. 2), and at Condamine 1 in mounds and depressions (Fig. 3); and almost normal shapes in mounds at Moonie 3 (Fig. 2). The EC and Cl in mounds at Moonie 1 had a peak at ~1.5 m then decreased (Fig. 2), which may indicate some 'non-normal' processes. Profiles at the Moonie 3 site continuously increased with depth in the depressions (Fig. 2). This is unusual, but could be explained by a continuous decrease in permeability with depth. Profiles at Condamine 2 had a 'bulge' shape, that is, a decrease in Cl in the lower profile (Fig. 3). This was associated with a change in texture from clay to sandy loam; however, other data presented later indicate that the site may be influenced by a shallow watertable.

High EC values with no corresponding peak in Cl values (e.g. Condamine 2, 1.0 m depth in Fig. 3) indicate the likely presence of gypsum or carbonates (as they contribute to EC but contain no Cl), although the high EC values did not consistently coincide with observation of gypsum or carbonate in the field.

There was a clear distinction in both the EC and Cl profiles between mounds and depressions at all Moonie sites, with higher values in the mounds than depressions (Fig. 2). The EC and Cl were also slightly higher in mounds at Condamine 1, but Condamine 2 had similar EC and Cl profiles in mounds and depressions (Fig. 3). The Moonie sites are on older, relict alluvia, whereas the Condamine sites are on younger alluvia where gilgai are less well developed. Condamine 2 is closest to the river and, hence, has the least developed gilgai (large horizontal interval, low vertical interval). Gilgai of greater age have had more time to develop differences in EC and Cl profiles. Much of the apparently random variation in EC and Cl profiles when sampling gilgaied soils is probably systematic variation.

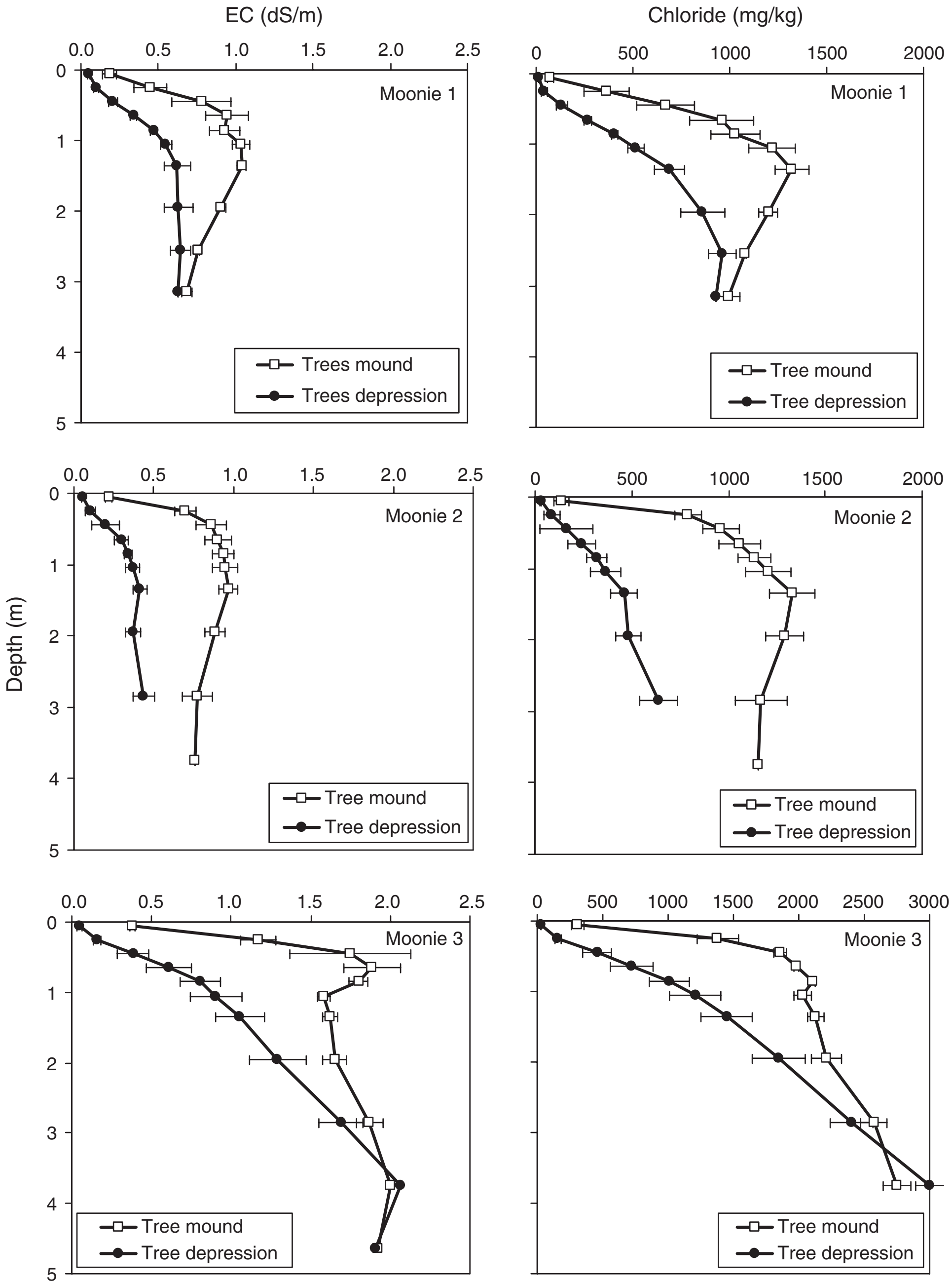

Fig. 2. Mean electrical conductivity ($EC_{1:5}$) and chloride profiles under native vegetation at Moonie sites. Bars are ±1 standard error.

These soils have considerable subsoil constraints to cropping at reasonably shallow depths when first cleared (Table 2). This is consistent with farmers' observations of crop performance when first cropped. Under native vegetation, Cl generally exceeded 1000 mg/kg at ~0.65–0.85 m (Table 2). Yield reductions of >10% are expected at critical soil Cl level (mg/kg) at all sites for chickpea (492), durum wheat (662), bread wheat (845), and canola (980), and at most sites for barley (1012), due to these high Cl levels (Dang *et al*. 2008).

Considerable Cl and total salt was stored under native vegetation. Chloride mass averaged 18.7 t/ha at 0–1.4 m depth and 57.5 t/ha at 0–3.2 m (Table 2). These masses of Cl are the equivalent of 1800 and 5640 years of rainfall Cl input (at 10 kg/ha.year), respectively. The total mass of salt would be 1.65 times the mass of Cl if all salts were NaCl.

