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Rapid internal drainage rates in Ferrosols

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Abstract. Adoption of conservation tillage practices on Red Ferrosol soils in the inland Burnett area of south-east Queensland has been shown to reduce runoff and subsequent soil erosion. However, improved infiltration resulting from these measures has not improved crop performance and there are suggestions of increased loss of soil water via deep drainage. This paper reports data monitoring soil water under real and artificial rainfall events in commercial fields and long-term tillage experiments, and uses the data to explore the rate and mechanisms of deep drainage in this soil type.

Soils were characterised by large drainable porosities ($\geq 0.10\ \mathrm{m^3/m^3}$) in all parts of the profile to depths of 1.50 m, with drainable porosity similar to available water content (AWC) at 0.25 and 0.75 m, but >60% higher than AWC at 1.50 m. Hydraulic conductivity immediately below the tilled layer in both continuously cropped soils and those after a ley pasture phase was shown to decline with increasing soil moisture content, although the rate of decline was much greater in continuously cropped soil. At moisture contents approaching the drained upper limit (pore water pressure = -100 cm H_2O), estimates of saturated hydraulic conductivity after a ley pasture were 3–5 times greater than in continuously cropped soil, suggesting much greater rates of deep drainage in the former when soils are moist.

Hydraulic tensiometers and fringe capacitance sensors monitored during real and artificial rainfall events showed evidence of soils approaching saturation in the surface layers (top 0.30–0.40 m), but there was no evidence of soil moistures exceeding the drained upper limit (i.e. pore water pressures ≤ -100 cm H_2O) in deeper layers. Recovery of applied soil water within the top 1.00–1.20 m of the profile during or immediately after rainfall events declined as the starting profile moisture content increased. These effects were consistent with very rapid rates of internal drainage. Sensors deeper in the profile were unable to detect this drainage due to either non-uniformity of conducting macropores (i.e. bypass flow) or unsaturated conductivities in deeper layers that far exceed the saturated hydraulic conductivity of the infiltration throttle at the bottom of the cultivated layer. Large increases in unsaturated hydraulic conductivities are likely with only small increases in water content above the drained upper limit. Further studies with drainage lysimeters and large banks of hydraulic tensiometers are planned to quantify drainage risk in these soil types.

Additional keywords: salinity, water balance, runoff, macropores.

Introduction

The Red Ferrosols of the inland Burnett region of south-east Queensland support predominantly rain-fed cropping systems producing summer grain legume and cereal grain crops. One common characteristic of these soils after long-term cropping is a loss of the original very high rainfall infiltration capacity—a key factor in successful rain-fed cropping (Bridge and Bell 1994). This has been attributed to 2 factors: firstly, a decline in labile organic carbon resulting in surface crusting, and secondly, subsoil compaction that reduces the hydraulic conductivity down the profile (Bell *et al*. 1997, 1998).

The use of kikuyu (*Pennisetum clandestinum*) and Rhodes grass (*Chloris gayana*) pasture leys were shown by Bell *et al*. (1997) to dramatically improve soil organic matter contents in the upper 0.30 m and infiltration rates into the soil profile. Unfortunately, subsequent experimental crops were unable to capitalise on the improved infiltration rates because of the relatively low available water capacity, around $0.1\ \mathrm{cm^3/cm^3}$ (Bridge and Bell 1994; Bell *et al*. 2001). Soil

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moisture monitoring in the abovementioned experimental crops confirmed that after large rainfall events, infiltrated water moved to depths of at least 0.90 m much more quickly in a pasture ley/zero till treatment than continuous crop/conventional till. In one instance, profile moisture in soils after pasture leys had returned to before-rain levels within 2 days, during which apparent total 'water use' from the profile was 14 mm/day, while evapotranspiration was only 4 mm/day (Bell and Bridge 2001).

A 'first cut' series of simulations using the APSIM model (McCown *et al.* 1996) combined with the SWIM model (Verberg *et al.* 1996) using local climate and soil properties also predicted a lack of crop response to improved soil structure and infiltration. Indeed, the simulations indicated that any reduction in runoff with improved infiltration would result in an equivalent increase in deep drainage (Bell *et al.* 2001). While reduction of runoff and associated soil erosion is desirable, doing so by increasing deep drainage also represents a significant risk to the long-term sustainability of cropping systems on these and associated soil types, especially those that are less permeable and that occupy lower positions in the landscape (Baillie and Searle 1998). Indeed, the inland Burnett has already recorded significantly higher water tables and increasingly frequent outbreaks of dryland salinity in both lower and mid-slope positions in the landscape, with most drainage lines in the inland Burnett also recording outbreaks of dryland salinity. An accurate quantification of deep drainage rates in these soils, and an assessment of the impact of changes to management practices on all water balance components, are clear prerequisites to the development of sustainable land-use mix at both subcatchment and catchment scales.

This paper presents the results of a series of investigations utilising artificial rainfall events, and a fortuitous natural one, to quantify the impact of management on rainfall infiltration in Red Ferrosols of the inland Burnett. Further, continuous monitoring of soil water content and pore water pressure at various points down the soil profile during infiltration events was used to provide insights into potential drainage losses.

Materials and methods

Experimental sites

Measurements were conducted over several years (1997–2002) on commercial properties at 2 main experimental sites, which are referred to as Goodger and Coolabunia. Both sites were situated on deep (>2.0 m) neutral (Coolabunia) or acidic (Goodger) strongly structured clay soils (Red Ferrosols, Isbell 1993) to the south of Kingaroy, in the inland Burnett region of south-east Queensland, Australia. The Goodger site was wholly located on one farm, while the Coolabunia site consisted of adjoining properties with contrasting management practices on either side of a local roadway.

Both sites had been cropped continuously for >50 years, using primarily conventional tillage and annual summer crops of grains [primarily maize (*Zea mays*) and sorghum (*Sorghum bicolor*)] and grain legumes [peanut (*Arachis hypogaea*)], with occasional opportunity winter cropping with wheat (*Triticum aestivum*). However, the Goodger property had moved to a minimum tillage system in the early 1990s, with soybeans (*Glycine max*) replacing peanuts and an increased frequency of wheat cropping. One of the Coolabunia properties has continued in a conventional tillage peanut–maize/sorghum system, while the other converted completely to a direct drill, opportunity-cropping system, also with soybeans replacing peanuts.

