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SOIL RESEARCH

Effects of farming systems, tillage, and traffic practices on deep drainage and soil salt loads in the Queensland Murray–Darling and Fitzroy Basins using soil chloride

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ABSTRACT

Context. Cropping in the Queensland Murray–Darling and Fitzroy Basins has precursors for secondary salinity – high soil salt loads and increased drainage after clearing. **Aims.** To measure changes in deep drainage, for key tillage, traffic, and cropping systems. **Methods.** Steady-state and transient chloride (Cl) mass-balance were applied to Cl profiles from four tillage and crop rotation trials and one controlled traffic trial in southern and central Queensland, to determine deep drainage below the root zone. **Key results.** Large downward movement of Cl occurred after clearing. Deep drainage from transient Cl balance for cropping was a small proportion of rainfall but considerably higher than under native vegetation. Deep drainage was consistently greater under zero than conventional tillage, for both winter and summer cropping. For example, deep drainage was greatest for zero tillage (~45 mm/year) and least for conventional, stubble mulch, and reduced tillage (2–6.3 mm/year) at the highest-rainfall site (677 mm/year). Deep drainage was 12.7 and 7.9 mm/year for zero and conventional tillage, respectively, at the lowest-rainfall site (497 mm/year). Drainage under continuous wheat conventional tillage was more than twice that where some summer crops were included. At Billa Billa, continuous wheat had greater deep drainage by three to five times than continuous sorghum for three of four tillage systems. No drainage was detected during 6 years of opportunity cropping. A pasture legume ley had only 1.7 mm/year of deep drainage. Deep drainage was less for compacted than non-compacted treatments (23.3 vs 38.2 mm/year). **Conclusion and implications.** Increased deep drainage with zero tillage and controlled traffic can be reduced using summer crops, particularly opportunity cropping where crops are planted when soil water is sufficient, and ley pastures.

Keywords: compaction, cracking clay, dryland salinity, native vegetation, opportunity cropping, steady-state mass-balance, transient mass-balance, Vertosols.

Introduction

The importance of deep drainage under different land uses, and its relationship to salinity risk has been studied extensively in the dryland cropping areas of inland Queensland (Qld), Australia, in recent years (Biggs *et al.* 2005; Searle *et al.* 2006; Chamberlain *et al.* 2007). Deep drainage is defined as water that moves below the root zone whereas recharge refers to water that arrives at the groundwater surface (Walker *et al.* 2002). Summer-dominant rainfall areas such as in Qld have been considered to have a lower risk of deep drainage than the winter-dominant rainfall zones of southern Australia, because a greater proportion of annual rainfall coincides with high potential evaporation (SalCon 1997; Walker *et al.* 2002). However, rainfall in northern Australia is more temporally variable and has larger daily maximums than in southern Australia which will tend to increase drainage.

Previous studies focused on differences between primary land uses – native vegetation, dryland pasture, and cropping. Soil chloride (Cl) sampling of paired sites of these land uses and steady-state and transient Cl mass-balance (CMB) were used to determine how much deep drainage has occurred throughout the northern grain growing zone [Belyando–Suttor (Belyando Suttor Implementation Group *et al.* 2004), Fitzroy Basin (Radford *et al.* 2009; Silburn *et al.* 2009) and Queensland Murray–Darling Basin (QMDB) (Silburn *et al.* 2011; Tolmie *et al.* 2011)]. Similar studies have occurred in northern New South Wales (NSW) (Silburn *et al.* 2011; Tolmie *et al.* 2011). Modelling studies (Paydar *et al.* 2001; Keating *et al.* 2002; Yee Yet and Silburn 2003; Owens *et al.* 2004; Robinson *et al.* 2010; Young *et al.* 2014) also compared land use effects on deep drainage. They found deep drainage in the order of annual wheat > annual sorghum > opportunity cropping > perennial pasture > native vegetation.

Abbs and Littleboy (1998), Ringrose-Voase *et al.* (2003), and Young *et al.* (2014) on the Liverpool Plains (northern NSW) and Young *et al.* (2014), Whish *et al.* (2006), Silburn *et al.* (2007), and Robinson *et al.* (2010) in the study area (Fig. 1), modelled effects of various farming systems, soil types and climates on deep drainage. These confirm the effects of land use on deep drainage as listed above. Deep drainage increased with decreasing plant available water capacity (PAWC) and average annual rainfall. The effects of PAWC and rainfall on deep drainage was confirmed by Tolmie *et al.* (2011) and Radford *et al.* (2009) using transient CMB.

Fallowing between crops (e.g. for 6 or more months) is used to increase stored soil water and mineral nitrogen, reduce disease incidence, and control weeds. Fallowing alters the pattern of soil water storage (Freebairn *et al.* 1997) compared with native vegetation, by allowing soil water to accumulate and therefore changes the frequency and magnitude of drainage episodes (Tolmie and Silburn 2003; Tolmie *et al.* 2003). O'Connell *et al.* (1995) found for dryland winter cropping in southern Australia that greater durations of fallowing increased deep drainage on two soil types. These effects of fallowing on deep drainage were supported by modelling (Zhang *et al.* 1999).

In addition to these studies of land uses, understanding deep drainage of historic and newer farming systems (e.g. annual winter and summer cropping, opportunity cropping), fallow management practices [e.g. intensive, reduced, and zero tillage (ZT)] and controlled traffic is also needed. Llewellyn *et al.* (2012) found that 90% of grain growers in Australia

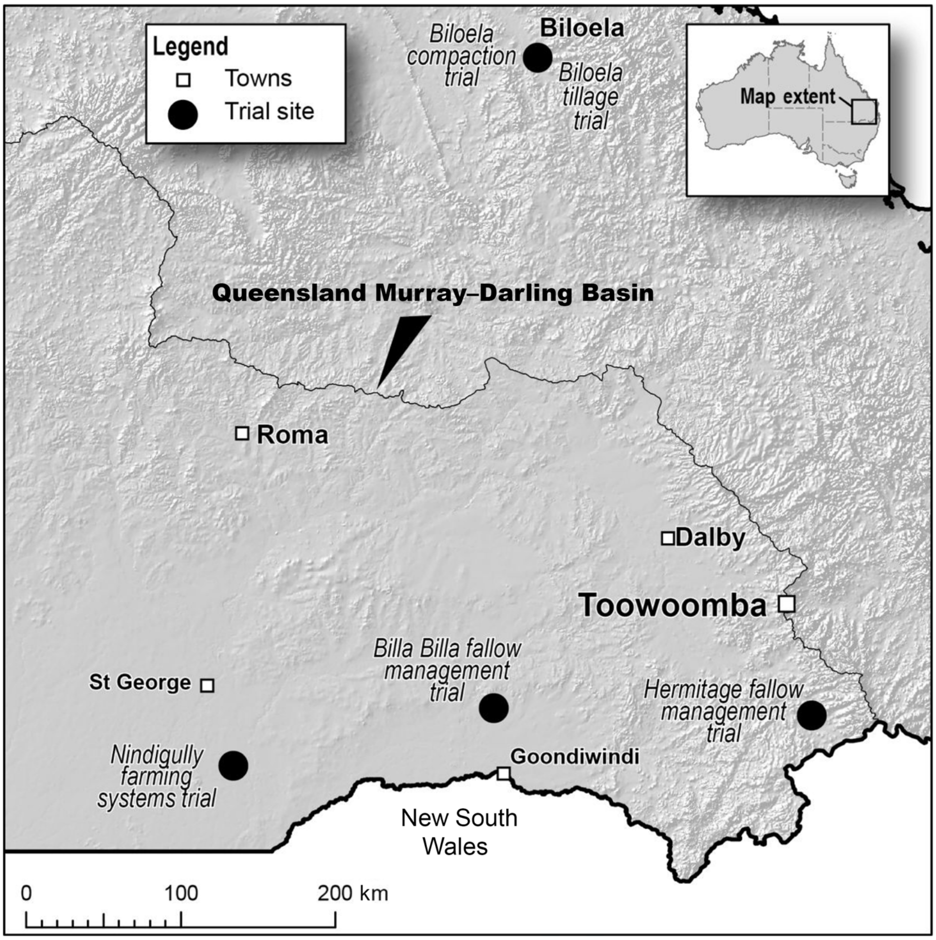

Fig. 1. Location map of trial sites and Cl sampling.

used ZT. Estimates of adoption for opportunity cropping are limited. Strahan and Hoffman (2009) used an estimate of 70% for adoption of farming systems that included opportunity cropping in central Qld, presumably based on their local knowledge. Chamberlain *et al.* (2021) found from remote sensing of cropping in the Fitzroy and Burdekin for 2009–2018 (Pringle *et al.* 2012), that 31% of the area only had one to three crops per 10 years, 21% had four to six crops, and 33% had seven to nine crops. Only 15% had 10 or more crops per 10 years, almost all with 10–13 crops. The infrequent cropping may be associated with ceasing cropping at the start of the period, opportunistic cropping when grain prices were high, or grazers growing forage crops. The occurrence of opportunity, high frequency cropping was limited (i.e. 15%) although for another 33% of the area, growers may still be opportunity cropping but do not achieve a crop frequency greater than 10 crops in 10 years.

Controlled traffic (Tullberg *et al.* 2007) had been adopted by about 50% of grain growers in central and southern Qld and northern NSW by 2016 and was expected to increase profit by AUD87/ha on the Darling Downs (southern Qld) (GRDC 2020).

Cover and soil differences which result from different tillage practices also affect infiltration and drainage. Evidence of greater soil Cl movement and implied greater drainage, under zero than under conventional tillage (CT) has been noted (Turpin *et al.* 1999; McGarry *et al.* 2000). Greater drainage with ZT compared to CT was also found with water balance modelling (Poulton *et al.* 2005; Young *et al.* 2014). Modelling with a calibrated water balance model for a tillage and runoff trial found deep drainage increased with greater stubble retention (Freebairn *et al.* 1990). Predicted average annual deep drainage was 38 mm/year for ZT and 10 mm/year for bare summer fallow.

However, measured effects of tillage practices on deep drainage are limited and more studies are needed.

Li *et al.* (2008) modelled water balances for a Black Vertosol for controlled traffic ZT and stubble mulch and trafficked ZT and stubble mulch. The model was calibrated to a runoff study with these treatments. They found average annual deep drainage of 130, 62, 46, and 9 mm/year for continuous wheat and 104, 46, 28, and 9 mm/year for continuous sorghum, respectively, for these tillage and traffic treatments. Modelled deep drainage was reduced with opportunity wheat–sorghum cropping (39, 12, 5, and 0.5 mm/year, respectively) compared with annual cropping. Soil structural decline also affects deep drainage. Connolly *et al.* (2001) found that deep drainage on a range of soils was reduced when compaction and surface structural degradation was modelled.