Deep drainage under native vegetation was consistently low at all sites (mean 0.18 mm/year, range 0.10–0.27, Table 2). These values are similar to deep drainage reported for native

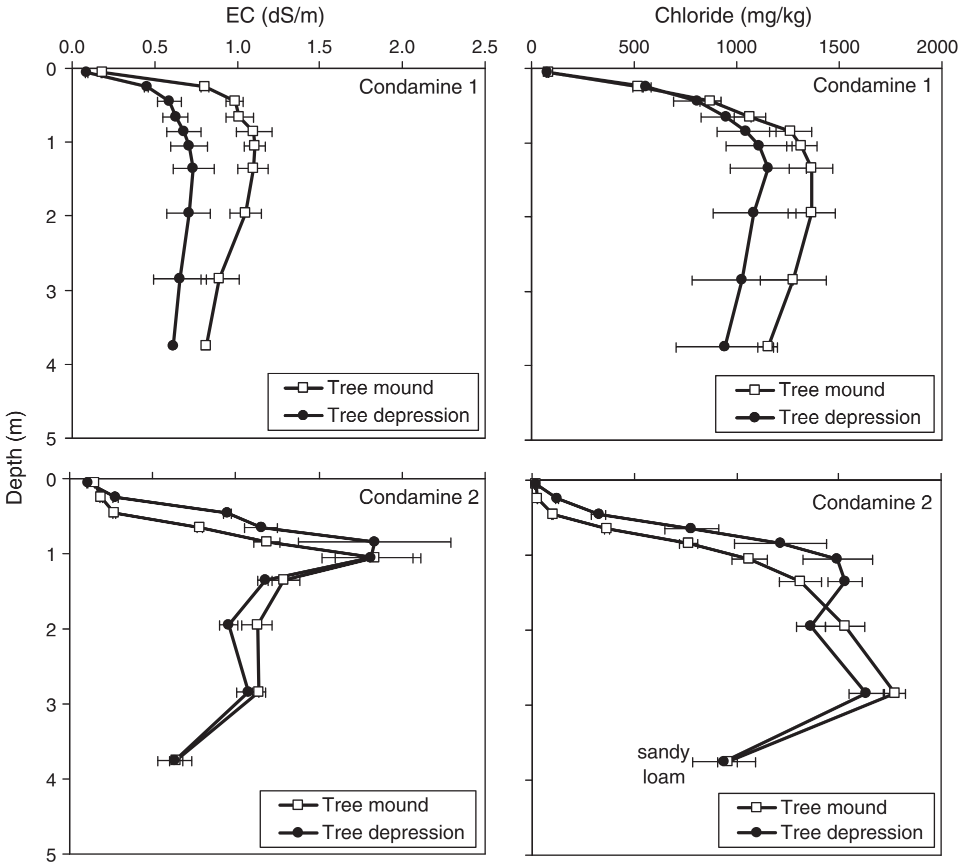

Fig. 3. Mean electrical conductivity ($EC_{1:5}$) and chloride profiles under native vegetation at Condamine sites. Bars are ±1 standard error.

Table 2. Soil chloride (Cl) and electrical conductivity (EC) under native vegetation

Gilgai	Shape of Cl profile	Depth to Cl >1000 mg/kg (m)	Mean Cl below that depth (mg/kg)	Mean EC at 1.2 m+ (dS/m)	Cl mass (t/ha)		Mean steady-state deep drainage 1.4–3.2 m (mm/year)
					0–1.4 m	0–3.2 m	
				Moonie 1			
Mound	Bulge	0.65	1139	0.85	19.3	51.6	0.18
Depression	Normal	1.95	945	0.63	7.5	34.7	0.24
				Moonie 2			
Mound	Normal	0.65	1191	0.84	24.4	64.1	0.11
Depression	Normal	780 at 1.1 m[A]	698	0.34	12.7	31.5	0.27
				Moonie 3			
Mound	~Normal	0.10	2112	1.81	36.4	103.3	0.10
Depression	Increase	0.65	1819	1.60	16.7	81.1	0.12
				Condamine 1			
Mound	Normal	0.65	1257	0.96	19.9	52.9	0.22
Depression	Normal	0.65	1061	0.68	17.4	44.0	0.25
				Condamine 2			
Mound	Bulge	0.85	1328	1.05	13.4	54.4	0.15
Depression	Bulge	0.65	1365	0.96	19.4	57.3	0.15
				Mean			
Mound			1405	1.10	23	65	0.15
Depression			1178	0.84	15	50	0.20
Mean all			1291	0.97	18.7	57.5	0.18
CV%			31.8	45.4	41.6	37.3	34.5

[A] Cl never exceeded 1000 mg/kg (Fig. 2).

vegetation on Vertosols, Sodosols, and other heavy-textured soils in the Queensland Murray–Darling Basin (Tolmie and Silburn 2003; Tolmie *et al*. 2003, 2011) and the Fitzroy Basin, Queensland (Radford *et al*. 2009; Silburn *et al*. 2009).

Cropping and pasture: EC and Cl profiles compared with native vegetation

Changes seen in EC profiles under cropping (e.g. lower EC levels), compared with those under native vegetation, were similar to changes in Cl profiles (e.g. lower Cl levels) (e.g. Fig. 4). Both sets of profiles ranked in the same order for land use treatments and gilgai (cropping and pasture EC data not shown) at all sites, except for mounds at Moonie 3 (Fig. 4). Mounds under cropping at Moonie 3 had higher EC than mounds under native vegetation at ~1 m depth, but lower Cl concentrations than mounds under native vegetation or pasture (Fig. 4).

Compared with their native vegetation equivalent (Table 3), Cl profiles were displaced downwards at all crop sites (Figs 4 and 5) and Cl mass (to 1.4 and 3.2 m) was smaller. For pasture sites, Cl profiles lay between those for native vegetation and cropping (i.e. pasture sites had lost Cl but not as much as cropped sites), except at Moonie 3 (Fig. 4) where Cl mass in depressions was slightly less under pasture than under cropping. The Cl lost from the profile under cropping and pasture had apparently moved below 4–5 m, indicating movement of water below 4–5 m under crops and pastures.

Cropping: Cl losses and deep drainage

Considerable Cl was lost from the soils under cropping, averaging 14.4 t/ha (mounds) and 9.9 t/ha (depressions) from 0–1.4 m depth (Table 3), which is 67 and 64% of the original mass under native vegetation. The Cl losses from 0–3.2 m depth were 28.0 t/ha (mounds) and 21.6 t/ha (depressions), or 45 and 47% of that under native vegetation. Considerably more Cl was lost from mounds than depressions at the Moonie sites, although mounds did start with more Cl under native vegetation (about double in the 0–1.4 m depth, Table 2). This may be because depressions generally have heavier texture in the upper profiles than mounds. However, at both Condamine sites, Cl loss was