Goodger site

A major experimental site was established on the Goodger property in spring 1990, to investigate options for soil physical rehabilitation of degraded cropping soils. A kikuyu pasture was established on part of the area, with a detailed description of treatments and management outlined previously (Bell *et al.* 1997). Briefly, the pasture plots were not cut or grazed during the next 4 years, while 4 management regimes were imposed: (*i*) low input pasture, where no fertiliser or other inputs were supplied; (*ii*) fertilised pasture, where annual applications of N, P, and K fertiliser were made; (*iii*) fertilised ripped pasture, where the soil was ripped to a depth of 0.35–0.40 m during year 2 of the ley; and (*iv*) fertilised pasture with earthworms, where locally adapted earthworms (*Fletcherodrilus unicus*, *Aporrectodea trapezoides*, and *Potoscolex corethurus*) were introduced during the initial year of pasture establishment.

At the end of the ley phase, the kikuyu was sprayed out with 1800 g/ha glyphosate and the plots were returned to cropping using either direct-drill, controlled traffic, or conventional till with random traffic practices. Additional plots of continuously cropped, degraded soil in adjoining contour bays were used as a reference. Treatments in these adjoining bays represented factorial combinations with or without deep ripping, and direct drill, controlled traffic or conventional cultivation, random traffic practices. Plots were sown to a sequence of crops over the next 5 summer seasons (soybean, maize, peanut, maize, and peanut from 1994–95 to 1998–99), with winter wheat double-cropped into the zero till plots in 1995, 1997, and 1998. Soil water was measured periodically during the growing season. The site was returned to the grower after harvest of the 1998/99 peanut crop.

Coolabunia site

After the Goodger experimental site was handed back to the landholder, a second site was selected near Coolabunia. This consisted of 2 adjacent paddocks under different management systems. One paddock ('conventional') had been regularly cropped using conventional tillage, with deep ripping to 0.35–0.40 m and subsequent scarifying before planting summer maize or peanut crops. The other paddock ('direct drill') had been under a zero till regime for 15 years growing maize, sorghum, soybean, and wheat in an opportunity cropping system. Measurements were made during winter, when the conventional site was in bare fallow (after deep ripping) while the direct drill site was supporting a wheat crop.

Application of artificial rainfall

Infiltration under high energy rain (29 J/m^2.mm) was measured using a portable rainfall simulator fitted with an oscillating boom (Bubenzer and Meyer 1965) that covered 2 adjacent plots of 1.6 m^2 each. These plots could be covered with straw to a depth of 50 mm ('covered' treatment) or have the vegetation clipped and removed and the surface cultivated with a mattock ('bare' treatment). Rainfall rates ranged from 100 to 120 mm/h, depending on treatment, and these were applied for 1 h. Runoff from the plots was collected in a trough and measured with a tipping bucket in a suction flow line. Infiltration parameters recorded were (*i*) time to commencement of runoff, (*ii*) cumulative infiltration over the hour (net of rain applied – runoff), and (*iii*) the final steady-state infiltration rate. The last was determined when plot runoff reached a constant value. There were at least 2 replications for each treatment.

Infiltration under low energy rain (3 J/m^2.mm) was measured at Goodger using the drip infiltrometer of Ross and Bridge (1985), which applied a very uniform rainfall over a 1-m^2 area. The initial application rate was 100 mm/h, and this was reduced when surface ponding reached 50% so that runoff did not occur. In this manner, the infiltration curve of the soil could be followed until steady-state occurred (Bridge and Ross 1985). Again, there were 2 replications per treatment.

Infiltration was also measured using modified disc permeameters (Perroux and White 1988), with supply potentials of -4, -3, -2, and -1 cm H_2O applied through a single contact sand pad (Bridge and Bell 1994). Measurements were made at 0.10–0.15 m depth in order to avoid large surface porosity caused by recent tillage or soil fauna. Shallow surface pits were dug and the pit surface 'picked off' to avoid smearing. Data were analysed using the method of Reynolds and Elrick (1991), which allowed estimates of the saturated hydraulic conductivity (K_{sat}) to be derived. There were 8 measurements for each treatment (Bell *et al.* 1997), with measurements made at Goodger on an annual basis from 1994 to1999.

Determination of soil moisture characteristic

Four replicate undisturbed soil cores, each 0.10 m diameter by 0.05 m long, were collected from 3 distinct layers in the soil profiles under direct drill and conventional till at the Goodger site, described by Bridge and Bell (1994) and Bell and Bridge (2001). These layers were at 0.25 m (immediately below the tilled zone), 0.75 m (at the bottom of the zone in which effects of vehicle traffic could be detected), and at 1.50 m (the bottom of the effective root-zone of most crop species).

The relationship between soil water potential and water content was determined using pressure plate extractors and psychrometric methods. Soil water potential in each core was varied systematically between -1 cm H_2O (saturation) and -15×10^3 cm H_2O (wilting point). Gravimetric moisture content at each new water potential was calculated from the change in core weight compared with the oven-dry weight of that core determined at the end of the measurements. Gravimetric moistures were ultimately converted to volumetric soil water contents using individual core bulk densities. As there were no significant effects of tillage system on the soil moisture contents at any suction, data were pooled ($n = 8$) to examine the differences in moisture characteristics between soils from the different depths.

Monitoring soil water during natural and artificial rainfall

Soil water content during infiltration was measured by the fringe capacitance method (Kraszewski 1980) as incorporated in an Enviroscan® monitoring system. Sensors were placed at 0.10-m intervals to 0.90 m depth inside a 50-mm access tube and read every minute by means of a data logger. Preferential flow down the sides of the access tube was prevented by means of a slurry made from the same soil material. The Enviroscan® sensors were calibrated against gravimetric soil water content over a crop drying cycle in the field by sequential sampling with 38-mm-diameter push tubes. Profile bulk densities were determined on moist profiles using 100-mm-diameter push tubes.

Water potentials in the soil during infiltration were measured by means of hydraulic tensiometers fitted with temperature-compensated absolute pressure transducers. The porous ceramic sensor tips (Watson 1967) were 5 mm in diameter and 30 mm long, attached to stainless steel tubing of the same diameter. The tensiometers were filled and de-aired before insertion into moist soil at 45° using a jig frame so that the tips were at depths ranging from 0.05 to 0.40 m vertically below the soil surface. The outputs from the pressure transducers were read using a high-quality digital voltmeter, and 2 tensiometers were inserted into containers of water so that changes in atmospheric pressure could be monitored. The accuracy of measurement was within 3 mm of water.

