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# The Brigalow Catchment Study revisited: Effects of land development on deep drainage determined from non-steady chloride profiles

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SUMMARY

A large area of woodland in the brigalow bioregion in semi-arid central Queensland was cleared for agriculture from the 1960s to the 1980s. To assess the risk of salinity associated with land clearing, soil chloride (Cl) was monitored at the Brigalow Catchment Study (BCS), in brigalow (*Acacia harpophylla*) scrub, a cropped catchment and a pasture catchment before and after clearing in 1982. The monitoring sites include three landscape positions, two on clay soils and one on a sodic duplex (Sodosol), within each catchment. An earlier report of deep drainage, using the early soil Cl profiles and steady-state and transient chloride (SODICS) mass balance, was revisited after a further 13 yr and four more sampling times.

Profile Cl mass changed little in 18.4 yr at scrub sites, justifying the use of native vegetation sites to represent pre-clearing Cl for paired cleared sites. Steady-state Cl mass balance (CMB) gave deep drainage of 0.13–0.34 mm/yr for nine pre-clearing scrub sites. Large losses of soil Cl occurred under cropping and smaller losses occurred under pasture. Transient CMB gave average deep drainage of 59 and 32 mm/yr for crop and pasture catchments, respectively, during the development phase (1981–1983) when the land was bare following clearing of native vegetation and prior to establishment of crops or pastures. In the 16.7 yr following establishment of agricultural land uses (1983–2000), transient CMB gave average deep drainage of 19.8 (range 3.3–50) and 0.16 (−2.2 to 1.4) mm/yr, respectively, in crop and pasture catchments. The drainage rate under pasture was similar to that under brigalow scrub. In the cropped catchment, 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). Drainage was greater for the Sodosol than for the clay soils under cropping. Deep drainage occurred under cropping even though the soils are considered to have low permeability and the climate is semi-arid, with potential evaporation exceeding rainfall, on average, in all months.

Increased drainage at cropped sites has driven a clear exponential loss of soil Cl, as predicted by the transient CMB theory. One cropped site is at or near a new steady-state and the others will reach a new steady-state 50–200 yr after clearing. The leachate is saline with an average Cl concentration of 7000 mg/L and would salinised any groundwater it entered. The salinity risk associated with the drainage is not well understood as yet and will depend on local hydrogeological conditions, which are poorly mapped in the Fitzroy. Effects of these losses of salts on sodicity, soil structure and permeability should also be investigated.



## Introduction

During the 1960s and 1970s extensive land clearing occurred in the brigalow bioregion of northern Australia. The region has extensive areas of clay soils dominated by brigalow (*Acacia harpophylla*) woodland, locally known as brigalow scrub. In central Queensland, in the north of the brigalow bioregion, some 4.5 million hectares of brigalow vegetation were cleared between 1962 and 1985 (Donohue, 1984). This land was developed for cattle grazing on pastures or for cropping. In response to this clearing, a hydrologic study, the Brigalow Catchment Study (BCS) (Cowie et al., 2007), was established to measure the effects of land development on runoff, erosion, soil properties, productivity and sustainability. This study, initiated in 1965 and still running, provides a rare opportunity to

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understand long-term hydrologic behaviour, including deep drainage (Thorburn et al., 1991).

This paper is concerned with the deep drainage component of the water balance at the BCS. Deep drainage below the root zone becomes groundwater recharge after percolating through the unsaturated zone, after some time lag. This recharge can provide a useful water resource where salinity is low or a salinity risk where it causes mobilisation and discharge of stored salts. Soils and regolith in drier parts of Australian often contain high levels of salts, accumulated from rainfall input over thousands of years. However, high salinities are not necessarily required where discharging water is subjected to evaporative concentration. Clearing of native perennial vegetation in southern Australia led to extensive secondary salinisation of land and streams (Allison et al., 1990; Ferdowsian et al., 1996; McFarlane et al., 2004). This is attributed to increased recharge leading to a rise in groundwater levels (Peck and Williamson, 1987; Allison et al., 1990; Clarke et al., 2002). It is not yet known whether the effects of clearing will be different in Queensland than in southern Australia.

Currently there are only scattered and generally small expressions of salinity (salinised land or streams) in central Queensland (Forster, 2007). Compared to other areas in Australia, there has been less time since land clearing. Also there has been a belief (not necessarily true) that deep drainage and salinisation of land are less likely due to the semi-arid climate (rainfall <700 mm/yr, potential evaporation > rainfall in all months) and the low permeability of the clay soils (Thorburn et al., 1991). However, soil water balance modelling indicates that deep drainage can still occur in semi-arid parts of Queensland (Yee Yet and Silburn, 2003; Owens et al., 2007; Silburn et al., 2007a) because rainfall is highly variable and exceeds soil water storage capacity for periods of days or months. Thus it is important to obtain empirical information on deep drainage under agricultural land uses in this area. The soil chloride (Cl) data from the BCS can provide this information.

Few measurements of deep drainage were available in Queensland agricultural lands (Tolmie and Silburn, 2003). Methods available for determining deep drainage have been well described by Zhang and Walker (1998), Walker (1998), Scanlon et al. (2002) and Walker et al. (1991, 2002). Methods suitable for measurement of low rates of deep drainage in semi-arid areas over long times (e.g. years to decades) in episodic events include the use of naturally occurring soil chloride as a tracer and soil water balance modelling. Soil water balance modelling was applied across the Fitzroy Basin by Owens et al. (2007) as part of an integrated salinity risk assessment (Chamberlain et al., 2007). We pursued the soil chloride mass balance (CMB) method, in part, to provide independent estimates with which to test the soil water balance modelling. The transient CMB method of Rose et al. (1979) and Thorburn et al. (1990) is particularly suited to the situation. The transient CMB method uses measurements of the change in Cl mass in a soil profile between two times, and known Cl inputs, to infer the rate of deep drainage below a chosen soil depth (at or below the root depth of the vegetation). Transient CMB can also be used to estimate the time to equilibrium (the new steady-state) and the new steady-state soil Cl content for that drainage rate.

In this paper, we (a) report soil chloride changes at the nine monitoring sites in the BCS, from 1981 to 2000, (b) test the assumption that chloride profiles are not changing (i.e. are in steady-state) under native vegetation, (c) determine deep drainage rates using steady-state and transient analysis of chloride profiles, and (d) determine the mass of chloride and total salt in the soils (an indicator of salinity hazard) and the mass and concentration lost below the root zone that will impact on groundwater. A broader survey of soil chloride changes and deep drainage across the croplands of the Fitzroy Basin is given in a companion paper (Radford et al., in press).

## Methods

### Location

The Brigalow Catchment Study is located on the Queensland Department of Primary Industries and Fisheries Brigalow Research Station in the Dawson sub-catchment of the Fitzroy basin, in central Queensland (Fig. 1a). The Research Station (24.81°S, 149.80°E Geocentric Datum of Australia 1994) is equidistant between Theodore to the south east and Moura to the north-east at an elevation of 151 m. The BCS is described in detail in Cowie et al. (2007), rainfall and runoff results are given by Thornton et al. (2007) and agronomic and soil fertility results are given in Radford et al. (2007).

### Climate

The region has a semi-arid to sub-tropical climate with wet summers and low winter rainfall. Seventy percent of the annual average rainfall of 720 mm falls between October and March. Annual potential evaporation is 2133 mm (Cowie et al., 2007). Average potential evaporation is at least twice the average rainfall in all months. Rainfall is highly variable, ranging from 11 mm or less in any month, to 165 mm in one day.

### Soils and groundwater

Soils in the catchments are associations of uniform fine-textured dark cracking clays (Black and Grey Vertosols), some with gilgai, and non-cracking clays (Black and Grey Dermosols), and subdominant soils (30–40% of area) of thin surfaced dark and brown sodic texture-contrast soils (Black and Brown Sodosols) (using Australian Soil Classification; Isbell, 1996) (Fig. 1b). The clay soils are described by Thorburn et al. (1991) as Mollic Torrerts and the Sodosols as Typic Natrustalfs (Soil Survey Staff, 1975). Slopes range from 1.8% to 3.5% and average 2.5%. Soil profile properties and geology are given in Cowie et al. (2007). A monitoring bore in the lower end of the cropped catchment had a standing water level of −20 m (2003–2006) and an electrical conductivity (EC) of 26,100 μS/cm. However, shallower, temporary water tables have been observed in bores (now destroyed) within the cropped catchment on several occasions.