The presence of several long-term farming systems/tillage trials in the study region provided an opportunity to study differences in deep drainage between farming practices. The aim of this study was to measure soil Cl movement and deep drainage under different tillage, traffic, and cropping treatments in dryland agriculture.

Materials and methods

Study area

The QMDB is primarily semi-arid, subtropical, with rainfall slightly summer-dominant and highly variable. The Fitzroy Basin is to the north of the QMDB, is warmer and experiences more summer-dominant rainfall and even greater variability. Cropping in both areas is primarily on cracking clay soils (Vertosols) of basaltic and non-basaltic (sedimentary rock) origin, on both hillslopes and alluvial plains.

Site selection

Sites where soil Cl data were obtained are shown in Fig. 1. Details of sites are presented in Table 1.

The sites are described in Tolmie *et al.* (2003), Tolmie and Radford (2004), and Thomas *et al.* (2007), except for the Biloela compaction trial (Radford *et al.* 2007) (Table 1). Details such as sampling dates, soil type, annual average rainfall, PAWC, and treatment are given in Table 1. The sites were chosen because of the following:

- Previous soil Cl sampling had occurred, with adequate sampling protocols time since clearing, and age of cultivation, cropping history, and soil type were known. A number of these sites were then re-sampled (Table 1) to give data at two or more times, so that the transient CMB could be used.
- They included comparisons of tillage/traffic treatments.

The early sampling (before 2002) was performed by the various trial operators. Sampling protocols were of good quality (e.g. number of cores taken, common and continuous sampling intervals) whether sampled by trial operators and our team, except that some earlier samplings were somewhat shallower. Data were rejected if they were too shallow. Site history, rainfall, bulk density, and field capacity data were recorded for each trial. Soil samples were analysed for Cl, electrical conductivity, pH, and air-dry moisture content. Native vegetation was used as the starting Cl profile for all trials.

Biloela tillage trial

The site was a tillage trial (Thomas *et al.* 1995) at the Biloela Research Station (24°22′S, 150°31′E; altitude 173 m) and was of low slope (i.e. ~0% slope). The soil comprises black cracking and non-cracking clays developed on alluvium and classified as *Tognolini, Melton,* and *Callide* (Shields 1989), respectively, or Black Vertosol, Black Dermosol, Black Chromosol, or Black Dermosol (Australian Soil Classification; Isbell 2002). Seventy percent of rainfall occurs in summer (October–March). The subsoil (0.8–1.6 m) had 5% coarse sand, 26% fine sand, 26% silt, 44% clay, 0.48% organic carbon, and

Table 1. Summary of trials and sampling sites.

Site	Dates sampled (No. cores)	Location[A]		Soil type (ASC)	Geomorphic unit[B]	Rainfall[C] (mm/year)	PAWC (mm)	Depth of sampling (m)	Treatments	Reference describing the site and previous research
		(Lat S, Long E)								
Fitzroy Basin										
Biloela tillage trial	August 1984, October 1993, May 2003 (*N* = 4)	–24.382	150.515	Black Vertosol	Alluvia	677	113	0–1.6 0–5.0 0–4.2	Native vegetation CT, stubble mulched, RT, ZT, four replicates: winter or summer crops	Radford *et al.* (1995), Radford and Thornton (2011)
Biloela compaction trial	October 1993 June 2003 (*N* = 2→8)[D]	–24.382	150.515	Black Vertosol	Alluvia	677	113	0–1.6 0–5.1	Native vegetation (same site as above) Two replicates × 2 × irrigation, 2 × compaction/amelioration, 2 × fertiliser: opportunity winter or summer crops	Radford *et al.* (2000, 2007), Radford and Thornton (2011)
Queensland Murray–Darling Basin (QMDB)										
Hermitage fallow management trial	December 1989, June 2002 (*N* = 9) bulked	–28.210	152.100	Black Vertosol	Alluvia	672	322	0–5.0+	Native vegetation CT, ZT, stubble burnt, stubble retained, four replicates: winter crops	Turpin (1995), Turpin *et al.* (1998), Dalal (1989)
Billa Billa fallow management trial	April 1985 May 1993 (*N* = 3)	–28.167	150.250	Red Sodosol	Brigalow uplands	613	140	0–2.0 0–3.0	Native vegetation CT, ZT, with stubble, without stubble, three replicates: wheat	Thomas *et al.* (1995)
Nindigully farming systems trial[E]	April 1996–2001, 2002 (*N* = 4)[D]	–28.501	148.733	Grey Vertosol	Alluvia	497	302	0–1.5 0–3.0	Native vegetation CT, ZT, opportunity cropping (ZT), four replicates: winter and summer crops	Thomas *et al.* (1998)

[A] Coordinates represent approximate site location only, using Geocentric Datum of Australia (GDA 94). [B] Biggs *et al.* (2005). [C] Rainfall is long-term (≥70 years) average. [D] Irrigation and fertiliser treatments were not significantly different and were averaged. [E] About 3900 Cl analyses were run for Nindigully alone.

ASC, Australian Soil Classification (Isbell 2002); PAWC, plant available water capacity; CT, conventional tillage; RT, reduced tillage; ZT zero tillage.

exchangeable sodium percentage (ESP) of 5% with a cation exchange capacity (CEC) of 38 (meq/100 g).

Native vegetation was cleared in 1924 and the site used for pasture and crop production until 1983, when the trial was begun (Radford and Thornton 2011). Four tillage treatments were applied, varying in tillage frequency, in the following order: conventional tillage (CT) > stubble mulch tillage (SM) > reduced tillage (RT) > ZT. No fertiliser was applied until 1989, when plots were split for fertiliser, either none (control) or nitrogen applied (100 kg N/ha, plus Zn) in the form of urea just before sowing from 1989 to 2002. Opportunity cropping was practised. A variety of summer and winter crops were grown annually.

Soil Cl samples were taken in 1984 (1 year after the trial began), 1993, and 2003. Samples were taken to a depth of 1.6 m in 1984 and 4.5 m in 1993 and 2003. Native vegetation was also sampled in 2003 in an area adjacent to the trial plot.

Biloela compaction trial

The study (Radford *et al.* 2000, 2001, 2007) was conducted for 10 years at Biloela (24°22′S, 150°31′E) on a Vertosol (50% clay, 28% silt, and 20% sand at 0–1.2 m) on the *Tognolini* soil (Shields 1989). Mean annual evaporation (class 'A' pan) is 1870 mm. The subsoil (0.6–1.5 m) had 4% coarse sand, 31% fine sand, 22% silt, 45% clay, (0.3–0.4 m) 1.0% organic carbon, and subsoil ESP of 1.7% in a CEC of 35 (meq/100 g).

The experimental design was two replications of two irrigation treatments (Io = rain grown, I = supplementary irrigation of 75 mm at crop anthesis), with each of these four main plots split into 14 subplots (seven compaction treatments by two fertiliser treatments; Fo and F; control, N-fertilised). The compaction treatments were control (no compaction) and extreme compaction (annual compaction of wet soil by a header with a 10-t axle load). There were eight samples from each compaction treatment: IoFo, IoF, IFo, and IF × two replications. All were farmed with no-till cropping with residue retention, with a mix of winter and summer crops. There was an initial 5-year phase (with annual compaction treatments) followed by a regeneration phase (with no further applied compaction between the permanent wheel tracks and no-tillage).

The trial was sampled to 3.6–5.4 m depth (or resistance) in the two reps, in 1993 (prior to the trial commencing) and June 2003. The native vegetation site was the same site as for the Biloela tillage trial.

Hermitage (winter crop) tillage trial

A fallow management trial was established in 1968 (remains ongoing) at Hermitage Research Station (28°12′S, 152°06′E), Warwick. The aim was to study effects of tillage and crop residue management on soil properties, fallow water storage, and crop yields (Dalal 1989). Soil type is a variant of *Waco* clay, a self-mulching Black Vertosol, developed on dominantly basaltic alluvium. The subsoil (1.2–2.1 m) had 7% coarse sand, 18% fine sand, 23% silt, and 52% clay. Soil at 0.6–0.1.2 m had 0.98% organic carbon and a ESP of 17% and a CEC of 61 (meq/100 g). Soil properties were similar for the native vegetation sites.

The native vegetation prior to cultivation supported grassland, which probably consisted of Queensland blue grass (*Dicanthium sericeum*) and wallaby grass (*Danthonia linkii*), with broad-leaved apple (*Angophora subvelutina*) and Queensland blue gum (*Eucalyptus grandis*) emergents (McKeown 1978). Native vegetation was cleared in the late 1890s, although actual early land use is unknown. The fallow trial area served several purposes between 1947 and 1968, including an oats trial and sheep grazing. In March 1961, pasture was ploughed out and extensive levelling work was conducted to improve surface drainage. The area was kept under cultivation until the fallow trial commenced in 1968 (L. Wilson pers. comm.). The Cl profiles from this site have been examined previously (Loch and Coughlan 1984; Dalal 1989) and are discussed in Turpin (1995).

Treatments consisted of a factorial combination of CT or ZT, crop residue retained or burned after crop harvest, and three rates of urea (0, 23, and 69 kg N/ha/year) applied just before sowing. Treatments were arranged in a randomised block design and replicated four times. Wheat or barley was grown annually. The CT treatment generally involved four or five primary tillage operations with a chisel plough during the fallow period.

Native vegetation soil was sampled in December 1989 (Turpin 1995; Turpin *et al.* 1998). The native vegetation site sampled by Turpin (1995) had less soil Cl (16.6 t/ha Cl at 2.4 m) than the trial site. Therefore, three other native vegetation (pasture) sites were sampled in 2002. The average of the 1989 and 2002 virgin profiles (with 27 t/ha Cl at 2.4 m) was more consistent with the Cl mass in the trial site soil. We have assumed this Cl profile is representative of the trial soil in 1947.

Turpin *et al.* (1998) sampled two of the four replicates in the trial to >5 m in December 1989 with one core at each of the northern and southern end of the plots. The Cl profiles were available for CT with stubble retained (CT + S) and ZT with stubble retained (ZT + S) treatments (no-added nitrogen, replications 1 and 4). Turpin *et al.* (1998) found that the nitrogen treatments had no significant main or interaction effect on the Cl concentrations. We sampled the same CT + S and ZT + S treatments in June 2002.

Billa Billa (wheat and sorghum) tillage trial

Wheat and sorghum fallow trials operated at this Billa Billa site from 1983 to 1996. The soil is a Red Sodosol (ASC) on a slope of 1%. The subsoil (0.8–1.5 m) had 4% coarse sand, 42% fine sand, 10% silt, 46% clay, 0.6% organic carbon (0.2–0.3 m), and subsoil ESP of 22% in a CEC of 25 (meq/100 g).