In order to monitor infiltration during natural rainfall, wide-range heat dissipation matrix soil water potential sensors were installed at depths of 0.50, 0.78, 1.08, and 1.35 m below the soil surface at the Coolabunia sites in October 2002. These sensors are a porous ceramic cylinder (15 mm diam. by 32 mm long) containing a heating element and thermocouple (Campbell Scientific # 229, Phene *et al.* 1989). They were inserted through 17-mm-ID stainless steel tubing installed at an angle of 45°, and the cables were run underground to a data logger that activated and read the sensors every hour. The #229 sensors had been calibrated in the laboratory using pressure plate extractors and vapour pressure measurements, which showed that the sensors would measure changes in pore water pressures between -75 cm H_2O and $<-15 \times 10^3$ cm H_2O. Prior to installation the sensors were saturated under vacuum.

Measurement events

Rainfall simulators were used to apply artificial, high intensity rainfall at Goodger in 1996 and 1997 and at Coolabunia in 2002. In the winter of 1996, rainfall applications were made to conventionally tilled, continuously cropped soil with or without surface cover at the Goodger site. The sites were pre-wet to the drained upper limit (DUL) and simulated rain was applied for 1 h at 120 mm/h. Soil water was monitored during the rainfall event using the Enviroscan®, with a single access tube inserted in one of each pair of simulator plots.

In the winter of 1997, measurements were made in the following 4 treatments at Goodger: (*i*) low input kikuyu with direct drill (LKDD), (*ii*) low input kikuyu with conventional tillage (LKCT), (*iii*) fertilised kikuyu plus worms with direct drill (FKWDD), and (*iv*) fertilised kikuyu plus worms with conventional tillage (FKWCT). All plots had approximately 10% stubble cover, Enviroscan® tubes were deployed similarly to 1996 and rainfall was applied for 1 h at 120 mm/h.

Four confined rainfall simulator plots were prepared on each of the 'conventional' and 'direct drill' sites at Coolabunia in 2002 in the following manner. A border trench 1 m deep by 0.2 m wide was dug around a 2.4-m-square area, black plastic sheeting placed around the inner face of the trench, and the trench was back-filled and consolidated to avoid any lateral flow. Two of these plots at each site (wet plots) were then wet up by forming a 3-m-square bund around the prepared area and flooding on 3 occasions over 3 consecutive days. These plots were then covered and allowed to drain for at least 3 days before rainfall simulation. The 2 remaining confined plots were designated 'dry' plots. In addition, 4 unconfined plots at each site were selected and 2 of these were flooded and allowed to drain in the same manner. All plots were then sampled gravimetrically for initial soil water content and bulk density to 1.20 m depth, the 100-mm-diameter push tubes being placed just outside the area covered by the rainfall simulator.

Rainfall was applied at rates of 115–140 mm/h to the plots for 1 h as described previously. Cumulative infiltration and final steady-state infiltration rates were recorded. One hour after rainfall ceased, each plot was again sampled gravimetrically for soil water using a 100-mm-diameter push tube to 0.70 m depth and a 50-mm-diameter push tube to 1.20 m depth.

At the end of the Goodger agronomic trial in 1999, 2 soil rehabilitation treatments, fertilised kikuyu plus deep ripping with direct drill (FKRDD), and fertilised kikuyu plus worms with direct drill (FKWDD), were compared with the continuously cropped and conventionally tilled (CCCT) treatment with regard to infiltration capacity and soil water storage. The drip infiltrometer was used to apply low energy rainfall to a 1-m^2 area of pre-wetted soil for 1 h, which contained an Enviroscan® access tube to 0.90 m depth and a vertical array of hydraulic tensiometers ranging from 0.08 to 0.40 m depth. The rainfall rate commenced at 100 mm/h and was decreased when necessary to follow the infiltration capacity of the soil with time. Enviroscan® readings were logged every 5 min during infiltration and for 2 h afterwards. The tensiometers were read every 10 min during infiltration and at 10-min intervals afterwards.

Results and discussion

Calibration of the Enviroscan® capacitance probe system

The plot of soil water (as mm H_2O in a 0.10 m layer) *v.* raw count data is presented in Fig. 1, together with the regression equation. The relationship was linear, and was able to account for a large proportion of the observed variation ($R^2 = 0.81$). This relationship was different from the one published by the manufacturers, primarily because the dielectric constant of the clay-textured sesquioxidic Red Ferrosols is lower than that of lighter textured siliceous soils (Bridge *et al.* 1996). Raw count data collected during the field wetting exercises were converted to soil water contents using this relationship.

Profile moisture characteristic

The relationship between applied suction and soil water content for the 0.25, 0.75, and 1.50 m depths in the profile at the Goodger site is shown in Fig. 2. There were consistent differences between depths from near saturation (1 cm H_2O) to permanent wilting point (PWP, 15×10^3 cm H_2O). The 0.25 m layers held significantly more water near saturation and significantly less water towards PWP than the soil from the 1.50 m layer, with the 0.75 m layer intermediate. The theoretical available water content (AWC) for these Red Ferrosols has been defined as water held between suctions of 100 cm H_2O and 15×10^3 cm H_2O (Bridge and Bell 1994). AWC declined with depth, ranging from 0.14 m^3/m^3 at 0.25 m, to 0.10 and 0.06 m^3/m^3 at 0.75 and 1.50 m, respectively. Most of this difference was due to the increasing water contents nearing PWP that were recorded at greater depths, a result consistent with the general increase in the clay-sized fraction with depth in these soil types (Bridge and Bell 1994).

Interestingly, despite the decline in theoretical AWC with increasing depth in the soil profile, all depths still exhibited large drainable porosities (i.e. capacity to store water between saturation and pore water pressures of −100 cm H_2O). This was highest at the 0.25 m depth (0.15 m^3/m^3) but was still 0.10 m^3/m^3 at 1.50 m, and represents a significant capacity to both store water during wet periods, but also to lose that water via deep drainage before utilisation by a crop root system. Indeed, Bell *et al.* (2001) have proposed that increased deep drainage losses was the reason for the lack of crop response to soil physical rehabilitation and increased rainfall infiltration on these soil types.

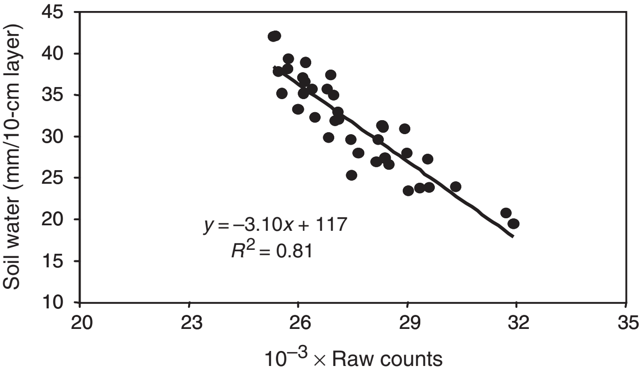

Fig. 1. Calibration of Enviroscan® soil moisture meter counts against volumetric soil moisture determined from sequential sampling during a drying cycle. Data represent samples from 0.10, 0.30, 0.50, and 0.70 m depths in a Red Ferrosol.