### Natural vegetation

Before clearing, vegetation had structural forms varying from medium open forest to medium woodland, usually shrubby. Three major vegetation communities occurred with most common canopy species of brigalow (*A. harpophylla*), brigalow and belah (*Casuarina cristata*) or brigalow and Dawson Gum (*Eucalyptus cambageana*) (Johnson, 2004). Further details are given in Cowie et al. (2007).

### Catchment history and land uses

The catchment study has three contiguous catchments (each 12–17 ha) referred to as C1, C2 and C3 (Fig. 1b). The catchments were initially under native brigalow scrub (Jan 1965–Mar 1982). C1 has been kept as a native vegetation control, while vegetation was cleared and burnt in C2 and C3 in March 1982. Following clearing, C2 was converted to cropping (mainly grains) and C3 to improved buffel grass pasture (*Cenchrus ciliaris* L. cv. Biloela) (Integrated Botanical Information System, 2005) with cattle grazing.

In C2 prior to commencement of cropping, residual unburnt timber was raked to lines on the contour and burnt, and soil conservation measures installed (contour banks and a grassed

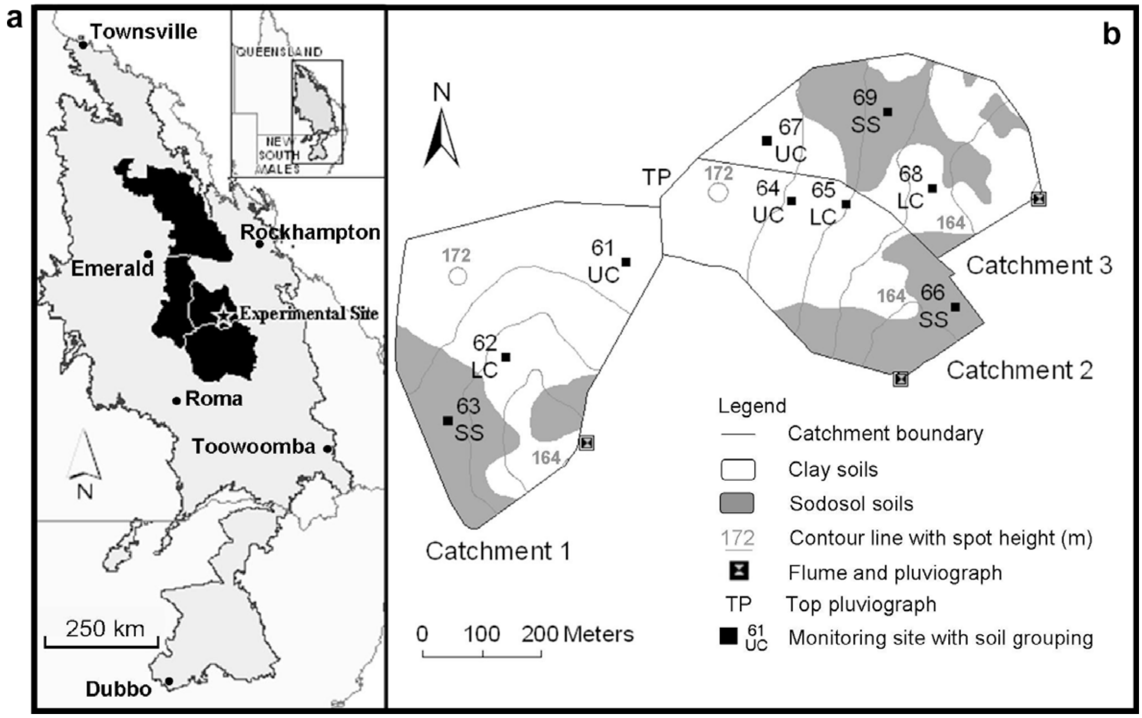


**Fig. 1.** (a) Location of the site (☆) within the brigalow bioregion of Eastern Australia (□) and the Fitzroy Basin Land Development Scheme of central Queensland (■). (b) Distribution of soils within the experimental catchments and locations of the permanent soil monitoring sites, runoff flumes and pluviographs.

waterway). The first crop sown in C2 was sorghum (September 1984), after which annual wheat was grown for 9 yr. During this period fallows were managed using mechanical tillage (disc and chisel ploughs), which resulted in significant soil disturbance and low soil cover. In 1992, minimum tillage was introduced, and in 1995 opportunity cropping replaced the fixed rotation of monoculture wheat. Under opportunity cropping, summer (sorghum) or winter (wheat) crops are planted whenever soil moisture is adequate and the prospects of in-crop rain are reasonable (Freebairn et al., 2006).

In C3, following clearing unburnt timber was left in place, and in November 1982 the catchment was sown by throwing buffel grass seed on the soil surface. The buffel grass pasture established well with >5 plants/m$^2$ and 96% groundcover before grazing commenced in December 1983. Stocking rates were adjusted to maintain pasture dry matter levels >1000 kg/ha without feed supplementation.

*Soil monitoring*

Three permanent monitoring sites (20 m × 20 m) were established in each catchment (numbered 61–69 as shown in Fig. 1b), using double stratification with random sampling to monitor changes in soil properties. Initial stratification was based on soil type and slope position, with one monitoring site in each catchment located in an upper slope position on clay soil (UC), one in a lower slope position on a clay soil (LC) and the third on a Sodosol (SS) more or less in an upper landscape position relative to the catchment boundary (Fig. 1b). Secondary stratification was by way of 10 sub-units within each site. Five soil cores (50 mm diameter) from 0 to 2 m (or resistance) were extracted, each from a different sub-unit, at each time of sampling. The cores were cut into 0.1 m increments and analysed separately.

The soil profile samples used for our deep drainage and chloride mass analysis were taken in 1981 (pre-development), 1983, 1985, 1987, 1990, 1997 and 2000. At some sites in some years the depth of sampling was too shallow for inclusion in the analysis. Samples were analysed for air-dry moisture content, chloride (Cl) and electrical conductivity, using the methods of Rayment and Higginson (1992) and earlier Bruce and Rayment (1982). Cl concentrations were determined in 1:5 soil:water suspensions after samples had been air-dried and ground to <2 mm. Low Cl concentrations (10–50 mg/kg) were found a one cropped site (66) in later samplings. Measurement of Cl has greater relative uncertainty at low concentrations; uncertainty was estimated as ±50% at 10 mg/kg Cl to about ±12% at 50 mg/kg (D. Lyons, Principal Chemist, Natural Resource Sciences, Indooroopilly, Australia; pers. comm.). The effects of these uncertainties on calculated deep drainage were assessed in the results. Air-dry moisture content was used to convert chloride concentrations measured on air-dried soil (40 °C) to oven-dry (105 °C) basis prior to calculations of chloride mass and deep drainage.

*Chloride mass balance*

Deep drainage under native vegetation was determined using steady-state chloride mass balance (CMB) (USSL, 1954). Transient CMB (Rose et al., 1979; Thorburn et al., 1990, 1991) was used to calculate deep drainage for various periods since clearing. These approaches rely on the water-soluble nature of chloride and assume complete mixing of the soil and water and one dimensional downward piston flow below the root zone. Both methods require an estimate of Cl input in infiltration and consideration of other potential sources and outputs.

*Cl concentration in rainfall and other inputs and outputs*

The chloride concentration in rainfall was taken as 1.5 mg/L (Thorburn et al., 1991). To calculate chloride input, runoff was subtracted from rainfall; runoff was 10% of rainfall for crop and pasture catchments and 5% for the scrub catchment (Thornton et al., 2007). For the average annual rainfall of 720 mm/yr (1965–2004) this resulted in infiltration of 650 mm/yr and Cl input of 9.8 kg/

ha/yr for the crop and pasture catchments, and infiltration of 684 mm/yr and Cl input of 10.3 kg/ha/yr for the scrub catchment. The transient analysis is only slightly sensitive to the amount and chloride concentration of rainfall (Tolmie et al., 2003). For example, using a chloride input in rain of 3.5 mg/L, as Thorburn et al. (1991) did to account for Cl input from ash from burning of the cleared vegetation, increased the calculated deep drainage by <0.4% for the UC cropping site. No Cl was added in fertilisers. Plants take up some Cl but this is only influential where considerable plant biomass is removed from the site. The net loss via grain harvest is small (Xu et al., 2000). The transient analysis is only slightly sensitive to these losses, as they are so small (a few kg/ha) compared the large loss from the soil (e.g. 10's of t/ha).