The native vegetation was cleared in 1971 and was belah (*Casuarina cristata*) open forest, with some brigalow (*Acacia harpophylla*), occasional poplar box (*Eucalyptus populnea*), and an understorey of wilga (*Geijera parviflora*) and false sandalwood (*Eremophila mitchellii*). Soil Cl was sampled after trial establishment in 1985 in a remnant area adjacent to the trial (G. Thomas pers. comm.). Results used here are from soil samples collected pre-planting on the wheat trial in 1989 and 1993, and in the sorghum trial in 1988 and 1991 both with no applied nitrogen for CT/frequent disc and ZT, each with stubble removed (CT − S) and stubble retained (CT + S). An adjacent farm paddock was sampled in 1990. It had a history of CT, then ZT, with mainly wheat and some summer crops.

Nindigully farming systems trial

A farming systems trial began at Nindigully in 1996 (Thomas *et al.* 1998) on an area that was cleared in 1956 and conventionally tilled with winter cereals interspersed with some medic pasture phases. Native vegetation was coolibah (*Eucalyptus microtheca*) and associated native grasses (G. Thomas pers. comm.). The soil is a epipedal to crusting Grey Vertosol (ASC) on alluvia. The subsoil (0.6–0.9 m) had 31% total sand, 15% silt, 54% clay, 0.4% organic carbon, and an ESP of 15% in a CEC of 22 (meq/100 g).

Trial plots had a range of tillage/crop/nitrogen treatments and were sampled annually since 1996 to a depth of 1.5 m, and in 2002 to 3 m. Harms and Dalal (2003) sampled sites nearby, under native vegetation and on areas cleared in 1967 and 1996 (their sites 38 and 39), to a depth of 1.2 m, and these data are also considered. The farmer used CT with four to five cultivations each fallow at site 39 and zero tillage at site 38 (Dalal and Mayer 1986; Dalal R. pers. comm., 2021). Native vegetation was sampled in April 2002 adjacent to the trial. Profiles across the site in 1996 were averaged to define Cl at the start of the trial. Results are presented to April 2002 for opportunity crop, CT, and ZT, for the no applied nitrogen treatments. The opportunity crop treatment had six crops (four summer, two winter) in 6 years; CT and ZT were continuous wheat with five crops grown from 1996 to 2002.

Soil sampling and analysis

Sites were geolocated and soil morphology described according to the standards in McDonald *et al.* (1990). A hydraulic soil coring rig was used to take soil samples for chemistry and measurement of field and air-dry soil moisture contents. Sampling details are given in the description of each trial. Variability was explored at two contrasting sites (see *Statistical analysis*) and in a separate soil Cl study in the Moonie area (Silburn *et al.* 2011).

$pH_{1:5}$, $EC_{1:5}$, and $Cl_{1:5}$ were measured for each depth increment, using the methods of Rayment and Higginson (1992) (methods 4A1, 3A1, and 5A2, respectively). Additional analyses were performed on samples for sites for which there were no existing chemistry data, particularly particle size analysis (PSA), exchangeable cations, and CEC. Measured bulk density and PAWC were available. All Cl concentrations (mg/kg) were calculated on an oven-dry basis before drainage (mm/year) and masses of Cl (t/ha) were determined. All relevant data are stored in the Department of Resources Soil and Landscape Information database (SALI).

CMB

The steady-state and transient CMB methods employed are described by other authors, and the ways they were applied in this study are discussed in Tolmie *et al.* (2011). Similar methods were presented by Thorburn and Rose (1990), Thorburn *et al.* (1990, 1991), Willis *et al.* (1997), Radford *et al.* (2009), and Silburn *et al.* (2009, 2011). In summary, CMB is based on conservation of mass of Cl within or below the root zone. We used steady-state CMB (USSL Staff 1954) to calculate deep drainage under native vegetation and groundwater recharge at Biloela using groundwater Cl data, and transient CMB (Rose *et al.* 1979; Thorburn *et al.* 1990) for cropping sites.

Steady-state mass-balance

The steady-state analysis calculates the long-term average annual drainage rate as the ratio of Cl concentration in rainfall (mg/L) divided by the concentration in the soil or in groundwater (mg/L), multiplied by average annual rainfall (mm/year). The Cl concentration (mg/kg) was converted to solute concentration (mg/L) by dividing by the moisture content at drained upper limit (DUL, g/g), following Thorburn *et al.* (1990, 1991). The Cl concentrations in groundwater were taken from 10 bores in the Biloela Research Station and used to estimate groundwater recharge. Calculated drainage is directly proportional to changes in rainfall, and Cl concentration in soil or groundwater and in rainfall.

SODICS transient solute mass-balance

A Microsoft Excel spreadsheet was used with Visual Basic code using the Solver function to iteratively solve the transient mass-balance equation (Rose *et al.* 1979; Thorburn *et al.* 1990) and determine the drainage rate from pairs of soil Cl data collected over time. The inputs follow:

- Rainfall and irrigation (mm/year).
- Time between sampling (years).
- Solute concentration of rainfall (mg/L) calculated using the equation for Cl concentration in rainfall with distance from the coast given by (Biggs 2006), and in irrigation water used in the Biloela compaction trial (140 mg/L), which were obtained from ionic chemistry samples from 10 groundwater bores at the station.

- Cl concentration for each soil layer (mg/kg) at two or more times.
- DUL moisture content for each soil layer (g/g) measured during the trials.
- Bulk density for each soil layer (kg/m^3) measured during the trials at each site.

Bulk density was used to convert soil Cl concentrations to mass per unit area (kg/ha) and does not affect drainage calculation (steady-state or transient). Drainage estimated from transient mass-balance is only slightly sensitive to the amount and Cl concentration of rainfall (Tolmie *et al.* 2003). DUL is used to calculate the average Cl concentration in the leachate. Drainage rates obtained using SODICS are an average over the time between soil samplings. Deep drainage only occurs during a small proportion of this time, given the episodic nature of drainage events in the region (Yee Yet and Silburn 2003).

Statistical analysis

For the Hermitage trial, only averaged Cl profile data were available because samples had been bulked across cores. Thus, statistical analysis was not possible. Statistical analyses were performed by Turpin *et al.* (1999) on older Hermitage data. Statistical analysis was used to determine if soil Cl profiles were significantly different for the other trials.

Analyses were performed in the context that Cl data for different depths are not independent; ANOVA was used to test for differences in mean Cl mass (t/ha) accumulated to the various sampling depths. For the Biloela compaction trial, the pre-trial Cl profiles (1993) were used as a covariate with the post-trial Cl profiles (2003). Genstat 5 release 11.1, second edition was used (Copyright 2008, VSN International Ltd). Linear regression was used to determine the relationships between rainfall, PAWC, subsoil ESP, and average annual deep drainage for the data presented here and for other published data.

Results and discussion

The Cl profile changes are presented for each trial site, followed by statistical comparisons and by deep drainage results.

Cl profiles

Biloela tillage and compaction trials

The Cl profile for native vegetation at Biloela was the 'normal' shape (increasing then constant with depth) for soils of moderate to low hydraulic conductivity, as defined by SalCon (1997). They followed the theoretical shape expected for water and salt drainage by matrix flow in a uniform soil subject to evapotranspiration, defined by Raats (1974). There were few signs of palaeoclimate, diffusion to a water table or bypass flow, as described by Allison *et al.* (1994). However, the depth of the peak Cl was at 1.5–1.8 m, deeper than the shallow depth to the Cl peak (about 0.5 m) common under native vegetation in more arid areas of Qld (Silburn *et al.* 2009, 2011; Tolmie *et al.* 2011).

In both the Biloela tillage (Fig. 2*a*) and compaction (Fig. 3) trials, the Cl profiles under cropping had a lower concentration than under native vegetation and the peak was displaced deeper in the profile. The shape of the profiles at the

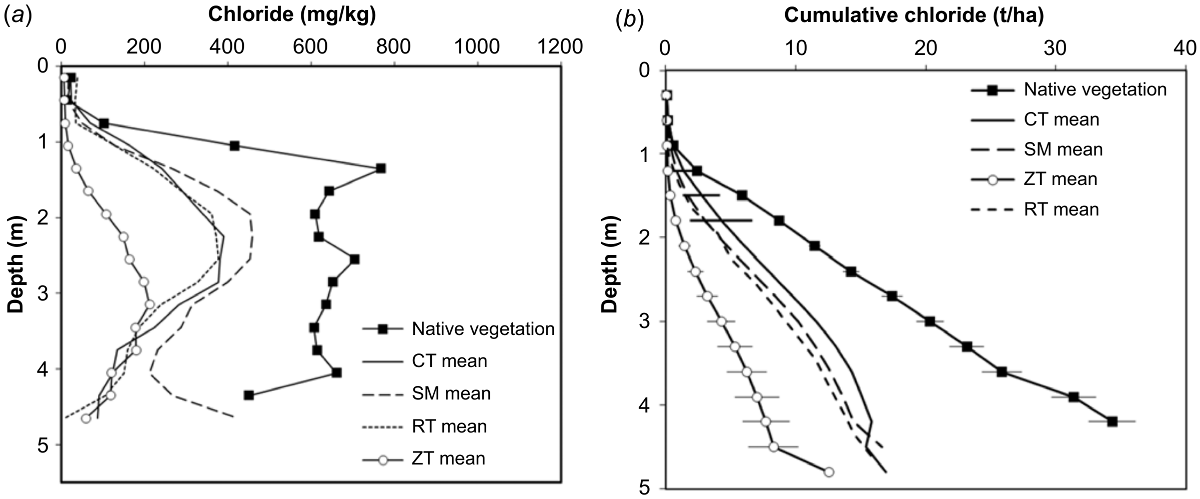

Fig. 2. Cl profiles for Biloela tillage trial for native vegetation and tillage treatments in 1993, as (*a*) concentrations (average of four cores) and (*b*) cumulative Cl mass. LSDs are shown on the CT mean profile (no bar indicates no s.d., see *Statistical analysis*) and s.e. are shown on the native vegetation and zero tillage lines. CT, conventional tillage; SM, stubble mulch; RT, reduced tillage; ZT, zero tillage.