Disc permeameter studies at Goodger: 1994–1998

Measurements on all treatments were made regularly during this cropping phase of the study. As the data accumulated, it became apparent that hydraulic conductivity of the various treatments varied considerably over time, with higher values being recorded when the soil profiles were dry. With this observation in mind, data from 2 contrasting treatments [direct drilling after kikuyu pasture (rehabilitated soil) and continuous cropping under farmer practice (degraded soil)] were pooled over the experimental period and hydraulic conductivity measurements were plotted against the initial soil water content.

The plots for hydraulic conductivity at supply potentials of −4 cm H_2O (K_{-4}) and −1 cm H_2O (K_{-1}), together with estimated K_{sat}, are shown in Fig. 3*a* and *b* for the rehabilitated soil and the degraded soil, respectively. All correlations were high and highly significant. Two major differences in the hydraulic behaviour of the 2 soils were apparent. First, the slopes of the K_{-1} and K_{sat} curves were much more negative for the degraded soil (−1690 and −1080 mm/h for K_{-1} and K_{sat}, respectively) than the rehabilitated soil (−510 and −400 mm/h for K_{-1} and K_{sat}, respectively). It can be readily seen that hydraulic conductivities in the degraded soil at initial water contents <0.15 g/g exceeded those for the rehabilitated soil.

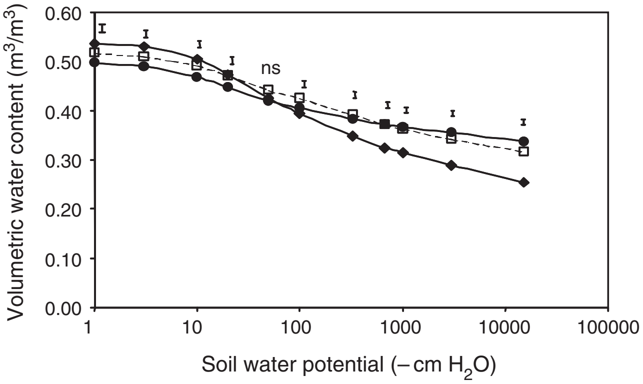

Fig. 2. Soil water contents (m^3/m^3) at soil water potentials between −1 cm and -15×10^3 cm H_2O, determined from undisturbed soil cores collected from the 0.25 m (◆), 0.75 m (□), and 1.50 m (●) depths in the profile at Goodger. Four independent samples were collected from both direct drill and conventional till treatments, and subsequently bulked as differences between tillage system were not statistically significant. Vertical bars represent lsd values ($P = 0.05$, $n = 8$) between soils from each depth and each soil water potential.

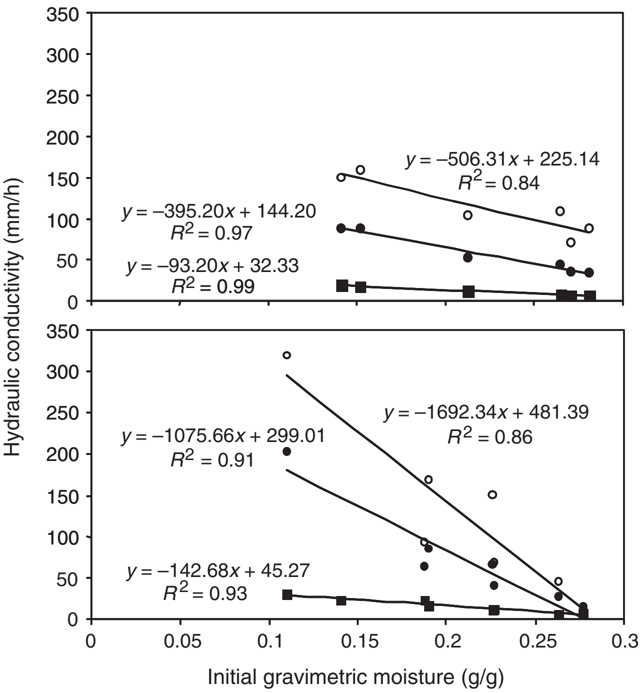

Fig. 3. The relationship between hydraulic conductivity at supply potentials of −4 cm H_2O (■), −1 cm H_2O (●) and 0 cm H_2O (saturation, ○), determined using disc permeameters, and initial gravimetric soil moisture for a Red Ferrosol soil at Goodger after (*a*) physical rehabilitation soil during 4 years of ley pasture and a further 4 years of direct drill cropping, or (*b*) under continuous cropping with minimum tillage during the entire 4-year period.

Second, the regression curves for K_{-4}, K_{-1}, and K_{sat} in the degraded soil converged at low hydraulic conductivities (7.4, 12.2, and 16.4 mm/h, respectively) at an initial gravimetric water content of 0.277 g/g (near the drained upper limit in these soils; Bridge and Bell 1994). By contrast, the same plots for the rehabilitated soil remained quite separated. The values of hydraulic conductivity were 6.5, 34.4, and 87.8 mm/h, respectively, at an initial gravimetric water content of 0.281 g/g.

This difference in hydraulic behaviour can be interpreted as follows. In the degraded soil, shrinkage cracks were observed at low water contents and these cracks rapidly conducted water at low supply tensions, e.g. −1 cm H_2O. The cracks tended to persist during the short time of the disc permeameter measurements, any strain caused by swelling being relieved by the cracks outside the wetted area. When these cracks were closed at high initial paddock soil water contents, water could only be conducted through the finer pores of the massively structured soil matrix, which were saturated at a supply potential of −4 cm H_2O. This supply potential will fill a cylindrical pore of 0.74 mm diameter. It is evident that increasing the supply potential to −1 cm H_2O had only a small effect on hydraulic conductivity, as there were virtually no pores between 0.74 and 3.0 mm diameter. Similar hydraulic behaviour has been observed in Vertosols (J. Foley, P. Tolmie, M. Silburn, pers. comm.).