*Steady-state mass balance*

In steady-state CMB, the long term average annual drainage rate is equal to the chloride concentration in infiltration (rainfall-runoff) divided by the concentration in the soil (or groundwater), multiplied by average annual infiltration. Cl concentrations in soil (mg/kg) were converted to solute concentration (mg/L) by dividing by the drained upper limit moisture content (DUL g/g; or field capacity), following Thorburn et al. (1990, 1991). Deep drainage (or recharge) was also calculated using steady-state CMB using groundwater Cl concentrations from 14 boreholes on the research station, including monitoring bore 13030825 near the outlet of the crop catchment. Calculated drainage is directly proportional to changes in rainfall, and chloride concentration in soil or groundwater and in rainfall. However, doubling/halving any of these variables will only change deep drainage from a fraction of a mm/yr to a slightly larger/smaller fraction of a mm/yr for the study conditions.

*Transient mass balance*

The transient mass balance analysis is widely reported (Rose et al., 1979; Thorburn et al., 1990, 1991; Slavich and Yang, 1990; Willis and Black, 1996; Tolmie et al., 2003) and is coded in the SODICS program (Thorburn et al., 1987) and EXCEL spreadsheets (Tolmie et al., 2003). Rose et al. (1979) developed a analytical model of solute dynamics in slowly permeable soils Eq. (1) to calculate the deep drainage rate from the change in mass of soil solute (e.g. chloride) between two times and known inputs of water and solute. The mass balance equation (using the notation of Thorburn et al., 1990) is

$$z\theta_v(d\widehat{S}/dt) = IC_I - LS_Z \quad \text{i.e. } \Delta \text{ storage} = \text{mass IN} - \text{mass OUT} \tag{1}$$

where $z$ is the soil depth (mm), downwards positive; $\theta_V$, moisture content at which leaching occurs ($m^3\ m^{-3}$); $\widehat{S}$, average Cl concentration of the soil water (meq/L) at $\theta_V$ to depth $z$; $t$, time (yr); $I$, average infiltration (mm/yr); $C_I$, average Cl concentration of infiltrating water (meq/L); $L$, deep drainage (mm/yr), past some soil depth $z$; $S_Z$, Cl concentration (meq/L) of soil water at depth $z$; at $\theta_V = Cl_Z X/W_Z$; $Cl_Z$, soil Cl concentration (mg/kg of oven dry soil) at depth $z$; $X$, conversion factor (meq/mg Cl) = $2.82.\ 10^{-2}$ and $W_Z$ is the moisture content at which leaching occurs (kg/kg) = $\theta_V$/bulk density.

The analytical solution, using $P = S_Z/\widehat{S}$, giving average profile Cl concentration through time, is

$$\widehat{S}_T = \widehat{S}_O + [((IC_I)/(LP)) - \widehat{S}_O][1 - \exp(-LPt)/(z\theta_v)] \tag{2}$$

where $\widehat{S}_O$ is the value of at $t = 0$.

Eq. (2) is solved iteratively to determine the average drainage rate ($L$) which give $\widehat{S}_T$ equal to the value measured at the second measurement time.

Data required for the transient CMB are chloride concentration for each soil layer (mg/kg), time between sampling (years), rainfall, chloride concentration of rainfall, DUL moisture content and bulk density for each soil layer ($kg/m^3$). Bulk density is used to convert soil chloride to mass per unit area (t/ha). DUL is used to calculate the average solute concentration in the leachate (mg/L) at a specified depth; the majority of deep drainage occurs when soil moisture contents are at or above DUL. Bulk density and DUL were measured to approximately 1.8 m at each site by soil coring and soil moisture monitoring (Cowie et al., 2007). The DUL in each layer at each of nine sites was taken as the maximum water content measured over time (99 observations per site), after discarding data where large rainfall events had occurred within a few days of the measurement, and checking that the DUL values in each layer occurred on several occasions and that they were about 3–5% less that the total porosity (Gardner, 1985).

The depth of drainage calculation needs to be below the root depth of the vegetation, otherwise some of the water may be removed by evapotranspiration and not become deep drainage. Lawrence and Sinclair (1989) determined the depth of water extraction, using the soil moisture monitoring data from the site, to be 1.0–1.2 m for crops, 1.0 m for pastures on clay soils and 0.8 m on duplex (SS) soil, and 1.8–2.0 m for native vegetation on clay soils and 1.0 m on SS soil. Thus deep drainage was calculated for both steady-state and transient analyses for each of the deeper soil layers (e.g. below 1.5 m for clay soils and 0.9–1.5 m for SS sites; Table 1). For the native vegetation, there is a possibility that evapotranspiration may remove some of the so called deep drainage. Limited deeper Cl sampling (B. Harms, unpublished data) in native vegetation indicates Cl concentrations are reasonably steady down the profile to about 6 m. In this case, the steady-state CMB will give similar deep drainage rates at each depth, that is, the same drainage rate as presented here. Deep drainage is reported as an average

**Table 1**
Average chloride mass in soil under brigalow in 1981 and under new land uses in 2000, average chloride loss and leachate concentrations.

| Site | Site | Land use | Soil depth (m) | Cl mass 1981 (t/ha) | Cl mass 2000 (t/ha) | Cl loss 1981–2000 (t/ha) | Cl loss 1981–2000 (%) | Leachate Cl concentration | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Mean (mg/L) | Peak (mg/L) |
| 61 | UC | Brigalow | 1.5 | 25.0 | 23.2 | 1.8 | 7.2 | 4400 | 6940 |
| 62 | LC | Brigalow | 1.5 | 26.5 | 25.1 | 1.4 | 5.3 | 3750 | 6750 |
| 63 | SS | Brigalow | 0.9 | 4.9 | 4.8 | 0.02 | 0.5 | 307 | 3910 |
| 64 | UC | Cropped | 1.5 | 20.7 | 7.0 | 13.7 [a] | 66 | 5700 | 5240 |
| 65 | LC | Cropped | 1.5 | 26.1 | 21.2 | 4.9 [b] | 19 | 10,400 | 9180 |
| 66 | SS | Cropped | 1.2 | 9.7 | 0.39 | 9.3 [a] | 96 | 775 | 2980 |
| 67 | UC | Pasture | 1.5 | 23.3 | 19.6 | 3.7 | 16 | 7490 | 8100 |
| 68 | LC | Pasture | 1.5 | 27.4 | 20.7 | 6.7 [a] | 25 | 6860 | 7510 |
| 69 | SS | Pasture | 1.5 | 26.1 | 20.9 | 5.2 | 20 | 8140 | 9400 |
| *Av. (ex. 63 and 66)* | | | | *25.0* | | | | *6700* | *7590* |
| St. dev. | | | | 2.3 | | | | 2300 | 1456 |

[a] Denotes significant Cl loss (l.s.d. $P < 0.05$ for soil depth 1.5 m = 5.2; 1.2 m = 4.1 t/ha).
[b] Possibly gaining Cl from temporary, shallow water table or lateral flow from upslope.

for these deeper layers, as described by Willis and Black (1996). Deep drainage was calculated for periods (a) between each consecutive sampling, (b) from sampling in 1981 (pre-clear) to various times after clearing, and (c) from 1983, after the development phase, to 1990 (for cropping) and 2000. For some samplings, the depths obtained were not depth enough (due to soil hardness), so these samplings could not be used.

The mean concentration of Cl in leachate was calculated by dividing the mass of Cl lost from the soil by the total volume of deep drainage, to give an indication of possible impacts of the leachate on groundwater salinity.

*Future steady-state*

The future subsoil chloride concentration, in equilibrium with the new drainage rate, and the time to the new equilibrium, was calculated using the method described by Thorburn et al. (1990) (their Eq. (5)). The final steady-state average soil concentration (meq/L) is

$$\widehat{S}_{\mathrm{f}} = (IC_I)/(LP) \quad (3)$$

where $I$ is the average infiltration rate of water (rainfall + irrigation – run-off) (mm/yr), $C_I$ is Cl concentration of infiltrated water (meq/L), $L$ is the drainage rate below depth $z$ (mm/yr), $P$ is the ratio of the Cl concentration in leachate (meq/L) at depth $z$ ($S_Z$) over the average soil solute concentration (meq/L) to depth $z$ ($\widehat{S}$).