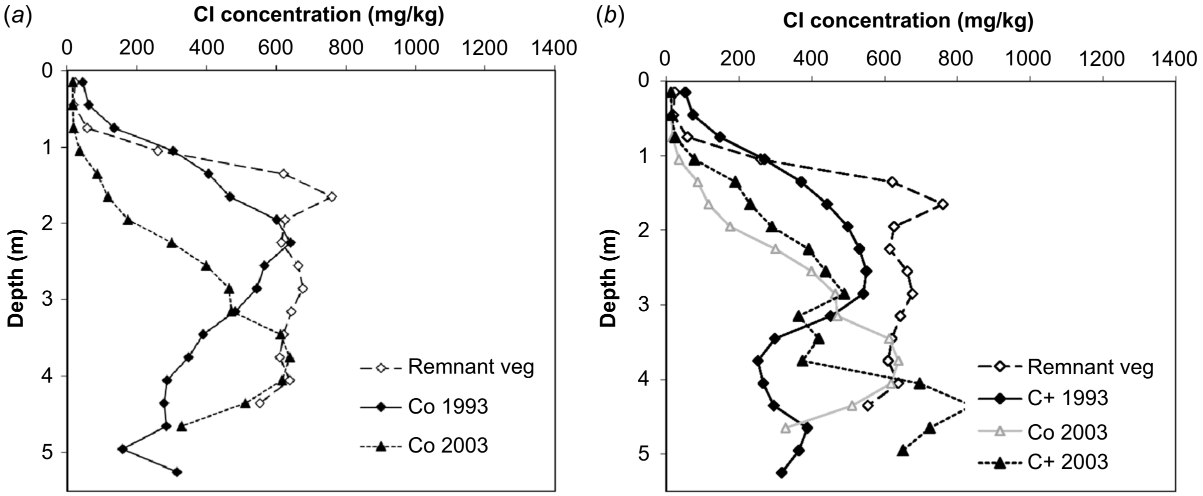

Fig. 3. Cl profiles for native vegetation and the Biloela (*a*) compaction trial control (Co) and (*b*) compaction (C+) treatments in 1993 and 2003 (and Co 2003 for comparison of compaction treatments). Profiles are the average of irrigation and fertiliser treatments, with two replications each. Cumulative Cl masses in 2003 (after 10 years of treatment) significantly differed between compaction treatments for 0–0.9**, 0–1.2*, 0–1.5**, 0–1.8**, and 0–2.1* m depths (*$P < 0.05$; **$P < 0.01$).

commencement of the trials (1983 for tillage trial and 1993 for compaction trial) had also changed to a 'bulge' or bell shape, with higher concentrations in the middle of the profile than deeper. This may indicate bypass flow. Indeed, SODICS transient mass-balance applied to these profiles gave greater deep drainage rate in these deep layers than in shallower layers. For the control treatment in the compaction trial, deep drainage was 2.5–2.8 mm/year at 1.8–3 m depths and 10 mm/year at 4.5 m. This is only plausible if 7–8 mm/year had flowed to 4.5 m without leaching Cl from shallower layers, i.e. bypass flow. This would be possible if old root channels remained in the soil after clearing of deep-rooted native vegetation or slickensides occurred in the upper layer. We observed live roots of native trees in the screens of groundwater monitoring bores at 20 m depth. However, we have no proof of bypass flow other than from the Cl profile data.

By 2003 in the Biloela tillage trial, the Cl peak had been displaced from ~1–3 m to around 4 m, in both treatments (Fig. 2). Low tillage intensity (i.e. higher cover) treatments lost more Cl than the intensively tilled treatment. Similarly, more Cl was lost from the non-compacted (Fig. 3*a*) than the compacted treatment (Fig. 3*b*), i.e. between 3 and 4 m depths in the compaction trial. For the compaction trial, cumulative Cl mass was greater for the compacted treatments in both 1993 and 2003 (Fig. 4). In 2003, these differences were significantly different to 2.1 m.

Hermitage fallow management trial

The Cl profiles (Fig. 5*a*) from the Hermitage fallow management trial (Loch and Coughlan 1984; Dalal 1989; Turpin *et al.* 1998) did not have a 'normal' shape. The Cl peaks at about 2 m depth under native vegetation, decreased with depth thereafter. This profile shape can indicate bypass flow through macropores, or intermittent capillary rise from, and diffusion of salts to, a watertable (Allison *et al.* 1994; SalCon 1997) or changes in texture. For this site, a watertable is likely to have influenced the shape of the Cl profiles. Alluvial

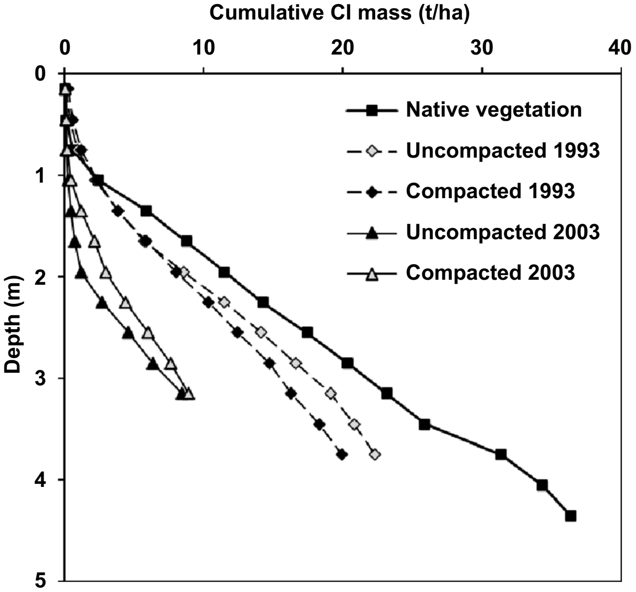

Fig. 4. Cumulative Cl profiles for native vegetation and the Biloela compaction trial control (Co) and compaction (C+) treatments in 1993 and 2003, averaged for fertiliser treatments, for non-irrigated treatments. Cumulative Cl masses in 2003 (after 10 years of treatment) significantly differed between compaction treatments for 0–0.9**, 0–1.2*, 0–1.5**, 0–1.8**, and 0–2.1* m depths (*$P < 0.05$; **$P < 0.01$; see *Statistical analysis*).

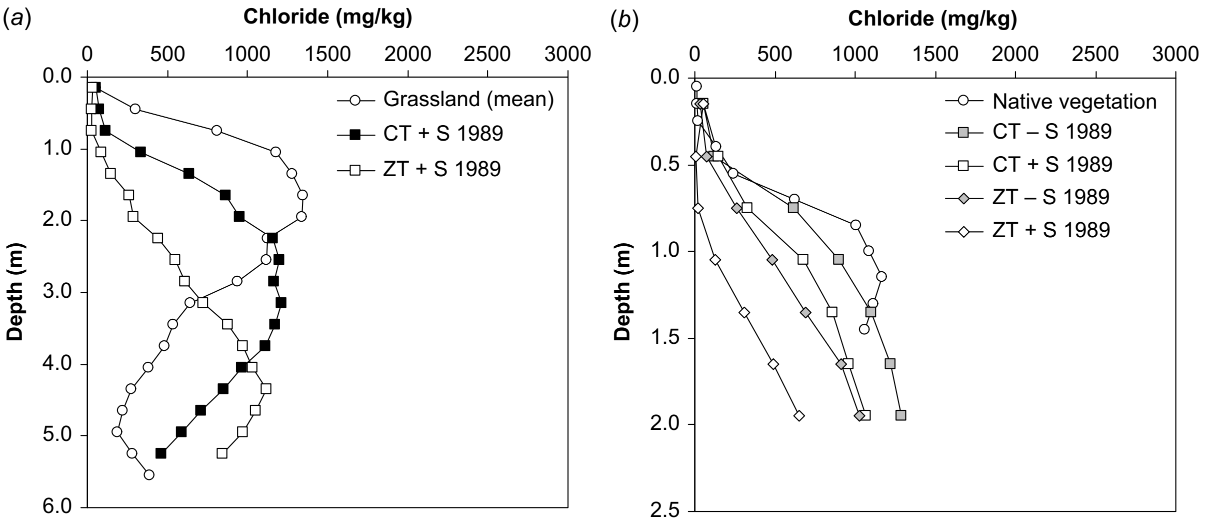

Fig. 5. Cl profiles for (*a*) Hermitage fallow management trial (Black Vertosol) [data are from bulked cores; crop data from Turpin *et al.* (1998), grassland from three sites sampled in 2002] and (*b*) Billa Billa wheat fallow management trial (Red Sodosol) (data are means of three cores; data from Greg Thomas, DERM, unpublished); cumulative Cl mass to 1.5 m was significantly different for CT compared to the other tillage systems (see *Statistical analysis*). CT, conventional tillage; ZT, zero tillage; +S, stubble retained; –S, stubble removed.

sites on the eastern Darling Downs, such as the Hermitage trial site, generally have shallow, fluctuating watertables (Silburn *et al.* 2006). Water levels in monitoring bores within 400 m of the Hermitage trial have fluctuated between –5 and –10 m since 1948. There were no significant changes in texture to 6 m at the site. Again, tillage treatments resulted in distinctly different Cl profiles (Fig. 5*a*). The ZT +S treatment lost more Cl than the CT + S treatment.

Billa Billa

The Cl profiles from the Billa Billa tillage trial (Fig. 5*b*) after 12 years of cropping and then 6 years of tillage treatments, showed distinct differences in Cl (significantly different to 1.8, 2.4, and 3.3 m). More Cl was lost for ZT than CT and with +S than –S. The stubble effect was also clear in the sorghum trial. However, the CT + S lost more Cl than the ZT + S. Some unknown amount of Cl was removed in the stubble for the –S treatments. Even so, the CT – S had the least loss of Cl by 1989.

Nindigully

The Cl profile for native vegetation at Nindigully has a slight ‘bulge’ (Fig. 6). For the cropping system treatments, most of the Cl lost from the upper part of the profile was displaced to lower in the profile (based on calculation of cumulative Cl in the profiles; data not shown), indicating that most deep drainage (and Cl loss) below 1.7 m was stored in the 1.7–3 m depth (Silburn *et al.* 2011). More Cl was lost from the ZT treatment, followed by CT; the least Cl was lost from opportunity cropping (ZT).

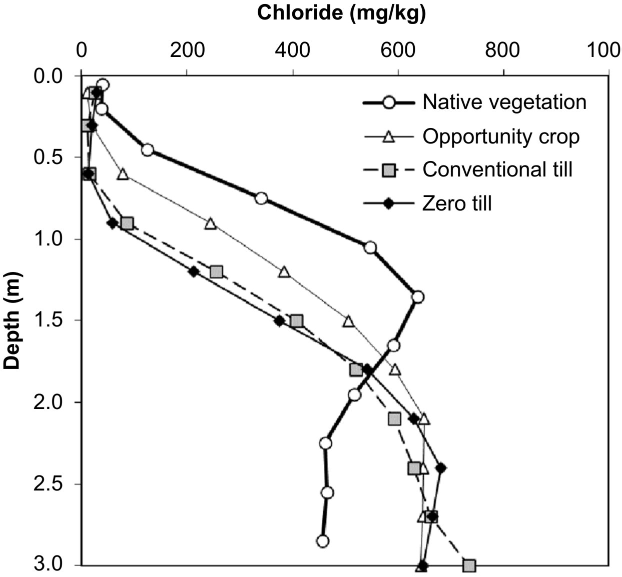

Fig. 6. Cl profiles for Nindigully farming systems trial (Grey Vertosol) (data from Greg Thomas, unpublished).