In the rehabilitated soil, there were no visible soil cracks at low initial water contents. This was consistent with the smaller slopes of the conductivity curves, but the fact that hydraulic conductivity still decreased with increasing initial water contents (albeit much more slowly) suggested that some cracks were still present. The large differences between the conductivities at the various supply potentials at high water contents can be attributed to the presence of stable macropores. Note that the value of K_{-4} here was 6.5 mm/h, similar to the value of 7.4 mm/h for the degraded soil, indicating little difference in the size of the pores in the soil matrix (<0.74 mm). The stable macropores associated with an estimated K_{sat} of nearly 90 mm/h at high soil water contents would be very conducive to deep drainage under high rainfall.

Rainfall simulator and Enviroscan® studies at Goodger: 1996–1997

The total amount of infiltrated water, final infiltration rate, and the maximum increase in the water stored in the 0.90 m profile for the 2 treatments in 1996 are given in Table 1.

Table 1. Rainfall infiltration and profile soil water contents determined during artificial rainfall events to evaluate the impact of surface cover at the Goodger experimental site (continuous cropping, conventional tillage) in 1996

Data are means of two replicate plots with two measurements/plot. Standard errors are in parentheses

Total. infilt. (mm H_2O)	Final infilt. rate (mm/h)	Profile water (mm) Initial	Profile water (mm) Max.	Max. water increase (mm)	Applied water recovery (%)	Max. increase in soil water in 0.10-m increments (mm): 0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.90
Bare soil													
51.2 (6.19)	27.1 (7.78)	327.3 (4.81)	346.2 (5.80)	18.9 (1.03)	37.5 (2.47)	5.7 (0.25)	6.3 (0.04)	3.9 (0.35)	1.5 (0.14)	1.0 (0.04)	0.5 (0.00)	0.2 (0.04)	0.0 (0.00)
Covered soil													
69.6 (5.69)	48.5 (3.18)	317.6 (0.11)	341.7 (4.07)	24.1 (3.96)	34.0 (2.83)	3.1 (1.03)	2.4 (0.64)	2.1 (0.64)	1.8 (0.35)	3.0 (0.18)	3.3 (0.11)	2.8 (0.25)	2.3 (0.39)

Recovery of applied water was nearly the same for both bare and covered soil, around 35%. More water infiltrated into the covered soil than into the bare soil, with final infiltration rates being higher in the former than in the latter. This was a direct result of surface crust formation under high rainfall energy (Loch 1994).

The Enviroscan® data showed that increases in soil water occurred to the depth of measurement (0.90 m) and probably beyond in the covered soil, whereas such increases only occurred to 0.70 m depth in the bare soil. Here, at least 60% of the applied water could not be accounted for, moving sideways from sorptivity, moving laterally/downslope on layers with low hydraulic conductivity (i.e. a hard pan), or passing rapidly through the soil profile via large macropores not detected by the Enviroscan®. With an initially wet profile near the DUL, sorptivity losses would be low (Philip 1957) and lateral movement outside the simulator plots was not observed.

In the 1997 simulation studies, both conventional till treatments had lower initial and maximum profile water than the corresponding direct drill treatments. The total amount of infiltrated water, final infiltration rate, and the maximum increase in the water stored in the 0.90 m profile for the 1997 simulator runs are given in Table 2. Measured profile soil water could only account for 69% (LKDD treatment) to 45% (FKWCT treatment) of the infiltrated soil water. On a plot-by-plot basis, there appeared to be a trend for lower initial profile water content to be associated with higher recovery rate of applied water. However, in the LKDD treatment, higher maximum profile water during infiltration could distort such a potential relationship. This relationship is examined further in the light of the 1996 results, and those of other experiments reported later in this paper.

Increases in profile water content again occurred to the measured depth of 0.90 m during the period of rainfall simulation. Indeed, data from the LKDD, LKCT, and FKWDD treatments indicated that water was moving below that depth during the 1-h application period. This was most obvious in the LKDD treatment, where profile water at 0.90 m depth had increased by 6%. As with the covered plots in 1996, it is reasonable to assume that the 30% of applied water not accounted for had moved beyond that depth. As with the bare plots in 1996, it is not immediately obvious that the 55% of applied water not accounted for had moved beyond 0.90 m depth in the FKWCT treatment, for virtually no increase in profile water content occurred at that depth. However, Hasegawa and Eguchi (2002) found that only small changes of 1–2% in volumetric water content occurred at depth in a porous volcanic ash soil despite a 50% change in rainfall. They attributed 25% of the deep percolation below 1.00 m depth to non-Darcian bypass flow. Such bypass flow through macropores with little change in soil water content (eg worm holes) below the cultivated layer may have been operating here.

Tensiometer and Enviroscan® study at Goodger: 1999

The amount of water applied to the soil, the final infiltration rate, and the maximum increase in the water stored in the soil for the 3 treatments studied in 1999 are given in Table 3. Recovery of applied water was poor in all treatments, being only 42% for the FKRDD treatment, 24% for the FKWDD treatment, and 13% for the CCCT treatment.

Table 2. Rainfall infiltration and profile soil water contents determined during artificial rainfall events at the Goodger experimental site in 1997

Data are means of two replicate plots for direct drill (DD) or conventionally tilled (CT) treatments with two measurements/plot. Standard errors are in parentheses

Total. infilt. (mm H_2O)	Final infilt. rate (mm/h)	Profile water (mm)		Max. water increase (mm)	Applied water recovery (%)	Max. increase in soil water in 0.10-m increments (mm):							
		Initial	Max.			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.90
DD after unfertilised kikuyu ley													
100.2	85.4	276.5	345.3	68.8	69.0	6.0	8.9	9.5	9.5	8.9	7.7	6.6	5.8
(1.84)	(2.76)	(0.74)	(0.46)	(0.28)	(1.41)	(0.74)	(2.72)	(0.46)	(2.30)	(1.13)	(0.28)	(0.28)	(0.64)
CT after unfertilised kikuyu ley													
74.3	46.8	265.3	301.3	36.0	41.5	6.4	5.7	5.9	5.8	4.1	3.5	3.3	1.9
(5.94)	(5.52)	(7.81)	(3.85)	(11.67)	(12.37)	(0.25)	(0.85)	(0.78)	(1.27)	(1.38)	(1.38)	(1.38)	(1.17)
DD after fertilised kikuyu ley with introduced earthworms													
105.9	91.4	281.3	324.8	43.5	41.0	3.9	2.6	3.2	5.0	9.9	8.3	4.3	3.3
(3.32)	(7.18)	(10.64)	(4.70)	(5.94)	(4.24)	(1.10)	(0.81)	(0.39)	(1.59)	(1.10)	(0.28)	(0.39)	(0.21)
CT after fertilised kikuyu ley with introduced earthworms													
59.8	27.8	265.3	292.4	27.1	45.0	9.9	4.3	3.9	4.6	3.1	2.5	1.5	0.1
(2.12)	(4.56)	(12.09)	(8.49)	(3.61)	(4.24)	(0.07)	(0.53)	(0.28)	(0.25)	(0.60)	(0.25)	(0.00)	(0.04)