The SODICS equation (Eq. (2)) can be solved (iteratively) to find the time to the new final steady-state ($t$) after a change in land use, using $\widehat{S}_{\mathrm{f}}t2 = \widehat{S}_{\mathrm{f}}$ and $L$ = deep drainage rate for the new land use. With an increase in drainage, the soil chloride changes more rapidly initially and then more slowly over time (i.e. a decaying exponential) with a long period required to achieve the last few percent of the change. Thus the time to new equilibrium was calculated to achieve 95% of the decrease in soil chloride, to avoid this long 'tail'.

*Analysis of variance*

Analysis of variance of soil Cl mass to 0.5, 1.0 and 1.5 m was performed using Genstat 10.2 (copyright 1996, Lawes Agricultural Trust, IACR-Rothamsted). Field constraints limited sampling depth at Sodosol sites 63 and 66 on some occasions, confining a valid analysis of variance to 0.6 m and 1.2 m, respectively.

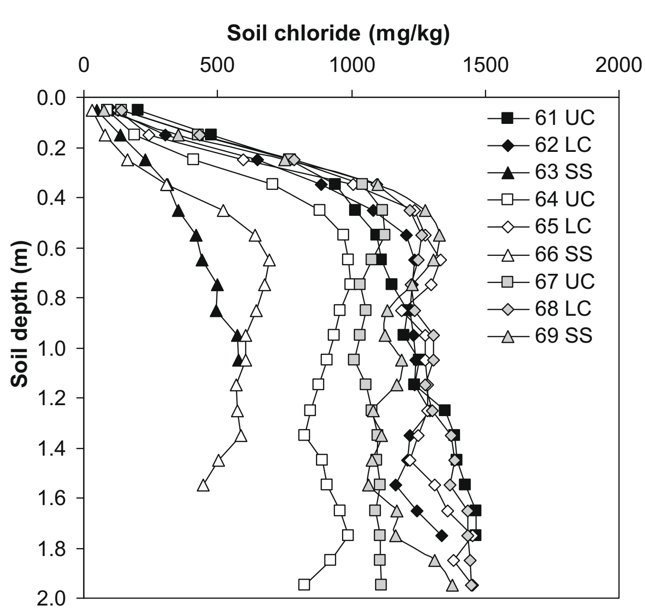


**Fig. 2.** Average soil Cl profiles under scrub in 1981 when all sites were under brigalow scrub (UC – upper clay, LC – lower clay, SS – Sodosol).

## Results and discussion

*Soil chloride profiles before clearing*

Cl profiles under scrub in 1981 typically increased to 0.4–0.6 m depth and then were relatively constant (Fig. 2). The shape of the Cl profiles largely follows the theoretical shape expected for water and salt drainage by matrix flow in a uniform soil subject to evapotranspiration defined by Raats (1974). There are few signs of variations in paleoclimate, diffusion to a water table or bypass flow, as illustrated by Allison et al. (1994). Cl concentrations deeper than 0.5 m for seven of the sites cluster around an average of 1200 (*s.d.* 148) mg/kg. Sampling to 6 m at the three upper slope sites indicated that similar concentrations occurred for the entire depth, with some random variation between depth increments (CV = 20%) (data of Ben Harms, NRW, pers. comm.). Two SS sites (63 and 66) had about half these concentrations (Fig. 2). Subsoil Cl of 1200 mg/kg would constrain grain yield (>10% reduction) of chickpea, durum wheat, bread wheat, barley and possibly canola (Dang et al., 2008). Subsoil Cl of 600 mg/kg would constrain grain yield for chickpea and possibly durum wheat, but not bread wheat, barley or canola.

In 1981, the majority of the scrub sites had reasonably similar Cl mass, with 25.0 (*s.d.* 2.3, CV = 9%) t/ha of Cl to 1.5 m depth (Table 1), while SS sites 63 and 66 had 4.9 and 9.7 t/ha to 0.9 and 1.2 m, respectively. The mean mass of Cl to 6 m depth was approximately 120 t/ha where the average subsoil concentration is 1200 mg/kg or 57 t/ha with a subsoil concentration of 600 mg/kg. This equates to 190 t/ha and 94 t/ha, respectively, of NaCl. These regolith salt masses are used as one indicator of salinity hazard (Chamberlain et al., 2007; Biggs et al., 2005).

*Changes in Cl over time*

*Scrub (woodland) catchment*

Site 63 showed a small but significant ($P < 0.001$) decline in Cl mass to 0.5 m over the period 1981–1983 (Fig. 3) associated with unseasonably high rainfall of 450 mm over 5 weeks in the autumn (fall) of 1983. No change occurred subsequently. While Cl mass under scrub to 1.0 m and 1.5 m varied somewhat (Fig. 3), there was no significant ($P > 0.05$) change through time at any site, for all times of sampling. Thus native vegetation sites can be used to provide the starting or pre-clear Cl profile for paired cropped sites.

*Cropping catchment*

Soil Cl profiles for two of the cropping sites, UC and SS, showed significant ($P < 0.05$) loss of Cl to 0.5, 1.0 and (for UC only) 1.5 m associated with the land development phase (1981–1983) (Table 1). Despite reductions in Cl load subsequently (1983–2000), changes were only statistically significant for Cl mass to 1.5 m at the UC site (Fig. 4). The decreases in soil Cl follow the exponential decline (Fig. 5) consistent with the transient Cl analysis of Rose et al. (1979) for increased drainage of water of low salinity in a saline profile. However, deviation of Cl around the exponential line in Fig. 5b for the SS site indicate Cl loss (and thus deep drainage) is variable over time, with most Cl lost in two periods, the development phase and 1985–1987.

One consequence of the increased deep drainage under cropping (described in 'Deep drainage'), was that almost the entire mass of soil Cl will be leached out of the soil profile (Fig. 5b), resulting in a new steady-state with much lower soil Cl (Table 2). The SS cropped site is already close to, or at, a new steady-state. The method of Thorburn et al. (1990) (their Eq. (5)) indicates that 95% of the new steady-state occurred 16 yr after clearing, in 1997. When SODICS was run to explore the sensitivity of drainage

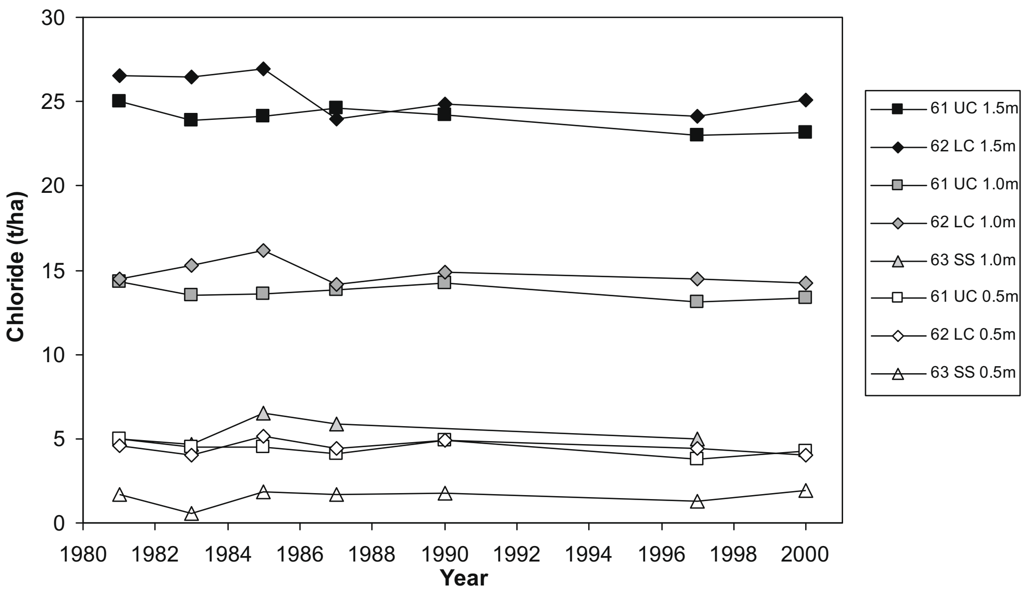


**Fig. 3.** Average soil Cl mass at three scrub sites, for various soil depths. (UC – upper clay, LC – lower clay, SS – Sodosol).