Statistical analysis of Cl differences due to management

For the Biloela tillage trial, cumulative Cl masses in 1993 (after 10 years) were significantly different between tillage treatments for 0–0.6, 0–0.9, 0–1.2, 0–1.5, and 0–1.8 m depths and were not significantly different for 0–0.3 m and all depths from 2.1 to 3.9 m (Table 2). Fertiliser had no

Table 2. Cumulative Cl mass for each sampling depth (m) in 1993, at the Biloela tillage trial, averaged for fertiliser treatments, and in 2002 at the Nindigully trial.

Tillage treatment	Cumulative soil Cl (t/ha)												
	0–0.3	0–0.6	0–0.9	0–1.2	0–1.5	0–1.8	0–2.1	0–2.4	0–2.7	0–3.0	0–3.3	0–3.6	0–3.9
Biloela tillage trial													
CT	0.08	0.21a	0.53a	1.42a	2.75a	4.29a	6.07	7.92	9.79	11.6	13.1	14.3	15.1
SM	0.08	0.17a	0.37ab	0.81ab	1.68ab	3.04ab	4.74	6.59	8.43	10.2	11.6	12.7	13.6
RT	0.11	0.21a	0.31bc	0.62b	1.16b	1.91ab	2.86	3.88	4.92	5.84	6.55	7.11	7.58
ZT	0.04	0.08b	0.13c	0.19b	0.35b	0.78b	1.45	2.30	3.23	4.27	5.33	6.25	7.02
l.s.d. ($P = 0.05$)	N.s.	0.07	0.20	0.67	1.43	2.40	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	0–0.1	0–0.3	0–0.6	0–0.9	0–1.2	0–1.5	0–1.8	0–2.1	0–2.4	0–2.7	0–3.3		
Nindigully trial													
Native vegetation	0.0052	0.016a	0.071a	0.226a	0.487a	0.802a	1.106a	1.38	1.63	1.88	2.13		
CT	0.0035	0.0066b	0.013b	0.052b	0.174b	0.377b	0.644b	0.96	1.34	1.69	2.18		
ZT	0.002	0.0080b	0.028b	0.098b	0.241b	0.460b	0.751ab	1.09	1.45	1.81	2.15		
l.s.d. ($P = 0.05$)	n.s.	0.005	0.025	0.093	0.186	0.287	0.380	n.s.	n.s.	n.s.	n.s.		
Native vegetation	0.0052a	0.016a	0.071a	0.226a	0.487a	0.802a	1.106a	1.38	1.63	1.88	2.13		
Continuous wheat	0.0035a	0.008b	0.014c	0.048c	0.160b	0.354b	0.626b	0.954	1.32	1.68	2.06		
Opportunity cropping	0.0013b	0.007b	0.041b	0.153b	0.337a	0.589a	0.893ab	1.24	1.59	1.94	2.28		
l.s.d. ($P = 0.05$)	0.0021	0.005	0.018	0.060	0.138	0.234	0.333	n.s.	n.s.	n.s.	n.s.		

Note: values in columns followed by the same letter are not significantly different.
CT, conventional tillage; SM, stubble mulch; RT, reduced tillage; ZT, zero tillage; n.s., non-significant.

significant effect on cumulative Cl mass. The Cl mass decreased with reducing intensity of tillage, from CT to ZT.

For the Biloela compaction trial, cumulative Cl masses in 2003 (after 10 years of treatment) were significantly different between compaction treatments for 0–0.9**, 0–1.2*, 0–1.5**, 0–1.8**, and 0–2.1* m depths (*$P < 0.05$; **$P < 0.01$), but not in shallower and deeper layers (data not shown). For fertiliser treatments, cumulative Cl masses in 2003 in layers to 1.2 m were significantly different. However, they were not significantly different to 1.5 and 2.1 m depths and were only significantly different at $P < 0.05$ for the 1.8 m depth, an important soil layer for CMB. Thus, the fertiliser treatment was considered secondary to the compaction treatments in their influence on Cl losses. Radford *et al.* (2001) found that fertiliser had few significant effects on crop yields. The soil is considered to have high inherent fertility. Cumulative Cl masses in 2003 only significantly differed between irrigation treatments for the 0–0.9 m depth ($P < 0.05$). Supplemental irrigation at anthesis, when the soil would often be dry to depth, did not alter the soil water balance. Thus, the irrigation and fertiliser treatments were averaged to give the most reliable estimates of deep drainage for the compaction treatments.

Turpin *et al.* (1999) found that Cl concentrations significantly differed for tillage and stubble treatments at the Hermitage fallow management trial, for soil between 1.8 and 3.3 m depth.

For the Billa Billa wheat trial (Table 2), cumulative Cl masses for ZT + S and CT – S (after 10 years of treatment) were not significantly different to depths of 0.6 and 1.8 m but significantly differed to 2.4 m ($P < 0.05$) and 3.3 m ($P < 0.01$). For the sorghum trial, in 1988, 5 years after the trial commenced, Cl mass was only significantly different for the 0.3–0.6 m layer, with greater Cl for CT than ZT. At the Nindigully trial, cumulative soil Cl masses significantly differed between native vegetation and the tillage treatments for 0.3–2.1 m depths (Table 2). Tillage treatments were not significantly different. Native vegetation Cl mass also significantly differed to that for continuous wheat and opportunity cropping, for all depths to 1.8 m (Table 2). The Cl masses significantly differed for continuous wheat and opportunity cropping for 0.9 and 1.2 m depths (Table 2). The statistical results ensure that we can be reasonably confident that Cl profiles differed between major tillage and compaction treatments.

Effects of tillage and crop residue management on deep drainage

Only the Nindigully and Biloela trials were sampled for soil Cl to sufficient depth for our purposes at the start of the trial, thus for the other trials we can only determine deep drainage for a period including pre-trial cropping and the trial treatment, relative to a native vegetation reference. The studies are discussed in order of decreasing rainfall.

1. Biloela tillage trial (mean of no-fertiliser and plus fertiliser), Cl loss and deep drainage were greatest for ZT (~45 mm/year) and least for the other tillage treatments (2–6.3 mm/year) (Table 3). Differences were small for the traditional, stubble mulch, and RT treatments (cumulative Cl mass to 1.8 m was not significantly different, Table 2).
2. At the Hermitage trial, considerably more Cl was lost under ZT (91%) than under CT (66%), to 1.5 m depth, over 42 years (Table 3). Deep drainage was 2.5 times greater for ZT than CT. Both sets of plots had the same cropping from 1947 to 1968 when the trial started and the same drainage. This drainage prior to the start of the trial masks the difference in drainage between treatments. It is logical that deep drainage for the 21 years of ZT during the trial was greater than the average (21.8 mm/year) calculated for the 42 years. If drainage during the pre-trial period was the same as for CT (8.65 mm/year), deep drainage of ZT would be 35 mm/year, or four times greater than for CT.
3. At the Billa Billa trial, 18 years after clearing and after 6 years of the trial, drainage and Cl loss were lower for wheat CT (frequent disc tillage) (3.3 and 10.4 mm/year, stubble removed and retained, respectively) than for ZT (16 and 30 mm/year), and lower for stubble removed than for stubble retained within each tillage treatment (Table 3). For the stubble retained treatments, drainage was three times greater under ZT than CT. Similar results were obtained in the sorghum trial for 1988–1991. The CT − S had less drainage (6.5 mm/year) than CT + S (14.2 mm/year), and ZT − S (29.5 mm/year), while ZT + S had 51.8 mm/year. For the 1971–1989/1988 period, deep drainage for wheat was greater than sorghum by three to five times, except for CT − S where sorghum had twice the deep drainage of wheat (Table 3). In the adjoining field under farmer practice (CT, wheat with some summer crops), deep drainage (4.4 mm/year) was similar to that for the CT − S treatment (Table 3).
4. At the Nindigully farming systems trial, drainage for 1996–2002 was 7.9 mm/year under CT and 12.7 mm/year under ZT, for annual winter cropping. Rainfall was above average for 1996–1999 and below average for 2000–2002. Long-term deep drainage prior to the trial (1956–1996) was lower than during the trial period. This low drainage is consistent with the site's low long-term average rainfall (497 mm/year) and high PAWC (300 mm).

Drainage was consistently greater under ZT (in annual winter cropping), by 7.1, 2.5, 2.9, and 1.6 times at Biloela, Hermitage, Billa Billa, and Nindigully, compared with CT, respectively. The results follow expected trends that infiltration increased under ZT and where stubble is retained (Thomas *et al.* 1997). Drainage increased because the annual crops were unable to use all the extra water stored. Much of the drainage will occur during the fallow, once the soil profile is nearly fully wet, before planting of the next crop. The increase with ZT was smaller at Nindigully, due to the large PAWC (300 mm) and lower rainfall. In contrast, the Billa Billa soil had a low PAWC (140 mm) and the increase in drainage with ZT was larger.

Thomas *et al.* (2007) provided a comprehensive review of tillage and crop residue management and impacts on sustainability and crop production in the subtropics of Australia. Stubble retention, RT and ZT generally achieves greater soil moisture storage and crop yields than intensive tillage if fertility and diseases are not limiting. Increased yields are associated with greater water use and/or greater water use efficiency. However, gains are smaller in wet years and in wetter climates, consistent with greater drainage under these conditions. The extra water infiltrated is shared between extra crop water use and increased deep drainage. This creates a challenge, because ZT, or at least RT, is required to control soil erosion (Freebairn and Wockner 1986). In regions with summer-dominant rainfall patterns, such as the current study area, winter cropping/summer fallowing has a higher potential for drainage than either summer or opportunity cropping (Freebairn *et al.* 1997; Yee Yet and Silburn 2003), which are both viable in this region.

Effects of cropping systems

Drainage was investigated at several sites where cropping systems (winter, summer, and opportunity) were compared. At the Billa Billa tillage trial, deep drainage was greater for wheat than for sorghum as discussed above and drainage in continuous wheat (CT + S) was more than twice that in the farmer's field where some summer crops were included (Table 3). At the Nindigully trial, no drainage was detected during 6 years of opportunity cropping (ZT), while 8 mm/year occurred for CT and 11 mm/year for ZT. Summer crops were grown in 4 out of 6 years of opportunity cropping whereas the other treatments involved annual wheat. Drainage was also low for pasture legume ley (1.7 mm/year) (Table 3).

Drainage in the region is driven by the interaction of crop–fallow soil moisture sequences and rainfall patterns. Tolmie *et al.* (2003) reported 3-year crop sequence trials at Jimbour and Macalister where Cl profiles show differences in drainage between sites and crop sequences caused by the coincidence of rainfall and fallow periods. Drainage was greater at both sites for the 'winter then summer crops' sequence, because above average rainfall coincided with the summer fallows. Drainage occurred in the 'summer then winter crops' sequence at one site due to greater rainfall late in one winter fallow – a winter crop at this time in the other crop sequence prevented this drainage.