Table 3. Rainfall infiltration and profile soil water contents determined during drip infiltrometer studies at the Goodger experimental site in 1999

Data are means of two replicate plots for direct drill (DD) or conventionally tilled (CT) treatments with two measurements/plot. Standard errors are in parentheses

Total. infilt. (mm H_2O)	Final infilt. rate (mm/h)	Profile water (mm)		Max. water increase (mm)	Applied water recovery (%)	Max. increase in soil water in 0.10-m increments (mm):						
		Initial	Max.			0.10	0.20	0.30	0.40	0.50	0.70	0.90
DD after deep ripping an unfertilised kikuyu ley												
112.5	100.0	317.1	363.8	46.8	41.5	2.4	2.6	7.5	8.8	8.6	3.1	3.7
(5.30)	(0.00)	(3.22)	(1.63)	(1.59)	(0.35)	(0.49)	(0.04)	(0.95)	(0.42)	(2.83)	(0.04)	(0.39)
DD after a fertilised kikuyu ley with introduced earthworms												
68.2	50.0	323.5	339.8	16.3	23.5	1.4	2.1	1.4	2.0	1.9	1.7	1.8
(2.23)	(0.00)	(5.02)	(4.77)	(0.25)	(0.25)	(0.49)	(0.67)	(0.07)	(0.04)	(0.18)	(0.25)	(0.32)
Continuous cropping with CT (no ley phase)												
64.8	40.0	337.9	346.1	8.3	12.5	2.5	1.5	1.8	1.0	0.2	0.0	0.0
(1.59)	(0.00)	(4.21)	(3.89)	(0.32)	(0.22)	(0.07)	(0.07)	(0.07)	(0.25)	(0.11)	(0.00)	(0.00)

Indeed, no increase in profile water was detected below 0.5 m depth in the CCCT treatment. This treatment had the highest initial profile water content, implying a low sorptivity (Philip 1957), and it is difficult to escape the conclusion that most of the water applied at 40 mm/h has passed rapidly through the 0.90 m profile without a detectable change in water content. The same conclusion applies to the FKWDD treatment, which was somewhat better drained due to the presence of some stable macropores. Only small increases in profile water content were observed at all depths. In the case of the FKRDD treatment, the high infiltration rate of 100 mm/h (due to the presence of many stable macropores) caused profile water content to increase quite measurably at all depths to 0.90 m, again strongly suggesting that water has moved deeper into the profile.

The pore water pressures in the upper part of the soil profile during infiltration are shown in Fig. 4*a*, *b*, and *c* for the FKRDD, FKWDD, and CCCT treatments, respectively. In the case of the FKRDD treatment, pore water pressures were −65 cm H_2O to −100 cm H_2O before infiltration, and rose to values between −10 cm H_2O and −40 cm H_2O after 40 min at the 0.10, 0.15, and 0.20 m depths. After 60 min of infiltration, pore water pressures at the 0.32 and 0.42 m depths had only risen to −50 to −60 cm H_2O, respectively. In the FKWDD treatment (Fig. 4*b*), pore water pressures at all depths were also around −65 cm H_2O to −100 cm H_2O before infiltration. At all other depths, pore water pressures rose gradually to values between −40 cm H_2O and −60 cm H_2O after 60 min.

The CCCT treatment (Fig. 4*c*) was initially characterised by slightly lower starting pore water pressures, around −90 cm H_2O to −130 cm H_2O. At the 0.10 and 0.15 m depths, pore water pressures had risen to −20 cm H_2O by 30 min, and maintained that pressure until the end of the infiltration run. The pore water pressure at 0.22 m depth increased more slowly to a value of −30 cm H_2O by 40 min, and that pore water pressure was also maintained until the end of the run. At the 0.32 m depth, no response was recorded until after 40 min, after which pore water pressures rose slowly to −50 cm H_2O

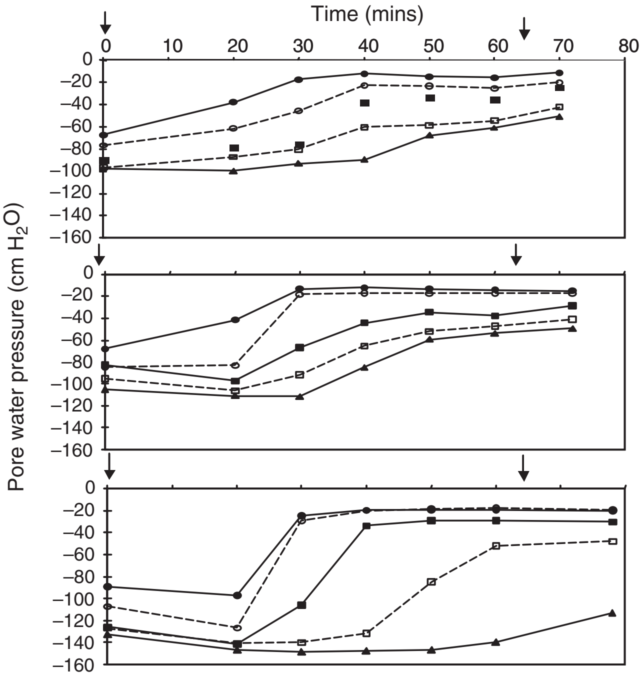

Fig. 4. Pore water pressures (cm H_2O) measured using banks of tensiometers inserted at 0.095 m (●), 0.145 m (○), 0.215 cm (■), 0.315 m (□), and 0.415 m (▲) depths during infiltration studies with drip infiltrometers at the Goodger site in May 1999. Data are shown for 3 contrasting management histories: (*a*) kikuyu ley pasture that had been cropped for 4 years using direct drill, then deep-ripped; (*b*) kikuyu ley pasture with introduced earthworms, also after 4 years of direct drill cropping; and (*c*) continuous cropping using conventional tillage. Vertical arrows indicate the start and finish of drip applications.

at 60 min. The tensiometers at 0.42 m did not respond until after 60 min, when there was a small increase in pore water pressure to −110 cm H_2O.