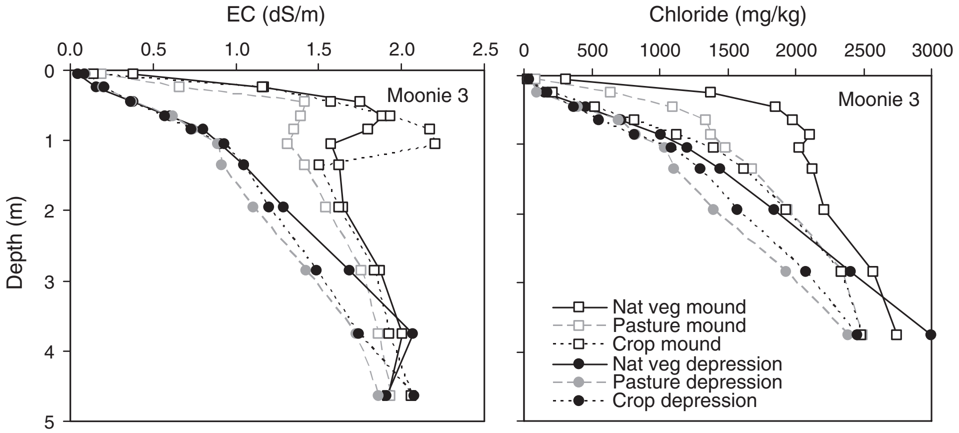

Fig. 4. Mean electrical conductivity (EC) and chloride profiles in mounds and depressions for paired native vegetation, pasture, and cropping land uses at Moonie 3.

Table 3. Chloride (Cl) loss, deep drainage (mm/year), and leachate concentration under cropping

Site	Gilgai	Cl lost (t/ha)		% Lost		Drainage	Mean drainage	Leachate	
		0–1.4 m	0–3.2 m	0–1.4 m	0–3.2 m	at 1.4 m	1.4–3.2 m	Cl (mg/L)	EC (μS/cm)
Moonie 1	Mound	6.7	7.8	35	15	3.1	3.4	6080	14 310
	Depression	3.0	9.9	40	28	3.0	4.4	2830	6660
Moonie 2	Mound	22.5	57.3	92	89	14.5	19.2	4320	10 170
	Depression	10.3	17.9	81	57	8.3	9.3	3460	8140
Moonie 3	Mound	17.5	21.0	48	20	6.5	6.9	9200	21 650
	Depression	2.3	12.4	14	15	1.5	2.7	5060	11 910
Mean	Mound	15.5	28.7	58	42	8.0	9.8	6530	15 380
	Depression	5.2	13.4	45	34	4.3	5.5	3780	8900
Condamine 1	Mound	13.3	19.7	67	37	11.8	10.9	3410	8030
	Depression	15.7	34.0	90	77	16.3	24.6	2920	6860
Condamine 2	Mound	12.2	34.1	91	63	7.5	9.4	3540	8330
	Depression	18.4	33.8	95	59	8.6	8.9	4650	10 940
Mean	Mound	12.8	26.9	79	50	9.7	10.2	3470	8180
	Depression	17.0	33.9	93	68	12.5	16.8	3780	8900
Mean (all)	Mound	14.4	28.0	67	45	8.7	10.0	5310	12 500
	Depression	9.9	21.6	64	47	7.5	10.0	3780	8900

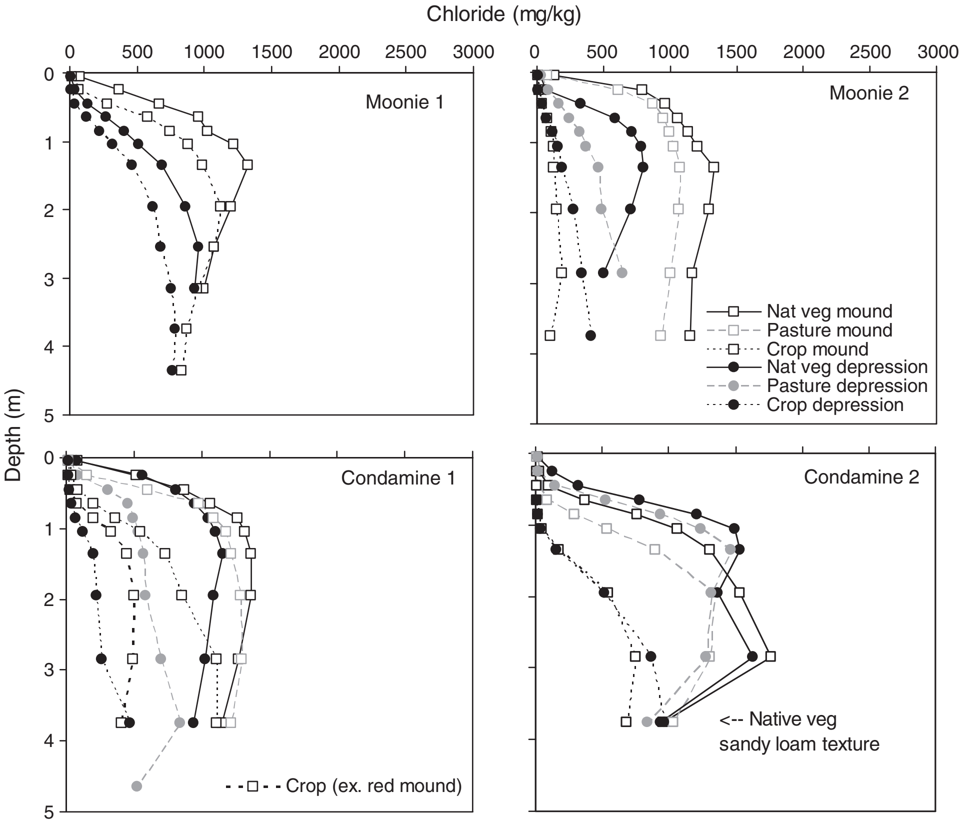

Fig. 5. Mean chloride profiles in mounds and depressions for paired native vegetation, pasture, and cropping land uses at four sites. Crop (ex. red mound): red mound was excluded. The 'red mound' at Condamine 1 was considered unusual and had much higher Cl (peaking at 2500 mg/kg at 3.6–3.9 m) than other mounds.

greater for depressions than mounds, and was greater overall than from the Moonie sites. Five sampling locations lost >80% of the original Cl from 0–1.4 m soil and >50% from 3.2 m. The smallest loss was 14% (0–1.4 m) from Moonie 3 depressions; this site also had unusual-shaped (continuously increasing) Cl profiles (Fig. 2), an indicator of somewhat different or 'non-normal' drainage processes.

Deep drainage under crops averaged over all five sites was 10 mm/year for both mounds and depressions (Table 3). Deep drainage was higher for mounds than for depressions at the Moonie sites (mean 9.8 *v.* 5.5 mm/year), but was lower for mounds than for depressions at the Condamine sites (10.2 *v.* 16.8 mm/year). Thus, position within gilgai did not have a consistent effect on deep drainage. Drainage ranged from 2.7 mm/year (Moonie 3 depressions) to 24.6 mm/year (Condamine 1 depressions). We assume that this variation was related to differences in sequences of crops and fallows over time, relative to the occurrence of higher rainfall periods (Yee Yet and Silburn 2003; Whish *et al.* 2006), and to differences in the soil plant-available water capacity (PAWC) (Silburn *et al.* 2007; Radford *et al.* 2009; Tolmie *et al.* 2011). However, there was no consistent relationship between PAWC measured at the sites and deep drainage. All sites had PAWC under cropping of ~200 mm to 1.8 m depth. PAWC probably increased over time, given the large changes in soil Cl and EC over time and farmer observations of poorer crop performance when first cropped. Thus, crop and fallow sequences and rainfall patterns appear to be the dominant influences on deep drainage.