Changes in soil Cl over time since clearing and subsequent average drainage rates, are illustrated in Fig. 7, with data from the Nindigully tillage trial and two nearby sites cleared in

Table 3. Cl and deep drainage at tillage and crop residue management trials.

Land use history	Time since clearing/ treatment (years)	Cl mass to 1.5 m at end (t/ha)	Cl lost 0–1.5 m		Average drainage (at 1.5 m) (mm/year)
			(t/ha)	(%)	
Biloela tillage trial – mean of no-fertiliser and plus fertiliser (Black Vertosol, 677 mm/year rainfall) Cleared in 1924. Trial started 1983					
Native vegetation		7.9			0.29
CT	9 (1984–1993)[A]	2.75a	0.55	19	6.3
SM	9 (1984–1993)[A]	1.68ab	0.53	29	4.7
RT	9 (1984–1993)	1.16b	0.1	4	2.0
	10 (1993–2003)		1.18	56	12.1
ZT	9 (1984–1993)[A]	0.35b	1.7	83	44.7
Hermitage wheat trial (Black Vertosol, 672 mm/year rainfall) cleared 1880s but probably not cropped until after 1947, trial started 1968					
Native vegetation		12.2			0.80
Conventional cropping then 34 years fallow trial (CT + S)	42 (1947–1989)	4.1	8.1	66	8.65
Conventional cropping then 34 years fallow trial (ZT + S)	42 (1947–1989)	1.1	11.1	91	21.8
Billa Billa (Red Sodosol, 658 mm/year rainfall) cleared 1971, trial started 1983					
Native vegetation		15.5			0.23
Wheat trial					
12 years cult, 6 years trial (CT – S)	18 (1971–1989)	13.7	1.76	11	3.34
12 years cult, 6 years trial (CT + S)	18 (1971–1989)	20.1	5.3	34	10.4
12 years cult, 6 years trial (ZT – S)	18 (1971–1989)	2.5	7.9	51	16.0
12 years cult, 6 years trial (ZT + S)	18 (1971–1989)	7.6	13.0	84	30.1
Sorghum trial					
12 years cult, 5 and 3 years trial (CT – S)	17 (1971–1988)	15.0	3.1	20	6.5
	3 (1988–1991)	12.4	2.6	18	6.3
12 years cult, 5 and 3 years trial (CT + S)	17 (1971–1988)	3.84	0.76	17	1.8
	3 (1988–1091)	2.92	0.92	24	14.2
12 years cult, 5 and 3 years trial (ZT – S)	17 (1971–1988)	3.3	1.35	29	4.8
	3 (1988–1991)	7.5	2.0	21	29.5
12 years cult, 5 and 3 years trial (ZT + S)	3 (1988–1991)	1.56	1.7	52	51.8
	17 (1971–1988)	9.5	6.0	39	10.2
Farm: wheat and summer crops	19 (1971–1990)	38.6	2.5	16	4.4
Nindigully (Grey Vertosol, 497 mm/year rainfall) cleared 1956, trial started 1996					
Native vegetation (tillage trial)		8.0			0.21
Native vegetation (Harms and Dalal 2003)		7.9			0.23
Pre-trial – wheat, pasture phases CT, ZT	34, 5 (1967/1996–2001)	4.9	3.8, 2.4[B]	48, 30[B]	2.2, 16.0[B]
Tillage trial					
Wheat CT	6 (1996–2002)	3.8	1.11	23	7.9
Wheat ZT	6 (1996–2002)	1.4	1.85	36	12.7
Opportunity cropping (ZT)	6 (1996–2002)	5.7	0.0	0.0	0.0
Grass–legume ley pasture	6 (1996–2002)	4.7	0.19	4	1.7

Note: statistical differences are given in a separate section.

[A] Cl mass increased between 1993 and 2003 so deep drainage could not be calculated.

[B] Two sites, CT and ZT.

CT, conventional tillage; SM, stubble mulch; RT, reduced tillage; ZT, zero-tillage; +S, stubble retained; –S, stubble removed.

different years. Prior to the start of the Nindigully tillage trial, almost half of the soil Cl was lost from the 0–1.5 m depth in 40 years. Apparent soil Cl changes during the trial (established in 1996) varied from year to year due to wet and dry periods and experimental error; however, the overall downward trend was clear. These data and analysis with SODICS indicate the inevitability of salt leaching after hydrologic change induced by land clearing.

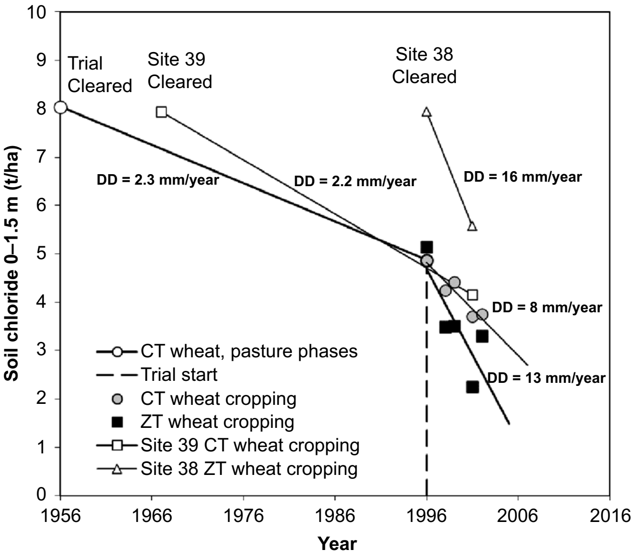

Fig. 7. Soil Cl vs time at the Nindigully tillage trial site (Thomas *et al.* 1998) and two Nindigully soil carbon sites 38 and 39 (Harms and Dalal 2003) with average deep drainage rates (DD) for each case. CT, conventional tillage; ZT, zero-tillage.

Biloela compaction trial

The Cl loss and deep drainage (Table 4) was greater for the non-compacted (80%, 38.2 mm/h) than the compacted treatment (59% and 23.3 mm/year), a 39% increase. Supplemental irrigation caused a decrease in deep drainage for both compaction treatments, particularly the non-compacted treatment. At anthesis when irrigation was applied there would have been a large soil water deficit and irrigation would not have caused deep drainage. Irrigation did cause a reduction in water use efficiency but not crop yield. However, as the cumulative soil Cl was not significantly different for these treatments, the drainage may not differ. Addition of fertiliser made little difference for the compacted treatment but caused an increase of deep drainage for the control. This does not fit with the logic of fertiliser increasing crop water use. However, the site had high fertility and crops did not respond to fertiliser.

Table 4. Cl and drainage at the Biloela compaction trial, with and without compaction, supplemental irrigation (Io, I+) and fertiliser (Fo, F+) with ZT winter and summer crop.

Treatment	Total Cl 0–1.8 m 1993 (t/ha)	Total Cl lost 0–1.8 m (t/ha)	Total Cl lost 0–1.8 m (%)	Deep drainage mean 1.5–2.4 m (mm/year)	Leachate Cl concentration at 1.8 m (mg/L)	Leachate EC if NaCl (µS/cm)
Native vegetation	7.9			1.1		
Pre-trial land use (1924–1993)	6.1	1.6	21	2.5		
CV (*N* = 8)	9%	35%	34%	24%		
Trial (1993–2003) (Black Vertosol, 603 mm/year rainfall)						
Control (all)	6.1	4.9	80	38.2	147	346
Compacted (all)	6.2	3.6	59	23.3	189	445
Compacted Io	5.9	3.6	62	28.9	181	427
Compacted I+	6.4	3.6	56	25.3	155	364
Compacted Fo	6.4	3.6	56	25.3	155	364
Compacted F+	7.2	4.5	54	26.7	166	391
Control Io	5.8	5.0	87	49.9	82	193
Control I+	6.5	4.8	73	38.7	142	334
Control Fo	5.9	4.3	72	33.9	161	378
Control F+	6.3	5.5	87	43.3	129	305
				Ratio Cl/EC		0.42
Mean groundwater Biloela Research Station				27.2[A]	141	792
CV (*N* = 10)				17%	17%	
				Ratio Cl/EC		0.18

Note: statistical differences are given in a separate section.

[A] Drainage calculated using steady-state Cl mass balance using Cl in groundwater.

The Cl concentrations and leachate salinity in the Biloela trial were similar to that of the alluvial groundwater and should not lead to the type of salinisation of the alluvial aquifer observed by Leaney *et al.* (2003), wherein leached salts increase the salinity of the groundwater. The soil profile drainage and groundwater recharge were similar (to the extent that the trial is indicative of cropping in the area). However, composition of ions differed in the leachate (dominantly NaCl) and the groundwater (with greater bicarbonate), as indicated by the Cl/EC ratios in Table 4. The groundwater had a lower Cl/EC ratio than NaCl. The soil profile Cl and EC data plotted close to the theoretical relationship indicating NaCl [EC due to Cl = 6.64 × %Cl (per weight of soil); SalCon 1997, p. 195] (data not shown), with a subset of data (15–20 out of 242) plotted with higher EC than the theoretical value (indicating EC due to gypsum or carbonates in addition to that from NaCl). The difference in ion composition is probably because the groundwater had another source of water and salt (e.g. lateral flow balanced in and out) or contained remnant salt from before clearing which had a different source.

Which factors explain deep drainage?

Previously, deep drainage for sites predominantly under winter cropping–summer fallow and CT was found to be related to average annual rainfall (Tolmie *et al.* 2011; R^2 = 0.63, N = 17) and soil PAWC (Radford *et al.* 2009; R^2 = 0.86, N = 7; and Tolmie *et al.* 2011; R^2 = 0.77, N = 9 for Vertosols). For the five sites in this study, rainfall explained 59% of the variance in average annual deep drainage for ZT but only 10% for CT. For ZT, PAWC explained 54% of the variance but only 18% for CT. No significant relationship was found with subsoil ESP for the tillage trials, so a regression was performed for all of the Cl-derived deep drainage data (N = 22, from the citations above). A significant relationship was found between subsoil ESP and deep drainage (Fig. 8). Shaw (1995) found that ESP at 80 cm depth was highly related to soil profile final infiltration rate. A lesser relationship for ESP (than for rainfall and PAWC) makes sense, since a soil with a medium subsoil hydraulic conductivity may drain over a few days whereas a soil with low subsoil hydraulic conductivity may drain over several weeks. If the subsoil water is not transpired, then the total drainage will be similar.