Although the fairly rapid increase in pore water pressures at all depths in the FKRDD and FKWDD treatments, combined with the higher infiltration rate in the former, gives support for losses by deep drainage (58% and 76%, respectively), the slow response in the CCCT treatment does not. There appears to be a conflict between the high loss in the CCCT treatment (87%) and the negligible response of the tensiometer at 0.42 m depth, about half the depth of soil water measurement. This is reinforced by the absence of any change in profile water content detected below 0.50 m depth. As stated previously, with an initially wet profile sorptivity losses would be low, but saturated lateral (down slope) flow in the upper layers may have occurred. This was not detected during the infiltration runs. If bypass flow down macropores was occurring, then the tensiometers and Enviroscan® access holes have not intersected these pores, or the process of installing the instruments has blocked them off.

Confined and unconfined rainfall simulator measurements at Coolabunia: 2002

The final steady-state infiltration rates for the confined and unconfined plots at both sites are shown in Fig. 5. From the figure it is seen that rates were higher in the dry treatments than in the wet treatments at both sites, presumably as a result of soil cracking. It is also seen that confinement had no effect on the final infiltration rate for either the dry or wet treatments. This latter result indicates that lateral movement in the unconfined plots was not detectable.

A comparison between cumulative infiltration for the confined and unconfined plots using both the rainfall simulator data and the soil water data collected by coring is shown in Fig. 6. The correlations were linear, with slopes very close to unity for both sets of data. The simulator data are considered the most reliable, and here the correlation was high and the intercept very small. Obviously, lateral losses from the unconfined plots were very low and can be safely neglected with respect to the previously reported results. The correlation was less precise for the soil water data, as would be expected from the limited amount of gravimetric sampling that was possible immediately after ceasing simulated rain. Jamming of very wet soil cores in the push tubes often occurred, delaying sampling while profile drainage was still occurring.

The total amount of infiltration into the soil, the final infiltration rate, and the increase in profile water content after infiltration for the confined and unconfined plots is presented in Table 4. All values are averages of 2 replications. High recovery rates of the applied water were obtained for the 'conventional' dry unconfined plots (96%), the 'direct drill' wet unconfined plots (103%), and dry unconfined plots (94%). Such high recovery rates were never obtained with the Enviroscan® soil moisture meter in the previously reported experiments, but the depth of sampling in this case was 0.30 m deeper. The data for the increase in profile water shows that the 1.20 m depth of sampling was probably adequate for the 'direct drill' site, where little change in profile water occurred below 1.00 m depth, but not for the 'conventional' site.

In contrast, the recovery rate for the 'conventional' wet confined plots was very low at 14%, and it can be seen that no detectable increase in soil water occurred below 0.50 m depth. In fact, substantial negative values were obtained below this depth, again pointing out the problem of variability in the soil water data. High variability at the 'conventional' site could be expected as a result of recent deep ripping, which would have created preferred pathways for water movement in the rip lines. Gravimetric sampling outside the rip lines would not have picked this up. Here, it was

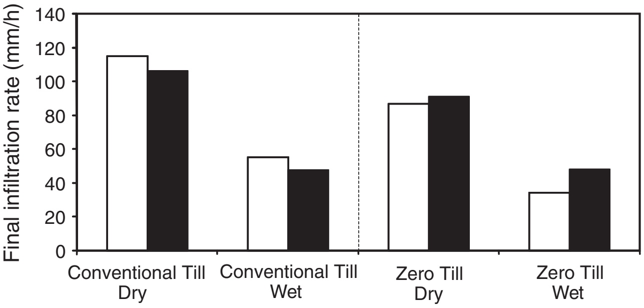

Fig. 5. Final steady-state infiltration into confined (solid bars) and unconfined (hatched bars) plots after 60 min of rain, Coolabunia, 2002. Sites had been pre-wet and allowed to drain to field capacity over 48 h (wet), or used in the existing soil moisture condition (dry). There were no significant interactions between soil moisture and confinement at either site. The l.s.d. ($P = 0.05$) values for comparing effects of soil moisture at each site are 6.0 and 10.3 mm/h for the conventional and zero till sites, respectively.

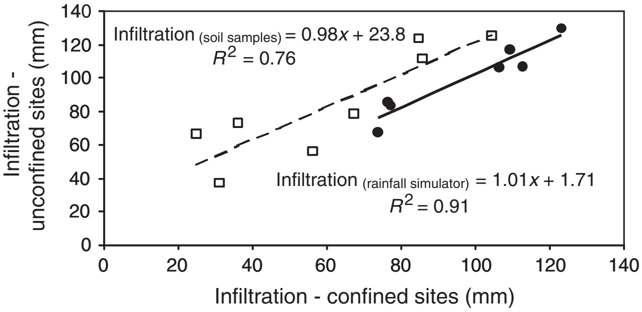

Fig. 6. Comparison of cumulative infiltration into confined and unconfined plots at the Coolabunia sites using estimates derived from the rainfall simulator data (rain applied – runoff, ●) and from the change in gravimetric soil water over the rainfall application period (□).

Table 4. Profile soil water contents determined during artificial rainfall events applied using the rainfall simulator at conventional till (CT) and direct drill (DD) sites at Coolabunia, 2002

Data are from confined (CO) and unconfined (UN) soil profiles, with (PW) or without (NW) pre-wetting, and were determined using soil coring before and after rainfall events. Values of l.s.d. ($P = 0.05$) for main effects or interactions are shown where appropriate; n.s., not statistically significant