Pasture: Cl losses and deep drainage

The Cl losses (0–3.2 m) for pasture were typically 10–19 t/ha (six of the eight sites). The Cl losses (0–1.4 m) were greater from mounds than from depressions at Moonie sites but somewhat greater from depressions than mounds at Condamine sites (Table 4), trends that were similar at the cropped sites. As for cropping sites, position in gilgai did not have a consistent effect on Cl losses, although on average, losses were greater from depressions. Percentage Cl loss averaged 32% at 0–1.4 m (range 15–56%) and 21.5% at 0–3.2 m (range 6–34%) and had no consistent pattern with gilgai position. Total Cl losses were reasonably similar at Moonie and Condamine. Chloride losses were lower for pasture than for cropping at all sampling locations except Moonie 3 depressions (again, the site with unusual-shaped profiles).

Deep drainage under pasture was similar, on average, for mounds and depressions at the Moonie sites (~4 mm/year) but was greater for depressions than for mounds at the Condamine sites (6.2 *v.* 2.7 mm/year) (Table 4). However, this difference was due to one Condamine location (Condamine 1 depressions) where drainage was highest (10 mm/year). Condamine 1 also had the greatest drainage under cropping. Excluding this site,

Table 4. Chloride (Cl) loss, deep drainage (mm/year), and leachate concentration under pasture

Site	Gilgai	Cl lost (t/ha)		% Lost		Drainage	Mean drainage	Leachate	
		0–1.4 m	0–3.2 m	0–1.4 m	0–3.2 m	at 1.4 m	1.4–3.2 m	Cl (mg/L)	EC (μS/cm)
Moonie 2	Mound	3.8	10.4	15	16	1.3	2.4	7960	18 750
	Depression	6.2	10.8	49	34	3.7	4.0	4650	10 950
Moonie 3	Mound	11.9	18.6	33	18	5.0	5.4	8200	19 310
	Depression	2.9	16.4	17	20	2.2	3.9	4530	10 670
Mean	Mound	7.8	14.5	24	17	3.2	3.9	8080	19 030
	Depression	4.6	13.6	33	27	3.0	4.0	4590	10 810
Condamine 1	Mound	3.5	3.4	18	6	2.8	2.2	3180	7480
	Depression	9.7	17.8	56	41	7.6	10.0	3180	7490
Condamine 2	Mound	6.2	11.8	46	22	2.3	3.2	5810	13 690
	Depression	3.6	8.5	19	15	1.1	2.3	7220	16 990
Mean	Mound	4.9	7.6	32	14	2.6	2.7	4490	10 580
	Depression	6.7	13.1	37	28	4.4	6.2	5200	12 240
Mean (all)	Mound	6.3	11.1	28	16	2.9	3.3	6290	14 810
	Depression	5.6	13.4	35	27	3.7	5.1	4900	11 530
Mean (ex. Condamine 1 depression)							3.4		

deep drainage averaged 3.4 mm/year for pasture, and was relatively consistent (range 2.3–5.4 mm/year, CV 35%). This is one-third of the average drainage rate found under cropping (Table 3). Excluding Condamine 1, drainage had no consistent pattern with gilgai position.

Cropping and pasture: leachate EC and Cl

Leachate salinity is of interest as it may affect groundwater quality at some time in the future. For cropped land, Cl leachate concentrations averaged ~3500–3900 mg/L (EC ~8000–9000 μS/cm) for Moonie depressions and Condamine mounds and depressions, and ~6500 mg/L (EC 15 400 μS/cm) for Moonie mounds (Table 3). There was no consistent pattern with gilgai position. However, groundwater would receive leachate from a mixture of mounds and depressions, so the mean of these sites is more relevant. These values were less variable, averaging 4550 mg/L (EC 10 700 μS/cm, CV 33%) and ranging from 3160 to 7130 mg/L (EC 7450–16 800 μS/cm). The lowest value occurred where deep drainage was greatest (more dilution) and the highest where deep drainage was lowest.

For pasture, Cl leachate concentrations averaged around 5600 mg/L (CV 36%) (Table 4) and mean leachate EC was ~13 200 μS/cm. Leachate from crop and pasture land, if undiluted in the groundwater, would generally be unsuitable for livestock drinking water (SalCon 1997). High EC values (>20 000 μS/cm) are common in the groundwater of the area (Biggs *et al*. 2005).

Soil water in subsoil

Chloride coring to 4.5 m

Subsoils (1.5–4.5 m) under native vegetation were reasonably dry at three of the four sites where soil water data were available (Fig. 6). Subsoils under cropping at these three sites were wetter than under native vegetation (Fig. 6), confirming that deep drainage had occurred. Cropped subsoils were wet to DUL for all or part of the depth sampled at all sites. However, at Condamine 2, the subsoil was also wet to approximate DUL under native vegetation. While this could indicate that the native vegetation has a shallower depth of water extraction than at the other sites, there are no differences in profile chemistry to support this. Also, large roots were noted in the soil cores to depths of 3–4 m. No large rainfall events occurred which would explain the additional water. The most likely explanation for the moist subsoil under native vegetation is the presence of a watertable below ~5 m. This is supported by the proximity of the site to the Condamine River (1.1 km) as a source of water, obvious fluvial features visible in aerial photographs, the presence of sandy material below 3 m, the shape of the Cl profiles under native vegetation, and the presence of manganiferous segregations in the subsoil.

Subsoils under pastures were also wet to approximately DUL at Moonie 3 and Condamine 1, but starting deeper in the profile (Fig. 6). This indicates that pastures were extracting water from depths of 2 m or more. For Condamine 2 pasture, subsoil in depressions was as wet as under cropping, but subsoil in mounds was substantially drier.

Soil water below 1.5 m was greater under cropped sites, relative to that under native vegetation, by an average of 152 mm in mounds and 124 mm in depressions (Table 5). This equates to an average increase of 4.3 and 3.6 mm/year, respectively, in the years since cropping commenced or about one-half of the average rate of deep drainage estimated from transient CMB (10 mm/year, Table 3). At individual sites, the rate of subsoil water increase (per year) was generally less than, or close to, the CMB deep drainage rate except for Moonie 3 depressions, i.e. the site with unusual Cl profile shapes. The subsoil water increase for Moonie 3 depressions was 5.3 mm/year, indicating that the 2.7 mm/year from CMB may be an underestimate. However, in general the wetted front of 'new water' entering the subsoil since clearing has to be deeper than the 3.9–4.5 m depth sampled with the Cl cores.