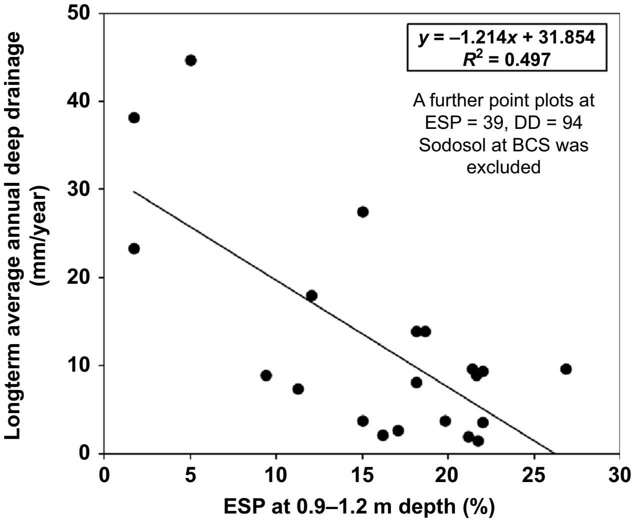

Fig. 8. Annual average deep drainage (DD) for long-term conventional tillage wheat sites plotted against exchangeable sodium percentage (ESP) in the subsoil (0.09–1.2 m depth). The regression was significant ($P < 0.001$).

General discussion

The results consistently showed that for annual fallow wheat and for one study with annual sorghum, deep drainage was greater for ZT than for CT. However, ZT is highly beneficial in reducing soil erosion and runoff which may be contaminated (Freebairn *et al.* 1996), slowing soil carbon decline (Page *et al.* 2013) and improving crop yields (Thomas *et al.* 2007). In central Qld, ZT is also more profitable than CT (Strahan and Hoffman 2009). Some parts of the northern grains zone have shallow soils (e.g. Central Highlands and eastern Darling Downs) and high rainfall erosivity. Under CT, erosion rates are high enough to reduce soil productivity rapidly (Freebairn *et al.* 1996; Loch and Silburn 1997). The shallowest soils become entirely unproductive and have been withdrawn from cultivation, surviving as low-productivity pastures. The results, previous field studies (Silburn *et al.* 2009, 2011; Tolmie *et al.* 2011), and modelling (Robinson *et al.* 2010; Whish *et al.* 2006) also show that the secondary salinity risks posed by ZT can be offset using opportunity cropping, growing more summer crops in rotations, and using ley pastures rather than continuous annual winter cropping. Whish *et al.* (2006) predicted that when opportunity cropping replaced fallowing and summer cropping, deep drainage was reduced by 50%. The modelling was validated against deep drainage estimated using transient soil CMB from Silburn *et al.* (2011). Thus, management practices that combine the benefits of ZT and reduce deep drainage are available to farmers in the study region. Thomas *et al.* (2011) found opportunity cropping to be successful in a field trial in semiarid southwest Queensland at Nindigully, on a Vertosol with a large PAWC. However, Robinson *et al.* (2010) warns that opportunity cropping can be unreliable in lower rainfall areas when cropping on soils with low PAWC, such as Kandosols, Chromosols, and Dermosols. Opportunity cropping with sorghum is more likely to succeed on Vertosols due to their higher PAWC.

We also found that deep drainage increased by 39% for controlled traffic, albeit at only one site. Compaction from traffic reduces infiltration (Connolly *et al.* 2001) and increases runoff (Tullberg *et al.* 2001), consistent with less deep drainage. However, annual traffic on wet soil can reduce seedling emergence, grain yield, and crop water use efficiency (Radford *et al.* 2001), which may lead to less crop water use and thus increased deep drainage. Controlled traffic has benefits in reducing soil erosion (Li *et al.* 2008), reducing costs and potentially increasing production (Tullberg 2010). Controlled traffic in conjunction with ZT provides the flexibility to facilitate opportunity cropping and grow more summer crops in rotations. This provides the opportunity to offset any potential increase in deep drainage.

Finally, we comment on the ability of the transient CMB to detect small rates of deep drainage. The method was successful for the Billa Billa trial with lower rainfall, 10 years between sampling and only three cores. However, at the Biloela tillage trial for 1993–2003, Cl mass increased for three of the four treatments. The difference was that Billa Billa had 8–20 t/ha of soil Cl while the Biloela site only had <1–3 t/ha. Detecting changes in such low levels of soil Cl appears to be at the limit of the technique.

Conclusions

We report results for soil Cl changes and deep drainage (below the crop root zone) determined by transient soil CMB, on heavier textured soils (Vertosols and a Sodosol) under dryland cropping and pasture. Measurements were made on four tillage/crop rotation trials and on one compaction trial, in the western and eastern Darling Downs and in the Callide. Steady-state and transient CMB (SODICS) were used to estimate deep drainage for contrasting tillage and compaction treatments. These methods can discriminate the small amounts of deep drainage that are expected in grain cropping in Qld.

Drainage was greater for ZT with annual winter cropping, and annual sorghum cropping in one trial, than for more intensive forms of tillage, in all four tillage trials. Stubble-retained treatments had more deep drainage than stubble-removed treatments, for both wheat and sorghum. Winter cropping (wheat) had greater deep drainage by three to five times than summer crops (sorghum) in three of the four tillage systems. Deep drainage was low (~0 mm/year) for opportunity cropping (with more summer crops) than for annual winter cropping (13 mm/year for ZT) at one trial site. Deep drainage was low (~2 mm/year) for grass–legume ley pasture. Controlled traffic increased deep drainage by 39% at the wettest trial site. Deep drainage was lower at sites with larger PAWC and with lower rainfall and was also related to subsoil ESP. Deep drainage was low at all native vegetation sites.

ZT and RT and controlled traffic have environmental and production benefits for grain cropping in the study region. The increase in deep drainage with these practices can be offset by using opportunity cropping, growing more summer crops and use of ley pastures.

References

Abbs K, Littleboy M (1998) Recharge estimation for the Liverpool Plains. *Australian Journal of Soil Research* **36**, 335–357. doi:10.1071/S97049

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

Belyando Suttor Implementation Group, Baxter N, Webb I, Chamberlain J, Cogle L, Mirtschin S, Hateley L, Velupillai R, Pitt G, Silburn M, Bourne G, Flint S, Heiner D, Dwyer M, Christianos N, Philip S, Claridge J, Owens J, Grundy M, Freebairn DM, Bruce P, Reading L (2004) ‘Understanding dryland salinity in the Belyando Suttor – some preliminary findings’. (Department of Natural Resources & Mines: Mareeba, Indooroopilly, Emerald)

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, Dwg B, Hebbard CL (2005) Salinity audit – Border Rivers and Moonie catchments, Queensland Murray–Darling Basin. QNRM05462. Department of Natural Resources and Mines, Toowoomba, Qld.

Chamberlain T, Silburn DM, Forster BA, Wearing CH, Moss JB, Reading LP, Owens JS, Pearce BR (2007) ‘Salinity risk assessment for the Fitzroy Basin, Queensland’. (Queensland Department of Natural Resources and Water: Indooroopilly, Qld)

Chamberlain T, Anzooman M, Rattray D, Owens JS, Silburn DM (2021) Modelling reductions of pollutant loads due to improved management practice in the Great Barrier Reef Catchments. Paddock modelling for grains, Technical Report. (Queensland Department of Resources: Toowoomba, Qld)

Connolly RD, Freebairn DM, Bell MJ, Thomas G (2001) Effects of rundown in soil hydraulic condition on crop productivity in south-eastern Queensland – a simulation study. *Australian Journal of Soil Research* **39**, 1111–1129. doi:10.1071/SR00089

Dalal RC (1989) Long-term effects of no-tillage, crop residue, and nitrogen application on properties of a Vertisol. *Soil Science Society of America Journal* **53**, 1511–1515. doi:10.2136/sssaj1989.03615995005300050035x

Dalal RC, Mayer RJ (1986) Long term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. I. Overall changes in soil properties and trends in winter cereal yields. *Australian Journal of Soil Research* **24**, 265–279. doi:10.1071/SR9860265

Freebairn DM, Wockner GH (1986) A study of soil erosion on vertisols of the eastern Darling Downs, Queensland. I. Effects of surface conditions on soil movement within Contour Bay catchments. *Australian Journal of Soil Research* **24**, 135–158. doi:10.1071/SR9860135

Freebairn D, Connolly R, Dimes J, Wylie P (1990) Optimising soil surface management in response to climate risk. In ‘Proceedings of the International Symposium on Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics’. (Eds RC Murchow, JA Bellamy) pp. 283–305. (CAB International: Brisbane)

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

Freebairn DM, Connolly RD, Dimes J, Wylie PB (1997) Crop sequencing. In ‘Sustainable crop production in the sub tropics: an Australian perspective’. (Eds AL Clarke, PB Wylie) pp. 289–305. (Department of Primary Industries Queensland: Brisbane)

GRDC (2020) Converting-to-controlled-traffic-pays-more-than-one-dividend. Available at https://groundcover.grdc.com.au/agronomy/soil-and-nutrition/converting-to-controlled-traffic-pays-more-than-one-dividend

Harms B, Dalal R (2003) Paired site sampling for soil carbon (and nitrogen) estimation – Queensland. National Carbon Accounting

System Technical Report No. 37. Australian Greenhouse Office, Canberra.

Isbell RF (2002) 'The Australian soil classification'. (CSIRO Publishing: Melbourne)

Keating BA, Gaydon D, Huth NI, Probert ME, Verburg K, Smith CJ, Bond W (2002) Use of modelling to explore the water balance of dryland farming systems in the Murray–Darling Basin, Australia. *European Journal of Agronomy* **18**, 159–169. doi:10.1016/S1161-0301(02)00102-8

Leaney FW, Herczeg AL, Walker GR (2003) Salinization of a fresh Palaeo-groundwater ground water resource by enhanced recharge. *Groundwater* **41**, 84–92. doi:10.1111/j.1745-6584.2003.tb02571.x

Li YX, Tullberg JN, Freebairn DM, McLaughlin NB, Li HW (2008) Effects of tillage and traffic on crop production in dryland farming systems: I. Evaluation of PERFECT soil-crop simulation model. *Soil and Tillage Research* **100**, 15–24. doi:10.1016/j.still.2008.04.004

Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204–212. doi:10.1016/j.fcr.2012.03.013

Loch RJ, Coughlan KJ (1984) Effects of zero tillage and stubble retention on some properties of a cracking clay. *Australian Journal of Soil Research* **22**, 8–91. doi:10.1071/SR9840091

Loch RJ, Silburn DM (1997) Soil erosion. In 'Sustainable crop production in the sub-tropics: an Australian perspective'. QDPI monograph, information series QI97035. (Eds A Clarke, P Wylie) pp. 27–41. (Queensland Department of Primary Industries: Brisbane)

McDonald R, Isbell R, Speight J, Walker J, Hopkins M (1990) 'Australian soil and land survey field handbook'. (Inkata Press: Melbourne)