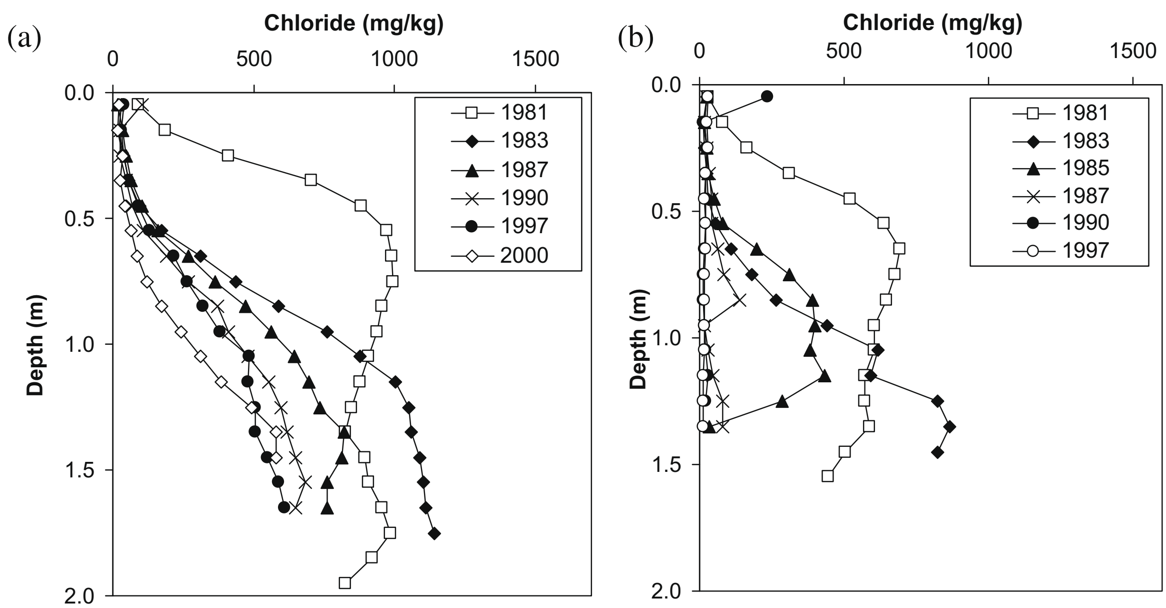


**Fig. 4.** Average soil Cl profiles at the cropping sites where the largest changes in Cl occurred: (a) UC and (b) SS (the 2000 profile was obscured by the 1997 profile and was removed for clarity).

calculated with transient CMB to changes (uncertainties) in these low Cl concentration (see 'Cropping catchment'), the transient mass balance was reasonably insensitive to changes in these data. However, in future it will not be possible to use transient CMB for the SS site, because of the Cl concentrations are too low to detect changes and because the site is at or near a new steady-state.

In contrast with the UC and SS cropped sites, the LC site had large fluctuations in soil Cl following the significant decline ($P < 0.05$) with land development (1981–1983). The pre-clearing (1981) Cl mass (0–1.5 m) of 26.1 t/ha reduced to 15 t/ha (1983) then varied between 23.9 (1985), 13.8 (1990) and finally 18.6 (2000) t/ha. Despite Cl mass reducing by 4.9 t/ha overall from pre-clearing levels (1981–2000) this was not significant (Table 1). Cl mass to 1.5 m increased significantly ($P < 0.05$) from 1983 to 2000 under cropping. However, about half of the Cl lost from 0–1.0 m soil during the development phase was never replaced and the Cl profiles do not have the characteristic shape indicating groundwater discharge and evaporative concentration. Rather, large increases and decreases occurred in the 1.0–1.5 m soil. The increases in soil Cl may be related to the position of the site in the landscape resulting in lateral or upward flow of water and Cl into the subsoil between drainage events (but not into the surface 0–0.5 m). That is, a temporary shallow water table was replacing the Cl at the site from higher up the slope or the drained water was perching below the sampling depth and flowed upward in dry times. This is consistent with observations of temporary water tables in monitoring bore (shallower than the 'regional' water table) in the cropping catchment on several occasions after large rainfall events. The LC scrub site also had more variability than the other scrub sites and an increase in Cl between 1981 and 1985. However Cl at the LC pasture site was no more variable than at the other pasture sites (Fig. 6).

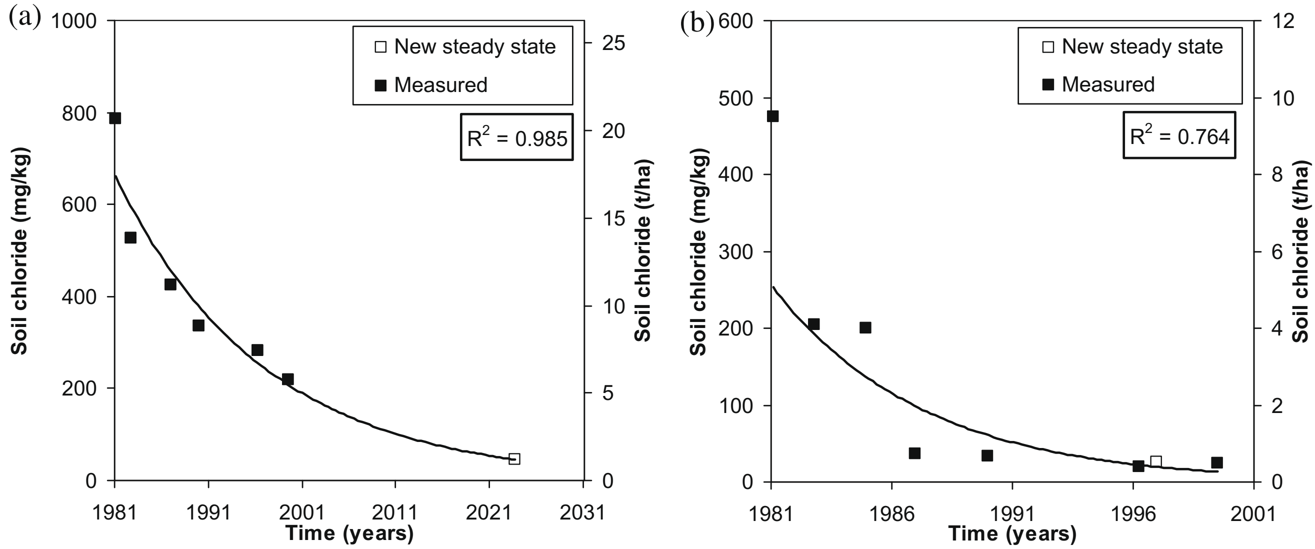


**Fig. 5.** Average soil Cl concentration and mass, measured and predicted for a new steady-state, at cropping sites since prior to clearing (1981): (a) UC for 0–1.5 m depth and (b) SS, for 0–1.2 m depth.

**Table 2**
New steady-state (NSS) for deep drainage 1981–2000 for cropped sites.

| Site | Soil | Land use | Soil depth (m) | Deep drainage[a] (mm/yr) | New steady-state | | |
|---|---|---|---|---|---|---|---|
| | | | | | Years to NSS | Soil chloride at NSS | |
| | | | | | | (mg/kg) | (t/ha) |
| 64 | UC | Cropped | 1.5 | 13.9 | 43 | 45 | 1.07 |
| 65 | LC | Cropped | 1.5 | 3.8 | 209 | 64 | 1.53 |
| 66 | SS | Cropped | 1.2 | 94 | 16 | 26 | 0.51 |

[a] Deep drainage is for the specified soil depth, rather than the averages for layers below the specified soil depth given in Table 3.

*Pasture catchment*

All pasture sites showed significant ($P < 0.05$) loss of Cl to 0.5, 1.0 and 1.5 m during the land development phase (1981–1983), but no subsequent change (1983–2000) (Fig. 6). Some fluctuations in Cl occurred after establishment of the pasture. As for the LC site in the cropping catchment, these fluctuations may represent sampling variation or real movement of Cl back into the soil profile. However, as these changes are not significant there is little point in attributing a physical explanation.