Soil water below 1.5 m under pasture was greater than under native vegetation at Moonie 3 and Condamine 1, by 52–236 mm (Table 5). Again, the increase per year since clearing was generally less than the deep drainage rates from transient

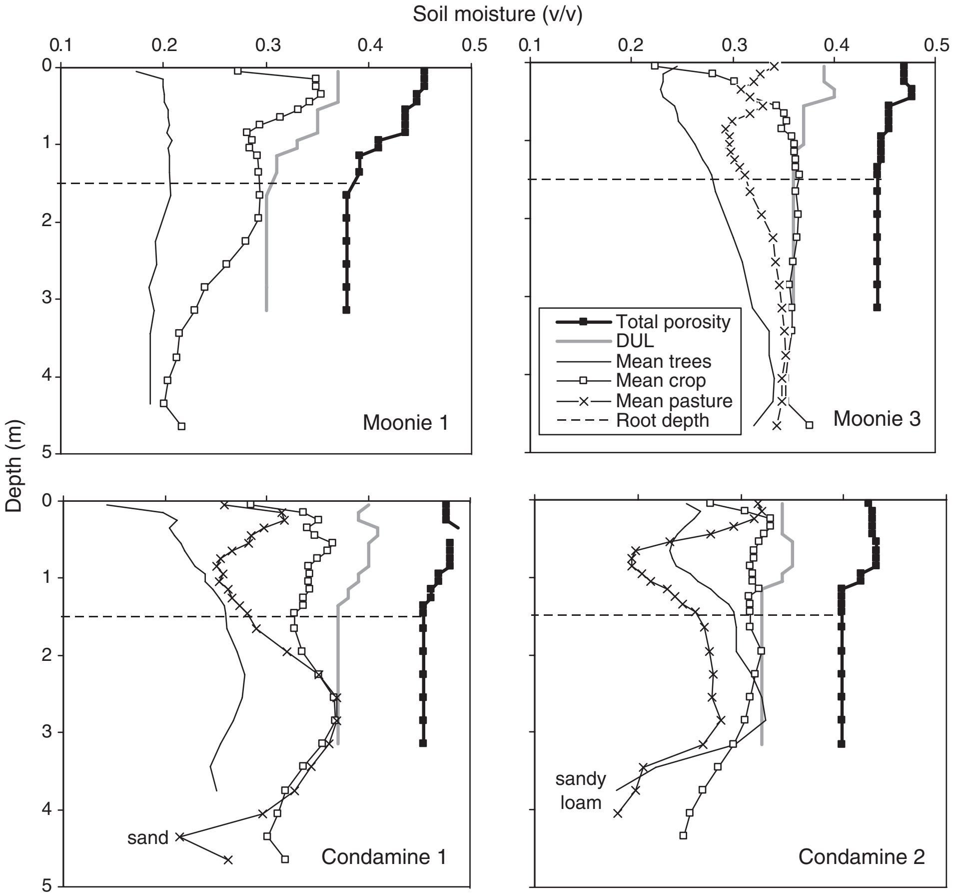

Fig. 6. Mean soil water under cropping and pasture compared with native vegetation, total porosity, and drained upper limit (DUL) at Moonie 1 and 3 and Condamine 1 and 2. For clarity, data are averaged for mounds and depressions. Trees: native vegetation.

Table 5. Soil water in subsoil at chloride (Cl) coring sites and difference in soil water compared with native vegetation (new water)

Site	Gilgai	Depth (m)	New water—crop (mm)	New water—crop (mm/year)	New water—pasture (mm)	New water—pasture (mm/year)
Moonie 1	Mound	1.5–4.5	161	4.5	No data	No data
	Depression		143	4.0	No data	No data
Moonie 3	Mound	1.5–4.5	70	2.4	52	1.8
	Depression		154	5.3	106	3.7
Condamine 1	Mound	1.5–3.9	265	8.0	166	4.2
	Depression		153	4.6	236	5.9
Condamine 2	Mound	1.5–4.5	113	2.4	–65	–1.4[A]
	Depression		126	2.7	–20	–0.4[A]
Mean (+ve only)	Mound		152	4.3	109	3.0
	Depression		124	3.6	145	4.1

[A] Condamine 2 was suspected of having a groundwater influence; subsoil under native vegetation was moist.

CMB, and the depth of the new water front was deeper than the depth sampled. At the Condamine 2 site, subsoil under pasture was drier than under native vegetation (which was unusually wet); thus, native vegetation was not a useful reference for soil water at this site. The increases in subsoil water had no consistent pattern in relation to position in gilgai, as for Cl losses and deep drainage rates.

Deep coring to 8 m

Subsoil was dry (matric potential –5000 to –7000 kPa) under native vegetation and wetter under cropping at the Moonie 1 site (Fig. 7). A change in soil texture from clay to sand occurred at ~4 m under native vegetation and 3 m under cropping. Soil water contents were also considerably greater under the cropped site than under native vegetation (Fig. 7).

Volumetric soil water contents were calculated using assumed values of bulk density (1600 kg/m^3) below 1.8 m. The resulting volumetric water contents under cropping were all less than or equal to the estimated DUL (calculated as total porosity minus an air content of 0.05 v/v; Gardner 1985), suggesting the bulk density estimates were acceptable. The difference in water stored below 1.2 and 1.5 m (approximate range of crop root depth) was summed down the profile (Fig. 7). This difference in water content below 1.2 or 1.5 m was assumed to be 'new water' stored since clearing. Some 200 mm of new water was stored to 4.2 m depth and 313 mm to 7.2 m depth (below 1.2 m). Jolly *et al*. (1989) found similar profiles of new (post-clearing) water in the Mallee in South Australia.

In the 38 years since clearing, the new stored water equates to 8.2 mm/year of deep drainage below 1.2 m, or 7.4 mm/year below 1.5 m. Both estimates were somewhat greater than the deep drainage of 3.4 and 4.4 mm/year for mounds and depressions, respectively, from transient CMB at this site (Table 3) but were less than deep drainage rates measured at other sites in the study. The difference in deep drainage may simply be due to spatial variability.

The storage capacity between 1.2 and 7.2 m was estimated as 640 mm (DUL minus soil water under native vegetation). Thus, the unsaturated zone to 7.2 m was only ~50% filled at the time of sampling. One consequence of these data is that deep drainage is not yet becoming recharge at the groundwater surface, unless (additional) bypass flow is occurring. This is consistent with the lack of response of groundwater levels to rainfall and the general lack of change in levels since installation of monitoring bores in the Moonie–Condamine area (Biggs *et al*. 2005).

The deep coring was not replicated and estimated bulk densities were used to calculate volumetric soil water contents. Therefore, the data are considered as indicative, but interesting results, and have allowed us to illustrate to farmers the idea of where the lost Cl and water has gone. Further deep coring has been initiated by the project team.