McGarry D, Bridge BJ, Radford BJ (2000) Contrasting soil physical properties after zero and traditional tillage of an alluvial soil in the semi-arid subtropics. *Soil and Tillage Research* **53**, 105–115. doi:10.1016/S0167-1987(99)00091-4

McKeown FR (1978) 'A land classification of the Hermitage Research Station'. (Department of Primary Industries: Brisbane)

O'Connell MG, O'Leary GJ, Incerti M (1995) Potential groundwater recharge from fallowing in north–west Victoria, Australia. *Agricultural Water Management* **29**, 37–52. doi:10.1016/0378-3774(95)01185-4

Owens JS, Tolmie PE, Silburn DM (2004) Validating modelled deep drainage estimates for the Queensland Murray–Darling. In '13th international soil conservation organisation conference'. pp. 1–6. (Australian Society of Soil Science Inc.: Brisbane)

Page KL, Dalal RC, Pringle MJ, Bell M, Dang YP, Radford B, Bailey K (2013) Organic carbon stocks in cropping soils of Queensland, Australia, as affected by tillage management, climate, and soil characteristics. *Soil Research* **51**, 596–607. doi:10.1071/SR12225

Paydar Z, Huth N, Ringrose-Voase A, Young R, Bernardi T, Keating B, Cresswell H, Holland J, Daniels I (2001) Modelling deep drainage modelling under different land use systems. 1. Verification and systems comparison. In 'Update of research in progress at Tamworth Centre for crop improvement 2001'. pp. 95–113. (NSW Agriculture: Tamworth, NSW)

Poulton PL, Huth NI, Carberry PS (2005) Use of simulation in assessing cropping system strategies for minimising salinity risk in brigalow landscapes. *Australian Journal of Experimental Agriculture* **45**, 635–642. doi:10.1071/EA03250

Pringle MJ, Denham RJ, Devadas R (2012) Identification of cropping activity in central and southern Queensland, Australia, with the aid of MODIS MOD13Q1 imagery. *International Journal of Applied Earth Observation and Geoinformation* **19**, 276–285. doi:10.1016/j.jag.2012.05.015

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

Radford BJ, Thornton CM (2011) Effects of 27 years of reduced tillage practices on soil properties and crop performance in the semi-arid subtropics of Australia. *International Journal of Energy, Environment, and Economics* **19**, 588.

Radford BJ, Key AJ, Robertson LN, Thomas GA (1995) Conservation tillage increases in soil water storage, soil animal populations, grain yield, and response to fertiliser in the semi-arid subtropics. *Australian Journal of Experimental Agriculture* **35**, 223–232. doi:10.1071/EA9950223

Radford BJ, Bridge BJ, Davis RJ, McGarry D, Pillai UP, Rickman JF, Walsh PA, Yule DF (2000) Changes in the properties of a Vertisol and responses of wheat after compaction with harvester traffic. *Soil and Tillage Research* **54**, 155–170. doi:10.1016/S0167-1987(00)00091-X

Radford BJ, Yule DF, McGarry D, Playford C (2001) Crop responses to applied soil compaction and to compaction repair treatments. *Soil and Tillage Research* **61**, 157–166. doi:10.1016/S0167-1987(01)00194-5

Radford BJ, Yule DF, McGarry D, Playford C (2007) Amelioration of soil compaction can take 5 years on a Vertisol under no till in the semi-arid subtropics. *Soil and Tillage Research* **97**, 249–255. doi:10.1016/j.still.2006.01.005

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

Ringrose-Voase A, Young R, Huth N, Paydar Z, Bernardi T, Martin B (2003) Deep drainage in the Liverpool Plains of northern NSW. In 'Update of research in progress at the Tamworth Agricultural Institute 2002'. pp. 1–5. (NSW Agriculture: Tamworth, NSW)

Robinson JB, Silburn DM, Rattray D, Freebairn DM, Biggs A, 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 PWA, Nielsen DR, Biggar JM (1979) Long-term solute dynamics and hydrology in irrigated slowly permeable soils. *Irrigation Science* **1**, 77–87. doi:10.1007/BF00263091

SalCon (1997) Salinity management handbook. DNRQ97109. Department of Natural Resources, Brisbane.

Searle R, Watling K, Biggs A, Secombe K (2006) Strategic salinity risk assessment in the Condamine Catchment. QNRM06218. Queensland Department Natural Resources and Water, Indooroopilly, Brisbane. Available at http://www.regionalnrm.qld.gov.au/

Shaw RJ (1995) A unified soil property and sodicity model of salt leaching and water movement. Ph.D. thesis, University of Queensland, Brisbane.

Shields P (1989) Soils of the Biloela Research Station, Queensland. Research Establishments Publication QR89001. Queensland Department of Primary industries, Queensland Government, Brisbane.

Silburn DM, Owens JS, Dutta S, Cresswell RG, McNeil V (2006) Hodgson Creek, QMDB – salinity and recharge studies and 2Csalt modelling. QNRM05513. In 'Murray–Darling Basin Groundwater Conference'. pp. 18–20. (Department of Natural Resources and Mines: Brisbane)

Silburn DM, Robinson JB, Freebairn DM (2007) Why restore marginal cropland to permanent pasture? Land resource and environmental issues. *Tropical Grasslands* **41**, 139–153. Available at http://www.scopus.com/inward/record.url?eid=2-s2.0-36649013433&partnerID=40&md5=42b2c6c343141450f6f6a5b7bbc11653

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, Tolmie PE, Biggs AJW, Whish JPM, French V (2011) Deep drainage rates of Grey Vertosols depend on land use in semi-arid subtropical regions of Queensland, Australia. *Soil Research* **49**, 424–438. doi:10.1071/SR10216

Strahan R, Hoffman A (2009) 'Estimating the economic implications for broad acre cropping farms in the Fitzroy Basin catchments of adoption of best management practices'. (Department of Employment, Economic Development and Innovation: Queensland)

Thomas GA, Gibson G, Nielsen RGH, Martin WD, Radford BJ (1995) Effects of tillage, stubble, gypsum, and nitrogen fertiliser on cereal cropping on a red-brown earth in south-west Queensland. *Australian Journal of Experimental Agriculture* **35**, 997–1008. doi:10.1071/EA9950997

Thomas GA, Felton WL, Radford BJ (1997) Tillage and crop residue management. In 'Sustainable crop production in the sub-tropics: an Australian perspective'. (Eds AL Clarke, PB Wylie) pp. 195–213. (Department of Primary Industries Queensland: Brisbane, Qld)

Thomas GA, Dalal RC, Weston EJ, Chicken CJ, Lehane KJ, King AJ, Orange DN, McNamara GT (1998) A farming systems study at Nindigully, South–West Queensland. In 'Proceedings of the 9th Australian agronomy conference, Wagga Wagga, NSW'. (Eds DL Michalk, JE Pratley) pp. 677–678. (Australian Society of Agronomy: Wagga Wagga, NSW)

Thomas GA, Titmarsh GW, Freebairn DM, Radford BJ (2007) No-tillage and conservation farming practices in grain growing areas of Queensland – a review of 40 years of development. *Australian Journal of Experimental Agriculture* **47**, 887–898. doi:10.1071/EA06204

Thomas GA, Dalal RC, Weston EJ, King AJ, Holmes CJ, Orange DN, Lehane KJ (2011) Crop rotations for sustainable grain production on a Vertisol in the semi-arid subtropics. *Journal of Sustainable Agriculture* **35**, 2–26. doi:10.1080/10440046.2011.530195

Thorburn PJ, Rose CW (1990) Interpretation of solute profile dynamics in irrigated soils. III. A simple model of bypass flow in soils. *Irrigation Science* **11**, 219–225. doi:10.1007/BF00190536

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

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

Tolmie PE, Radford BJ (2004) Effect of tillage practices on chloride movement and deep drainage at Biloela, Central Queensland. In '13th International Soil Conservation Organisation Conference'. pp. 1–4. (International Soil Conservation Organisation: Brisbane)

Tolmie PE, Silburn M (2003) 'Estimating deep drainage in the Queensland Murray–Darling Basin: review of past research'. (Department of Natural Resources and Mines: Toowoomba)

Tolmie PE, Silburn DM, Biggs AJW (2003) Estimating deep drainage in the Queensland Murray–Darling Basin using soil chloride. QNRM03020. Department of Natural Resources and Mines, Toowoomba.

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. doi:10.1071/SR10172

Tullberg J (2010) Tillage, traffic and sustainability – a challenge for ISTRO. *Soil and Tillage Research* **111**, 26–32. doi:10.1016/j.still.2010.08.008

Tullberg JN, Ziebarth PJ, Li Y (2001) Tillage and traffic effects on runoff. *Australian Journal of Soil Research* **39**, 249–257. doi:10.1071/SR00019

Tullberg JN, Yule DF, McGarry D (2007) Controlled traffic farming – from research to adoption in Australia. *Soil and Tillage Research* **97**, 272–281. doi:10.1016/j.still.2007.09.007

Turpin J (1995) 'Fate of nitrogen fertiliser, with emphasis on leaching, for cereal cropping under different fallow management systems on the Darling Downs'. (University of Queensland: Brisbane)

Turpin JE, Thompson JP, Waring SA, MacKenzie J (1998) Nitrate and chloride leaching in Vertosols for different tillage and stubble practices in fallow–grain cropping. *Australian Journal of Soil Research* **36**, 31–44. doi:10.1071/S97037

Turpin JE, Bridge BJ, Orange D, Thompson JP (1999) Water and bromide movement in a Vertosol under four fallow management systems. *Australian Journal of Soil Research* **37**, 75–89. doi:10.1071/S97108

USSL Staff (1954) Diagnosis and improvement of saline and alkali soils. In 'United States Department of Agriculture Handbook. Vol. 60'. (Ed. LA Richards) (USDA: Washington, DC)

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

Whish J, French V, Tolmie PE, Silburn DM (2006) Simulating historic cropping systems to understand the interaction between crop choice and deep drainage. In 'Proceedings of the 13th Australian Agronomy Conference, Perth, WA'. pp. 1–4. (Australian Society of Agronomy: Perth)

Willis TM, 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 QMDB using water balance modelling. QNRM03021. Department of Natural Resources and Mines, Toowoomba.

Young R, Huth N, Harden S, McLeod R (2014) Impact of rain-fed cropping on the hydrology and fertility of alluvial clays in the more arid areas of the upper Darling Basin, eastern Australia. *Soil Research* **52**, 388–408. doi:10.1071/SR13194

Zhang L, Dawes WR, Hatton TJ, Hume IH, O'Connell MG, Mitchell DC, Milthorp PL, Yee M (1999) Estimating episodic recharge under different crop/pasture rotations in the Mallee region. Part 2. Recharge control by agronomic practices. *Agricultural Water Management* **42**, 237–249. doi:10.1016/S0378-3774(99)00034-7

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