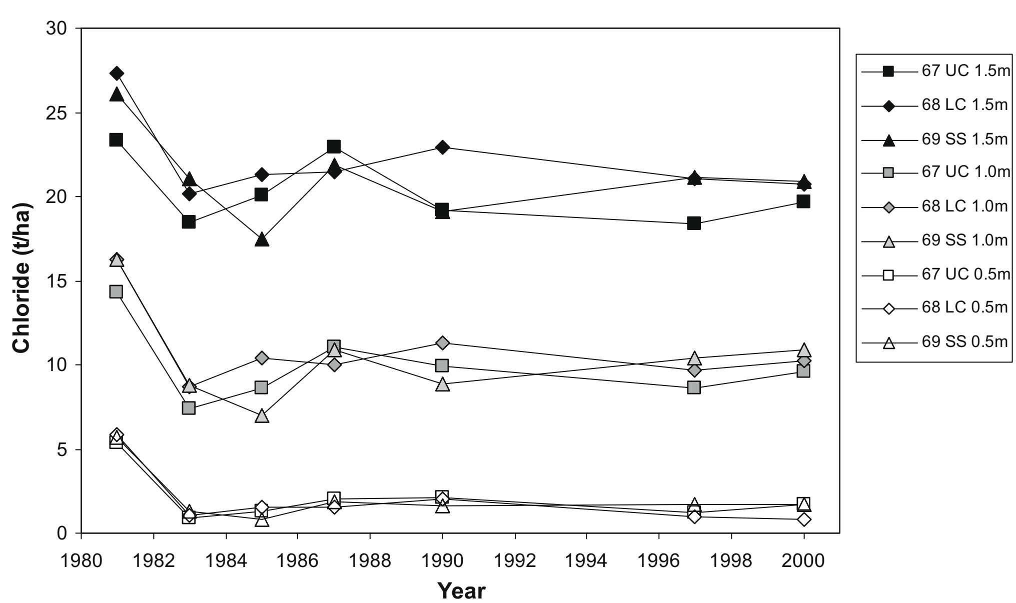


**Fig. 6.** Average soil Cl mass under the three pasture sites, for three soil depths. (UC – upper clay, LC – lower clay, SS – Sodosol).

*Deep drainage*

*Scrub (woodland) catchment*

The steady-state deep drainage under scrub in 1981 (all nine sites) averaged 0.17 (*s.d.* 0.03) mm/yr for the clay sites and 0.26 (*s.d.* 0.11) mm/yr for the SS sites (Table 3), similar to the steady-state estimates by Thorburn et al. (1991). The average deep drainage rates for the scrub, crop and pasture catchments (when all under scrub) were 0.20, 0.24 and 0.14 mm/yr, respectively. The average for the pasture catchment was slightly lower because the SS site had high Cl (similar to clay sites), unlike the SS sites in the other catchments. These low steady-state drainage rates are similar to those determined for native vegetation on Vertosols and Sodosols in the Queensland Murray-Darling Basin (QMDB) (Tolmie and Silburn, 2003; Tolmie et al., 2003, in press), in the Moonie catchment in south west Queensland (Silburn et al., in press) and in the Fitzroy (Radford et al., in press). The low drainage rates reflect the consistently high subsoil Cl concentrations in these soils, accumulated from rainfall accessions of Cl under native vegetation, and the high water use efficiency of the vegetation.

Transient CMB gave deep drainage of 12–15 mm/yr during 1981–1983 at two of the three sites under brigalow scrub, and negative drainage of a similar magnitude at the other (62 LC) (Table 3), where Cl increased (Fig. 3). Over longer time periods (1981–1997, 1981–2000) the transient CMB gave smaller but consistently positive drainage rates (Table 3), due to the inclusion of the 1981–1983 drainage event. Transient analysis for the period after 1983 (avoiding the period of high autumn (fall) rainfall) gave a catchment average drainage rate of 0.24 mm/yr, similar to the steady-state values. While drainage probably occurred under the scrub in 1981–1983, over the longer term this small amount of water and Cl moved back up into the overlying dry soil.

While the transient CMB can resolve drainage rates from small changes in Cl levels (Fig. 3), the analysis for the scrub catchment is probably at the limit of resolution where differences in Cl through time, which are not statistically (and practically) significant, appear as small positive and negative drainage rates (data not shown). The data do confirm that Cl profiles under native vegetation, on soil of lower permeability, change little over time. Thus it is reasonable to assume that Cl sampled under native vegetation can be used to represent pre-clearing conditions for a paired (e.g. cropped) site (space-for-time substitution approach; Pickett, 1989), under similar circumstances.

*Cropping catchment*

Transient CMB between samplings indicated consistently positive deep drainage for the cropped UC and SS sites (Fig. 7), and a mix of positive and negative values for the LC site. There was no relationship between drainage and total rainfall during the sampling periods. Rather, drainage is related to larger events and soil moisture accumulation during fallows between crops (Yee Yet and Silburn, 2003). All cropped sites had large rates of drainage (~60 mm/yr) in the development phase (1981–1983) (Table 3) when there was no vegetation on the cropped catchment and 450 mm of rain fell in 5 weeks, as reported by Thorburn et al. (1991).

Longer term deep drainage rates were calculated using transient mass balance for the cropping catchment after clearing (1981 onwards) and after the development phase (1983 onwards) (Table 3). For 1981 to 2000, catchment average deep drainage was 34 mm/yr. During the cropping phase, average deep drainage was 20 mm/yr. Deep drainage was consistently greatest at the SS site and lowest at the LC site. This may be related to the shallower depth of soil, lower water holding capacity and lower crop yields and nitrogen status of the Sodosol (Radford et al., 2007). Close inverse relationships between deep drainage and PAWC were found by Radford et al. (in press) and Tolmie et al. (in press). In contrast with the UC and SS cropped sites, the LC site had large fluctuations in soil Cl. Applying the transient mass balance to shorter sampling periods results in positive and negative drainage rates (Fig. 7). However, there has been a decrease in Cl over time, indicating net drainage of about 3 mm/yr post development (Table 3).

Management of the cropped catchment changed over time (Cowie et al., 2007). Disc tillage followed by chisel and scarifier operations was replaced by minimum tillage in 1992. Crops were mainly annual wheat until opportunity winter and summer cropping was adopted in 1995. We expect greater deep drainage under annual wheat-fallow cropping than for summer or opportunity cropping and greater drainage under minimum tillage than intensive tillage (Tolmie et al., 2003). However, comparing deep drainage for these management practices is difficult because the Cl sampling times do not align well with the changes in management

**Table 3**
Deep drainage from steady-state (SS) and transient analysis of average chloride profiles.

| Site | Soil | Land use | Soil depth (m) | Average deep drainage (mm/yr) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | SS Pre-clear | | Transient Post clearing | | Transient Post development | |
| | | | | 1981 | 1981–1983 | 1981–1997 | 1981–2000 | 1983–1990 | 1983–2000 |
| 61 | UC | Brigalow | 1.5 | 0.15 | 11.8 | 2.5 | 2.3 | n.d. | 1.19 |
| 62 | LC | Brigalow | 1.5 | 0.16 | −11.6 | 1.2 | 0.2 | n.d. | 1.37 |
| 63 | SS | Brigalow | 0.9 | 0.30 | 14.8 | 1.5 | 0.4 | n.d. | −2.18 |
| *Catchment average* [a] | | | | *0.20* | *4.5* | *1.8* | *1.0* | | *0.24* |
| | | | | | | | | (Wheat) | |
| 64 | UC | Cropped | 1.5 | 0.22 | 60.2 | 17.7 | 14.1 | 17.6 | 10.3 |
| 65 | LC | Cropped | 1.5 | 0.16 | 58.7 | 7.6 [b] | 3.11 [b] | −30.1 [b] | 3.3 [b] |
| 66 | SS | Cropped | 1.2 | 0.34 | 58.5 | 162 | 93.2 | 105 | 50.0 |
| *Catchment average* [a] | | | | *0.24* | *59.2* | *57.2* | *34.1* | *27.2* | *19.8* |
| 67 | UC | Pasture | 1.5 | 0.16 | 33.7 | 4.4 | 2.7 | n.d. | −0.80 |
| 68 | LC | Pasture | 1.5 | 0.14 | 47.5 | 5.4 | 4.7 | n.d. | −0.60 |
| 69 | SS | Pasture | 1.5 | 0.13 | 21.1 | 3.6 | 3.7 | n.d. | 1.35 |
| *Catchment average* [a] | | | | *0.14* | *32.4* | *4.3* | *3.7* | | *0.16* |
| | | Clay | Mean | 0.17 | | | | | |
| | | Sodosol | Mean | 0.26 | | | | | |

[a] Average weighted by proportion of each soil (scrub and cropped – 0.35 UC, 0.35 LC, 0.30 SS; Pasture – 0.29 UC, 0.29 LC, 0.42 SS).
[b] Possibly gaining Cl from temporary, shallow water table or lateral flow from upslope.