Consequences of the dry unsaturated zone time-lags

The storage capacity of the unsaturated zone creates a time-lag between an increase in deep drainage after land development and an increase in recharge to groundwater. With deep drainage of 10 mm/year, the time-lag would be 100 years for each 10 m of unsaturated zone for clay with 0.1 v/v soil water storage capacity, or 50 years for sand with 0.05 v/v storage capacity (Biggs *et al*. 2005). Once the unsaturated zone time-lag is passed, groundwater will start to rise. For example, deep drainage of 10 mm/year equates to a groundwater rise of 0.2 m/year if the aquifer has a storativity of 0.05 v/v, if no groundwater discharge occurs. This requires 40 years for groundwater to rise to within 2 m of the ground surface if groundwater started 10 m below ground surface. The time-lags will be shorter where deep drainage is greater and where the unsaturated zone is shallower. This simplistic analysis illustrates the long time-lags, of the order of 50–150 years, involved in salinisation in a reasonably dry area. Note that much of the Condamine–Moonie area has now been cleared for 40–50 years. Anecdotal evidence suggests that areas of the Queensland Murray–Darling Basin cleared in the late 1800s developed localised salinity problems by the 1950s. This mirrors the experience in the south-west of Western Australia (Peck and Hatton 2003) and southern Australia (Jolly *et al*. 1989; Allison *et al*. 1990).

Applicability of transient CMB

The transient CMB method used here, which is based on soil profile Cl sampling (e.g. 0–3 m), has been used to estimate deep drainage for irrigated agriculture in Australia (Lyle *et al*. 1986; Slavich and Yang 1990; Thorburn *et al*. 1990; Dowling *et al*. 1991; Willis and Black 1996; Willis *et al*. 1997; Weaver *et al*. 2005; Hulugalle *et al*. 2010) and widely applied (e.g. ~25 paired land-use sites) for non-irrigated cropping and pastures in Queensland (Radford *et al*. 2009; Silburn *et al*. 2009; Tolmie *et al*. 2011). These studies have largely been on clay soils or, at least, soils of low permeability, and in areas with moderate to low rainfall (e.g. <700 mm/year), where soils have naturally occurring medium to high levels of soil Cl.

The main criterion for success with transient CMB methods is that a measureable change (reduction) in soil Cl must occur between times of sampling; this is more likely where starting soil Cl or drainage is greater. For instance, we found the method

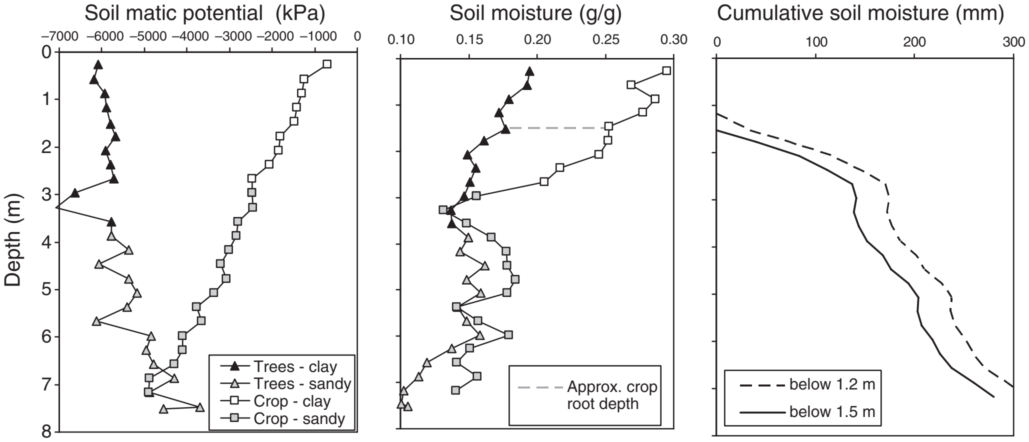

Fig. 7. Matric potential, soil water profiles in native vegetation and cropped locations, and cumulative 'new water' for two approximations of crop root depth, at Moonie 1.

could not be used on Red Ferrosols and Red Kandosols, due to a lack of soil Cl (see Tolmie *et al*. 2011). The methods can be applied successfully whether this measureable change is given by allowing long times between sampling (as applies here and other non-irrigated studies) or by having large rates of deep drainage and large Cl fluxes (as in the case of the irrigation studies cited). At longer times after land-use change, almost complete loss of soil Cl may limit further use of the methods (e.g. Scanlon *et al*. 2007; Silburn *et al*. 2009). The transient methods were developed in Australia and until recently have rarely been applied elsewhere. For instance, the transient Cl front displacement method has been applied in the southern High Plains, United States, for comparing pre-cultivated and cultivated land uses (Scanlon *et al*. 2007). Scanlon *et al*. (2007) also combined CMB with deeper sampling of soil matric potential and moisture content.

In some situations, particularly with irrigation, a steady-state is attained within a short time (years) after the change in water balance, and steady-state CMB can be used (Thorburn *et al*. 1990; Willis *et al*. 1997; Weaver *et al*. 2005; Hulugalle *et al*. 2010), although it is important to confirm that steady-state is attained. Use of the transient CMB provides this check and accounts for both situations (Thorburn *et al*. 1990). Use of steady-state CMB where transient conditions apply will greatly underestimate drainage. Willis *et al*. (1997) compared drainage estimation using measured water balance, Darcian flux calculations, and CMB, and found that repeatable and comparable estimates could be made using the water balance and CMB approaches; they recommended applying both methods. Weaver *et al*. (2005) also found results from CMB and measured soil water balances in irrigated systems were comparable. The Cl profiles also provide some indication of the drainage processes (e.g. occurrence of preferential flow) that are happening (Allison *et al*. 1994).

Modelling and management of deep drainage

Soil water balance modelling of the Moonie and Condamine sites using the farmers' cropping histories and rainfall was used by Whish *et al*. (2006) to determine the historic patterns of drainage and to test alternative cropping systems for management of drainage and productivity. The modelling indicates that drainage was greater for the annual wheat–fallow farming used in earlier periods (~1960–90) compared with more-modern, opportunity cropping sequences. Opportunity cropping involves more summer crops and greater crop frequency (Freebairn *et al*. 1996). Use of summer crops has significantly reduced deep drainage, and in rotation with optimal winter crop sowing, has reduced the loss of water below the root-zone by 50% (Whish *et al*. 2006). Silburn *et al*. (2009) found that deep drainage for modern farming systems (less tillage, more summer/opportunity crops) was about half that of older farming systems (wheat–summer fallow, more tillage, less stubble retention) on Vertosols and a Sodosol in central Queensland. The modelling highlighted the episodic nature of deep drainage, which generally occurred when heavy rains coincided with a near fully wet soil profile, as in memorable wet seasons such as 1983 and 1998. The modelling also showed that the expected reduction in runoff and potential increase in deep drainage with stubble retention and no till (Freebairn *et al*. 1996) were off-set by the use of summer crops, increased sowing opportunities, and higher cropping frequencies.

Comparison of deep drainage values obtained by modelling the historic cropping sequences and rainfall with the values derived from transient CMB also improved confidence in the soil water balance model estimates of deep drainage. Average modelled drainage was 10 mm/year (Whish *et al*. 2006), the same as average drainage from transient CMB (Table 3), and simulated crop yields were similar to yields recorded by farmers. Similar deep drainage from transient CMB and soil water balance modelling was also found for cropping, pasture, and native vegetation on a Black Vertosol (Owens *et al*. 2004) and cropping on Black/Grey Vertosol (Huth *et al*. 2010). This is important for the credibility of both the Cl and modelling results, as this study was conducted in a participatory process with the Condamine and Moonie farmers groups (Whish *et al*. 2006).

Conclusions

Our study has shown that a large proportion of the salt and Cl stored in soil profiles under native vegetation on Grey Vertosols in the Moonie and Condamine catchments is mobilised as a result of clearing native vegetation and farming. Deep drainage since clearing was greater under cropping (mean 10 mm/year) than under pasture (mean 3 mm/year) or native vegetation (0.1–0.3 mm/year). The drainage leachate has high salinity and Cl concentrations.

This deep drainage was confirmed by wetter soil below crop and pasture root depths (1.5–4 m, to 7.2 m at one site). Subsoil was very dry (<–5000 kPa) under native vegetation, and a large remnant soil water deficit must be filled before deep drainage becomes groundwater recharge at the watertable. This remnant soil water deficit has acted as a buffer preventing groundwater recharge. Modern farming practices such as opportunity cropping can utilise this buffer to limit further salt movement while maintaining the productivity of the land. Collaborative soil water balance modelling found deep drainage similar to that presented here and that deep drainage was greater for older wheat–fallow cropping systems compared with more-modern, no-till, opportunity cropping. Farmers and researchers found the Cl profiles and the loss of Cl compelling evidence that deep drainage occurred despite heavy clay soils and a semi-arid to subtropical climate.

Acknowledgments

Funding from GRDC projects ‘Eastern Farming Systems’ (DAQ00050) and ‘How much water is leaking from dryland agriculture—measurement and solutions’ (DNR15) is gratefully acknowledged. The second author’s involvement was funded in part by the Maranoa–Balonne Grain and Graze project QP16 (funded by Land and Water Australia, Grains Research and Development Corporation, Meat and Livestock Australia). Our sincere thanks to: Phil Egan, Phil Gurner, Don Taylor, and Rowland and Allan Cook for access to field sites and site information; John Cooper, Lawrence Price, and Allan Peake for assistance in the field; Lauren Eyre for additional site descriptions and sampling; Dr John Standley and the teams at Leslie Research Centre and Indooroopilly Natural Resource Sciences analytical laboratories for soil analyses; David Burton for making maps; and Bruce Radford and Dr Tim Ellis and two referees for critical comments on the manuscript which improved the paper.

References

Allison GB, Cook PG, Barnett SR, Walker GR, Jolly ID, Hughes MW (1990) Land clearance and river salinisation in the western Murray Basin, Australia. *Journal of Hydrology* **119**, 1–20. doi:10.1016/0022-1694(90)90030-2

Allison GB, Gee GW, Tyler SW (1994) Vadose-zone techniques for estimating groundwater recharge in arid and semiarid regions. *Soil Science Society of America Journal* **58**, 6–14. doi:10.2136/sssaj1994.03615995005800010002x

Biggs AJW (2006) Rainfall salt accessions in the Queensland Murray–Darling Basin. *Australian Journal of Soil Research* **44**, 637–645. doi:10.1071/SR06006

Biggs AJW, Power RE, Silburn DM, Owens JS, Burton DWG, Hebbard CL (2005) Salinity audit—Border rivers and Moonie catchments, Queensland Murray–Darling Basin. Department of Natural Resources and Mines, Queensland. Report No. QNRM05462.

Cartwright I, Weaver TR, Stone D, Reid M (2007) Constraining modern and historical recharge from bore hydrographs, ^{3}H, ^{14}C, and chloride concentrations: applications to dual-porosity aquifers in dryland salinity areas, Murray Basin, Australia. *Journal of Hydrology* **332**, 69–92. doi:10.1016/j.jhydrol.2006.06.034

Dalgliesh NP, Foale MA (1998) 'Soil matters. Monitoring soil water and nutrients in dryland farming.' (Agricultural Production Systems Research Unit/CSIRO: Toowoomba, Qld)

Dang YP, Dalal RC, Mayer DG, McDonald M, Routley R, Schwenke GD, Buck SR, Daniells IG, Singh DK, Manning W, Ferguson N (2008) High subsoil chloride reduces soil water extraction and crop yield from Vertosols. *Australian Journal of Agricultural Research* **59**, 321–330. doi:10.1071/AR07192

Dowling AJ, Thorburn PJ, Ross PJ, Elliot PJ (1991) Estimation of infiltration and deep drainage in a furrow-irrigated sodic duplex soil. *Australian Journal of Soil Research* **29**, 363–375. doi:10.1071/SR9910363

Freebairn DM, Loch RJ, Silburn DM (1996) Soil erosion and soil conservation for vertisols. *Developments in Soil Science* **24**, 303–362. doi:10.1016/S0166-2481(96)80011-0

Gardner EA (1985) Soil water. In 'Identification of soils and interpretation of soil data'. pp. 197–234. (Australian Society of Soil Science Inc., Queensland Branch: Brisbane)

Hochman Z (2006) A virtual meeting space to support farmers learning about natural resource management. RIRDC Publication No. 06/113. December 2006.

Hulugalle NR, Weaver TB, Finlay LA (2010) Soil water storage and drainage under cotton-based cropping systems in a furrow-irrigated Vertisol. *Agricultural Water Management* **97**, 1703–1710. doi:10.1016/j.agwat.2010.06.001

Huth NI, Thorburn PJ, Radford BJ, Thornton CM (2010) Impacts of fertilisers and legumes on N_2O and CO_2 emissions from soils in subtropical agricultural systems: a simulation study. *Agriculture, Ecosystems & Environment* **136**, 351–357. doi:10.1016/j.agee.2009.12.016

Isbell RF (1996) 'The Australian Soil Classification.' Australian Soil and Land Survey Handbook, Vol. 4. (CSIRO Publishing: Melbourne)

Jeffrey SJ, Carter JO, Moodie KB, Beswick AR (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling & Software* **16**, 309–330. doi:10.1016/S1364-8152(01)00008-1

Jolly ID, Cook PG, Allison GB, Hughes MW (1989) Simultaneous water and solute movement through an unsaturated soil following an increase in recharge. *Journal of Hydrology* **111**, 391–396. doi:10.1016/0022-1694(89)90270-9

Lyle CW, Mehanni AH, Repsys AP (1986) Leaching rates under a perennial pasture irrigated with saline water. *Irrigation Science* **7**, 277–286. doi:10.1007/BF00270437

Maher JM (1996) Understanding and managing soils in the Murilla, Tara and Chinchilla shires. Queensland Department of Primary Industries, Brisbane. Report No. DNRQ96001.