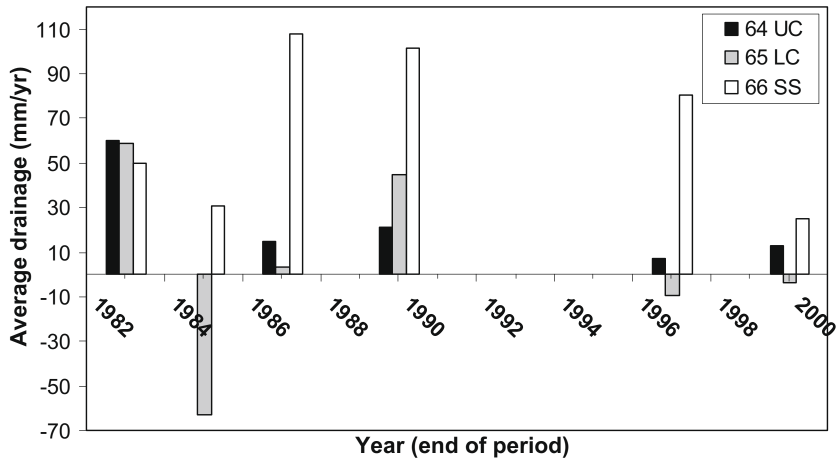


**Fig. 7.** Deep drainage for each Cl sampling period under crop sites UC, LC and SS, from transient CMB. Data are plotted at the end of each period (site 64 UC data not available in 1984).

and because of variation in rainfall over time. Crop yields and soil fertility also declined over time (Radford et al., 2007) which may potentially increase deep drainage.

One possible comparison is between 1983–1990 (mainly wheat-summer fallow, more tillage, less stubble retention), when average annual rainfall less runoff was 652 mm/yr, and 1990–2000, with less tillage and more summer/opportunity crops and rainfall less runoff of 560 mm/yr. For the UC site, deep drainage was 17.6 mm/yr (2.7% of rainfall less runoff) for the early period and 9.2 mm/yr (1.6%) for the latter period. For the SS sites, deep drainage was 105 mm/yr (16.1%) for the early period and 60.0 mm/yr (11%) for the latter period. For the LC site, deep drainage was negative for both periods. While by no means definitive (due to the different rainfall), the lower drainage for more modern farming systems, with greater crop frequency, agrees with results from soil water balance modelling (Abbs and Littleboy, 1998; Yee Yet and Silburn, 2003; Whish et al., 2006; Owens et al., 2007) and from transient CMB on Cl profiles from tillage trials (Tolmie et al., 2003, in press).

As the cropped sites are losing a large proportion of their original soil Cl (Table 1) but still have high Cl concentrations in the subsoil during the transition (Fig. 4), the use of a steady-state mass balance model will give an incorrect estimate of deep drainage. For instance, for Cl concentrations at 1.5 m at the UC site in 1997, steady-state analysis indicates drainage of 0.37 mm/yr whereas transient analysis indicates drainage was 17.7 mm/yr for 1981–1997. The steady-state estimate reflects the previous land use and drainage rate, as found by Cartwright et al. (2007).

For the SS cropped site Cl concentrations were low in the latter years of measurement (e.g. 10–20 mg/kg) (Fig. 4b). This raises concerns about uncertainties in the measurements and the resulting uncertainty in deep drainage calculations. To determine the effects of errors in Cl measurement, SODICS was run for the SS cropped sites for the post clearing period (1981–2000) and the post development period (1983–2000) with the soil Cl in 2000 adjusted by +50% (×1.5) and −50% (×0.75), that is, a reasonably large change. This resulted in changes in drainage estimates for the transient analysis of −13% and +11%, respectively, for the post clearing period, and −16% and +12% for the post development period. Thus a large relative change in soil Cl does not result in large changes in the drainage calculated with the transient CMB. The transient CMB is mostly driven by the total mass of Cl lost; it then determines how much water needed to drain at the leachate concentrations to remove this mass of Cl. However, for the steady-state CMB, the change deep drainage is more or less proportional to the changes (errors) in Cl concentration.

*Pasture catchment*

Deep drainage averaged 32.4 mm/yr during the development phase, ranging from 47.5 (LC) to 21.1 mm/yr (SS) (Table 3). Drainage was lower than in the cropped catchment because the pasture sown in November 1982 partially covered the catchment by the wet autumn (fall) of 1983. However, deep drainage was greater under pasture than the brigalow scrub, where there would have been a greater soil moisture deficit. Transient CMB after the development phase (1983–2000) gave a catchment average deep drainage similar to the steady-state rate under pre-clear conditions (Table 3). Excessive deep drainage appears to be unlikely under the pasture, unless a wet period occurs when the pasture has low transpiration (e.g. autumn or winter), or when it has been ploughed in to allow establishment of crops or new pasture.

*Cl and salt concentrations in leachate and groundwater*

Cl and salt concentrations in the leachate are of concern because of the effects they can have on groundwater salinity and salinisation where groundwater discharges. To assess the salinity of the leachate, mean Cl concentrations were calculated from the total mass of Cl leached below the depths indicated in Table 1 and the total deep drainage (1981–2000). Cl concentrations in the leachate averaged 6700 (*s.d.* 2300) mg/L for the majority of sites, or an equivalent total dissolved ion (TDI) concentration of 11,000 mg/L (assuming NaCl). This is equivalent to a theoretical EC of 23,600 μS/cm, or about half the salinity of seawater. The two SS sites (63 and 66) with lower Cl had average Cl concentrations in the leachate of 420 mg/L (*s.d.* 158), or an equivalent TDI concentration of 690 mg/L. However, an average peak concentration of 3450 mg/L (*s.d.* 656) Cl (TDI 5680 mg/L) occurs at SS sites, as the Cl bulge moves through the bottom of the profile, and this may lead to transient salinity.

The monitoring bore in the lower end of the cropped catchment had a standing water level of −20 m, a TDI concentration of 15,970 mg/L and 9870 mg/L Cl. Other bores on the Brigalow Research Station (i.e. within a few km) screened in the same sandstone had TDI varying from 1422 to 13,430 mg/L (mean 5420) and Cl from 270 to 7900 mg/L (2840) when constructed in the 1970s or 1980s. The lowest Cl (270 mg/L) is unusual on the Station; only four of the 14 bores had water with Cl < 1000 mg/L. Between the salt levels in the subsoil and regolith (Ben Harms, NRW, pers. comm.) discussed earlier and in groundwater, the landscape has a high to very high salt load.

The variation in Cl in groundwater indicates a range of historic recharge rates and possibly different recharge mechanisms at some sites (e.g. recharge from streams). Steady-state mass balance using rainfall and groundwater Cl indicates a recharge rate of 0.1 mm/yr for the cropped catchment borehole, consistent with the low rates of deep drainage under brigalow scrub. Steady-state recharge rates for the other Station bores ranged from 0.12 to 3.6 mm/yr, averaging 0.86 mm/yr, with only four bores with recharge of >1 mm/yr. These are probably somewhat unusually high for the area, being biased by the fact that the purpose of the drilling was to find good quality water and was not necessarily a random sample.