McDonald RC, Isbell RF, Speight JG, Walker J, Hopkins MS (1990) 'Australian soil and land survey field handbook.' (Inkata Press: Melbourne)

NRM (2002) Salinity hazard mapping for the Queensland Murray–Darling Basin. Digital data. Department of Natural Resources and Mines, Queensland.

Owens JS, Tolmie PE, Silburn DM (2004) Validating modelled deep drainage estimates for the Queensland Murray–Darling Basin. In 'Conserving soil and water for society: Sharing solutions. Proceedings 13th International Soil Conservation Organisation Conference'. Brisbane, Qld. (Eds SR Raine, AJW Biggs, NW Menzies, DM Freebairn, PE Tolmie) Paper 742. (ASSSI/IECA: Brisbane)

Peck AJ, Hatton T (2003) Salinity and the discharge of salts from catchments in Australia. *Journal of Hydrology* **272**, 191–202. doi:10.1016/S0022-1694(02)00264-0

Raats PAC (1974) Steady flows of water and salt in uniform soil profiles with plant roots. *Soil Science Society of America Proceedings* **38**, 717–722. doi:10.2136/sssaj1974.03615995003800050012x

Radford BJ, Silburn DM, Forster BA (2009) Soil chloride and deep drainage responses to land clearing for cropping at seven sites in central Queensland, northern Australia. *Journal of Hydrology* **379**, 20–29. doi:10.1016/j.jhydrol.2009.09.040

Rayment G, Higginson F (1992) 'Australian laboratory handbook of soil and water chemical methods.' (Inkata Press: Melbourne)

Robinson JB, Silburn DM, Rattray D, Freebairn DM, Biggs AJW, McClymont D, Christodoulou N (2010) Modelling shows that the high rates of deep drainage in parts of the Goondoola Basin in semi-arid Queensland can be reduced with changes to the farming systems. *Australian Journal of Soil Research* **48**, 58–68. doi:10.1071/SR09067

Rose CW, Dayananda DR, Nielsen DR, Biggar JM (1979) Long-term solute dynamics, hydrology in irrigated slowly permeable soils. *Irrigation Science* **1**, 77–87. doi:10.1007/BF00263091

SalCon (1997) Salinity management handbook. Department of Natural Resources, Queensland. Report No. DNRQ97109.

Scanlon BR, Reedy RC, Tachovsky JA (2007) Semiarid unsaturated zone chloride profiles: archives of past land use change impacts on water resources in the southern High Plains, United States. *Water Resources Research* **43**, W06423. doi:10.1029/2006WR005769

Silburn DM, Biggs AJW, Owens JS, Tolmie PE, Foley JL, Cresswell RG (2008) Salinity in Queensland—hydrologic change from soils to catchments. In '2nd International Salinity Forum'. Adelaide. 31 March–3 April 2008. (CD-ROM) (Conference Logistics: Kingston, ACT)

Silburn DM, Cowie BA, Thornton CM (2009) The Brigalow Catchment Study revisited: effects of land development on deep drainage determined from non-steady chloride profiles. *Journal of Hydrology* **373**, 487–498. doi:10.1016/j.jhydrol.2009.05.012

Silburn DM, Robinson JB, Freebairn DF (2007) Why restore marginal cropland to permanent pasture? Land resource and environmental issues. *Tropical Grasslands* **41**, 139–153.

Slavich PG, Yang J (1990) Estimation of field scale leaching rates from chloride mass balance and electromagnetic induction measurements. *Irrigation Science* **11**, 7–14. doi:10.1007/BF00189989

Thorburn PJ, Cowie BA, Lawrence PA (1991) Effect of land development on groundwater recharge determined from non-steady chloride profiles. *Journal of Hydrology* **124**, 43–58. doi:10.1016/0022-1694(91)90005-3

Thorburn PJ, Rose CW, Shaw RJ, Yule DF (1990) Interpretation of solute profile dynamics in irrigated soils. 1. Mass balance approaches. *Irrigation Science* **11**, 199–207. doi:10.1007/BF00190534

Tolmie PE, Silburn DM (2003) Estimating deep drainage in the Queensland Murray–Darling Basin. Review of past research. Department of Natural Resources and Mines, Queensland. Report No. QNRME04100.

Tolmie PE, Silburn DM, Biggs AJW (2003) Estimating deep drainage in the Queensland Murray–Darling Basin using soil chloride. Department of Natural Resources and Mines, Queensland. Report No. QNRM03020.

Tolmie PE, Silburn DM, Biggs AJW (2011) Deep drainage and soil salt loads in the Queensland Murray–Darling Basin using soil chloride: comparison of land uses. *Soil Research* **49**, 408–423.

USSL (1954) 'Diagnosis and improvement of saline and alkali soils.' US Salinity Laboratory. US Department Agriculture Handbook 60. (USDA: Washington, DC)

Van Dijk DC (1985) Soil geomorphic history of the Tara clay plains, S.E. Queensland. Soils and geomorphology. *Catena Supplement* **6**, 95–120.

Walker G, Jolly I, Cook P (1991) A new chloride leaching approach to the estimation of diffuse recharge following a change in land use. *Journal of Hydrology* **128**, 49–67. doi:10.1016/0022-1694(91)90131-Z

Walker GR, Zhang L, Ellis TW, Hatton TJ, Petheram C (2002) Estimating impacts of changed land use on recharge: review of modelling and other approaches appropriate for management of dryland salinity. *Hydrogeology Journal* **10**, 68–90. doi:10.1007/s10040-001-0181-5

Weaver TB, Hulugalle HR, Ghadiri H (2005) Comparing deep drainage estimated with transient and steady state assumptions in irrigated vertisols. *Irrigation Science* **23**, 183–191. doi:10.1007/s00271-005-0106-5

Whish J, French V, Tolmie PE, Silburn DM (2006) Simulating historic cropping systems to understand the interaction between crop choice and deep drainage. In 'Ground-breaking stuff. Proceedings of the 13th Australian Agronomy Conference'. Perth, W. Aust. (Eds NC Turner, T Acuna, RC Johnson) (The Regional Institute: Gosford, NSW)

Willis T, Black AS (1996) Irrigation increases groundwater recharge in the Macquarie Valley. *Australian Journal of Soil Research* **34**, 837–847. doi:10.1071/SR9960837

Willis T, Black AS, Meyer WS (1997) Estimates of deep percolation beneath cotton in the Macquarie Valley. *Irrigation Science* **17**, 141–150. doi:10.1007/s002710050032

Yee Yet JS, Silburn DM (2003) Deep drainage estimates under a range of land uses in the Queensland Murray–Darling Basin using water balance modelling. Department of Natural Resources and Mines, Queensland. Report No. QNRM03021.

Zhang L, Walker GR (Eds) (2002) 'The basics of recharge and discharge.' (CSIRO Publishing: Melbourne)

Manuscript received 18 October 2010, accepted 8 April 2011