*Consequences for salinity risk*

Analysis of this long sequence of soil Cl data indicates that deep drainage is consistently greater under cropping than under pasture or brigalow woodland, in contrast with the interpretation of Thorburn et al. (1991) based only on the 1981–1987 BCS Cl data. However, there are currently few expressions of salinity in the brigalow lands (Forster, 2007). The majority of catchments in the Fitzroy with less than 900 mm/yr average annual rainfall had salt balance ratios (stream salt export/rainfall salt input) between 0.5 and 2.0 (Silburn et al., 2007b). Salinised catchments are expected to have salt balance ratios considerably higher than 2.0. This lack of salinity expressions in the Fitzroy is related, in part, to the time lags for drainage to fill a dry unsaturated zone and then for groundwater to rise.

The groundwater surface at the outlet of the cropped catchment is at −20 m, has not responded to rainfall since installation of the borehole in March 2003, and has a Cl concentration indicating low recharge. With a deep drainage rate of 20 mm/yr, the total drainage in the 18.4 yr since clearing is 370 mm. We believe this deep drainage is slowly filling the historic soil moisture deficit in the unsaturated zone, created under the previous brigalow woodland.

Radford et al. (in press) found soil below the root depth of crops was wetter than under native vegetation at seven sites in the Fitzroy, and was near saturation at three of the cropped sites. Silburn et al. (in press) found soil was dry under brigalow to 7.2 m, with an available water storage capacity of approximately 640 mm between 1.2 and 7.2 m. Under a neighbouring cropped site, 313 mm more water was stored between the same depths. This difference in water content is assumed to be new water stored since clearing 38 yr earlier. Jolly et al. (1989) found similar profiles of new (post-clearing) water where Mallee vegetation was cleared in South Australia. Thus there could be a considerable moisture deficit in the unsaturated zone, in the order of 1000–2000 mm over a depth of 20 m, under the BCS cropped catchment. This results in a time lag of the order of 50–100 yr before the new deep drainage becomes recharge to the groundwater. Once the new drainage water reaches the water table, a drainage rate of 20 mm/yr would produce a groundwater rise of 0.4 m/yr, if unfilled porosity was 0.05 v/v, requiring a further 50 yr for the water table to reach the ground surface (if no lateral loss or gain of groundwater occurred).

It is also possible that the draining water is (or will be) trapped above less permeable layers in the unsaturated zone, such as siltstone and shale layers, and may flow laterally. The periodic increases in soil Cl at the LC cropped site indicate that water may be discharging under that site during some sampling periods. If such perching occurs, salinity will eventually occur in localised areas in crop lands, depending on variations in geology. If perching does not occur, the wetted front will eventually reach the watertable and cause a rise in the saline groundwater. To resolve these issues, further sampling is needed to determine the moisture status of the unsaturated zone in the crop and woodland catchments, and a network of shallow, nested boreholes needs to be installed in the cropped catchment.

Thus, the BCS soil Cl study indicates that there has been a change in the subsurface hydrology where perennial vegetation has been replaced with annual cropping. This hydrologic change has increased the risk of future salinity, but there will probably be a long time delay (decades) before it is expressed, as has been found elsewhere in low rainfall areas in Australia (Jolly et al., 1989). The salinity of the leachate and groundwater are high enough to cause severe salinisation where they discharge. This reinforces the need to continue using and developing the most water-efficient practices possible e.g. opportunity cropping (Freebairn et al., 2006) and perennially transpiring vegetation such as pastures (Silburn et al., 2007a). This might lead to salinisation of the soil. However, as shown by the steady-state salt balance under native vegetation, the low deep drainage rate in a very water-efficient non-irrigated system (<1 mm/yr) is enough for rainfall input to equal drainage times leachate concentration (output) and thus maintain a constant subsoil salinity.

*Consequences for soil properties and crops*

Farmers often ask if the reduction in soil Cl will relieve subsoil salinity constraints (Dang et al., 2008) and improve the crop root zone. The BCS soil moisture records indicate no change in lower-limit soil water contents or depths of soil water extraction in the cropped catchment over time (B.A. Cowie, unpublished data). Thus the initial soil Cl concentrations, which were slightly limiting to some crops, according to the criteria of Dang et al. (2008), may have had a small adverse effect on yields but apparently not on water use. Rather, crop yields have declined over time due to declining nitrogen fertility (Radford et al., 2007), apparently a more limiting constraint than soil Cl. The large reductions in soil Cl, in combination with the considerable exchangeable sodium which remains in cropped sites, may lead to changes in soil structure (dispersion) and permeability. The BCS offers an opportunity to study these changes, using the brigalow and pasture catchments as reference sites.

*Comments on CMB methods*

Transient Cl mass balance is capable of resolving deep drainage rates that are low and episodic, which would be difficult to determine by other methods. It is also backward looking. That is, drainage can be estimated from paired sites sampled for Cl (e.g. native vegetation v cropped), using the native vegetation Cl profile to represent Cl in the cropped site at the time of land use change. This allows deep drainage to be estimated for long time periods (e.g. 20–70 yr), which may be needed to approximate the average deep drainage in subtropical and semi-arid areas. Determining such long-term averages is more difficult using other methods, such as measured water balance, soil physics and lysimetry, requiring many years of measurement.

The study showed, as did Thorburn et al. (1991), that use of the steady-state CMB in situations where soil Cl is changing will give false estimates of deep drainage, unless the Cl profile has come into steady-state with the new drainage rate. For the BCS cropped catchment, steady-state CMB underestimated deep drainage by two orders of magnitude. The study also showed that the transient CMB analysis is insensitive to errors in the Cl input in rainfall and to errors in Cl measurements which may occur once Cl concentrations decline to low values.

This study is part of a network of deep drainage and soil Cl studies in Queensland (Belyando Suttor Implementation Group, 2004;

Tolmie et al., 2003, in press; Radford et al., in press; Silburn et al., in press), providing a significant updating of understanding of deep drainage, and potential groundwater recharge, across the inland cropping lands. Data from these studies are being used to test soil water balance modelling of deep drainage (e.g. Owens et al., 2004), which underpin salinity risk assessments (Chamberlain et al., 2007). Owens et al. (2004) found good agreement between deep drainage estimates from soil water balance modelling and transient CMB, for cropping, pasture and native vegetation at a site in southern Queensland. Use of the soil Cl profiles with Queensland farmers (e.g. French et al., 2006), who generally have an appreciation of soil chemistry (e.g. nutrient) data, showed that they provide clear and compelling visual evidence of deep drainage; if the Cl has moved down they can appreciate that water moved down as well.

## Conclusions

Soil chloride profiles changed little at brigalow scrub sites, justifying the use of paired native vegetation sites to represent pre-clearing Cl levels at cleared sites. Steady-state Cl mass balance (CMB) gave deep drainage of 0.13–0.34 mm/yr for nine scrub sites; these low rates allowed a large mass of salt to build up in these soils. Large losses of soil Cl occurred under cropping while smaller losses occurred during the development phase for pasture, but not after pasture was fully established. Transient CMB gave average deep drainage during the development phase, when the land was bare, of 59 and 32 mm/yr for the crop and pasture catchments, respectively, and over the 18.4 yr since clearing, 34 and 3.7 mm/yr, respectively. Excluding the development phase, average drainage was 20 mm/yr for the cropped catchment and a rate similar to the steady-state rate under pasture. Drainage under cropping was greater for older farming systems (more tillage, annual wheat) than for more modern farming systems (less tillage, more summer/opportunity crops), and on the Sodosols than on clay soils.

Increased drainage in two of the three cropped sites has driven a clear exponential loss of Cl, in agreement with the transient theory. For cropped sites, up to 13.7 t/ha of Cl, or 66% of the original Cl, was lost below 1.5 m; one site is at or near a new steady-state and the others will reach a new steady-state 50–200 yr after clearing.

Deep drainage occurred even though the soils are considered to have low permeability and the climate is semi-arid to sub-tropical, with potential evaporation exceeding rainfall, on average, in all months. While these conditions led to high salt storage under native vegetation over thousands of years, they do not prevent deep drainage and salt leaching under cropping. Cl concentrations in the leachate were around 7000 mg/L (approximately EC of 23,600 μS/cm) and the unsaturated zone and groundwater also contained large stores of salt. The salinity risk associated with the increased drainage is not well understood as yet and will depend on local hydrogeological conditions and the lime lag for filling of the unsaturated zone, both of which are poorly defined. Effects of the losses of soil salts on sodicity, soil structure and permeability, should be also investigated.

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