Treatment	Total infilt. (mm H_2O)	Final infilt. rate (mm/h)	Profile water		Max. water increase (mm)	Applied water recovery (%)	Max. increase in soil water in 0.10-m increments (mm):										
			Initial (mm)	Max. (mm)			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	1.20
CT,PW,CO	76.8	47.6	452.5	463.4	10.9	14	13.1	5.8	3.7	2.6	0.6	−1.5	−2.0	−2.6	−3.2	−1.4	−4.2
CT,PW,UN	84.4	55.0	458.9	506.8	47.9	57	14.8	6.4	5.7	5.2	3.2	1.7	4.6	2.1	1.4	0.6	2.2
CT,NW,CO	116.3	106.1	383.1	478.2	95.1	84	24.8	10.6	9.8	10.8	8.3	7.3	6.2	4.2	3.6	3.8	5.7
CT,NW,UN	123.6	114.7	383.1	501.4	118.3	96	24.8	12.6	12.6	15.2	11.8	8.4	7.1	6.0	4.9	5.3	9.6
DD,PW,CO	76.8	47.8	457.4	501.4	44.0	57	13.2	4.4	5.1	8.8	6.6	2.8	0.2	1.8	1.4	−0.4	0.1
DD,PW,UN	60.5	34.4	455.0	517.1	62.1	103	10.6	6.6	5.6	8.8	9.5	10.3	5.8	3.5	0.2	1.2	0.4
DD,NW,CO	104.1	91.1	378.4	453.2	74.8	72	27.2	14.2	13.5	11.0	4.2	1.6	1.2	1.0	1.2	−0.1	−0.2
DD,NW,UN	105.3	86.9	378.4	477.8	99.4	94	27.1	14.4	14.4	15.8	13.3	7.7	3.3	3.0	1.6	−0.4	−0.8
l.s.d. ($P = 0.05$)	Wet 8.02; other n.s.	Wet 8.29; other n.s.	Wet 7.09; other n.s.	Con 25.8; other n.s.	Wet, con 23.8; other n.s.	Wet, con 23.1; site*wet 24.7; other n.s.	Wet 3.1; other n.s.	Wet 1.9; other n.s.	Wet 1.7; other n.s.	Wet 3.8; other n.s.	Wet, con 4.7; other n.s.	Till* wet 5.3; other n.s.	Till* wet 1.9; other n.s.	Till* wet 8.5; other n.s.	Wet 2.6; other n.s.	Till 0.7; other n.s.	Till 3.7; other n.s.

likely that there were substantial losses of applied water below the depth of sampling in the 'conventional' wet confined treatment. Recovery rates in the 2 remaining wet treatments ('conventional' wet unconfined and 'direct drill' wet confined) were both 57%, indicating that around 40% of the applied water could have moved below the depth of sampling. Both the 'conventional' and 'direct drill' dry confined plots had reasonable recovery rates of 84% and 72%, respectively, with some indication of water movement below the depth of sampling in the former.

Data showed that confining significantly reduced the maximum profile soil water content, the maximum increase in profile water content, and the recovery of applied water at both sites. These findings suggest that despite all precautions taken in backfilling the border trench used to insert the confining plastic, some preferential flow adjacent to the plastic sheeting may have occurred.

Pore water pressures under natural rainfall at Coolabunia

In order to illustrate the phenomenon of rapid internal drainage under less intense natural rainfall events, data from the #229 wide range tensiometers are shown for a period in February 2003 for the Direct Drill site at Coolabunia (Fig. 7). The field had been fallow after a winter wheat crop in 2002, which had depleted soil moisture reserves primarily in the top 0.80–0.90 m (data not shown). Subsequent rainfall (110 mm in the 3 months following the wheat harvest, including 40 mm in 3 falls in the 10 days preceding the monitoring period in Fig. 7), had partially replenished these reserves, such that mean pore water pressures were −533 ± 40, −480 ± 40, −370 ± 40, and −250 ± 20 cm H_2O for the 0.50, 0.78, 1.08, and 1.35 m depths, respectively. During the 13-day period from 14 to 27 February, 182 mm of rain fell (Fig. 7). The majority was at quite low intensities, with only one 30-min period in the night of 20 February in which rainfall intensity was >50 mm/h (actually 58 mm/h). The rest of the rain fell at intensities of <20 mm/h, significantly less than the steady-state infiltration rates recorded on this site the previous year without stubble cover (Table 4). As a result, there was no runoff recorded during the period.

The #229 wide range tensiometers did record changes in pore water pressures in response to these large rainfall events. However, while the response times for these deeper sensors were notably slower than those recorded with the hydraulic tensiometers at Goodger under artificial (and much higher intensity) rainfall events (e.g. Figs 4 and 5), at no stage did the recorded pore water pressures even approach −100 cm H_2O, much less indicate conditions approaching saturation. This observation is also reflected in the lack of apparent drainage occurring after cessation of the rainfall period, suggesting that there had been no significant accumulation of water in the substantial drainable porosity characteristic of these soils (Fig. 2), at least at depths ≥0.50 m.

This data again show an inability to account for significant amounts of infiltrated rainfall in these soils. The moisture characteristic curves shown for varying profile depths at the Goodger site (Fig. 2) were used to estimate profile water contents at saturation and the DUL (drained upper limit, −100 cm H_2O). They were also used, in combination with the measured pore water pressures (Fig. 7), to estimate the soil water content of the profile at the onset of rain at

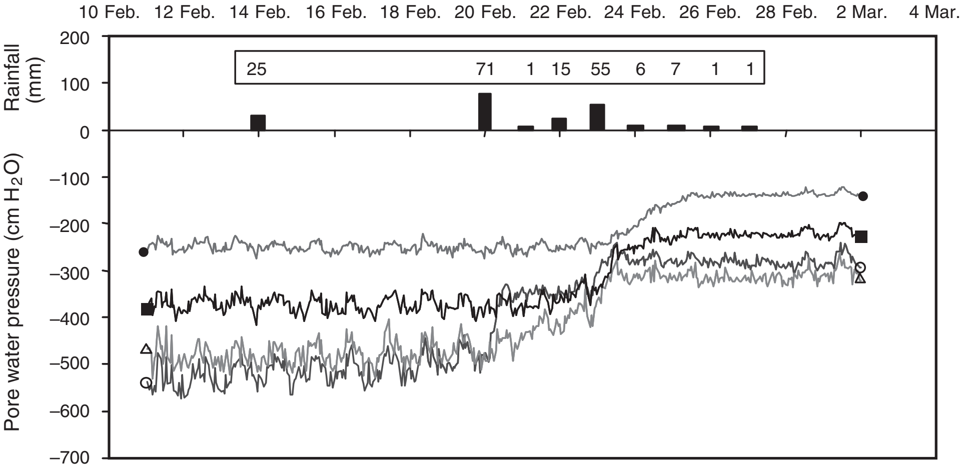

Fig. 7. Pore water pressure (cm H_2O, lines) and rainfall (mm, vertical bars) at the direct drill Coolabunia site during February 2003. Pore water pressures were measured using two separate banks of #229 wide range tensiometers inserted at 0.50 m (○), 0.78 m (△), 1.08 m (■), and 1.35 m (●) depths in September 2002. Data are means of the 2 tensiometers at each depth, with data logged every hour during the measurement period. Rainfall represents daily totals, with actual amounts shown for the respective days. The site was fallow after a wheat crop in 2002 winter.

depths $\geq$0.50 m. A series of assumptions were then made about the moisture contents of the top 0.40 m of the soil, ranging from all layers being at PWP through to all layers at moisture contents equal to that suggested by the pore water pressures at 0.50 m. Collectively, these calculations suggested that 55–75 mm of rain should have been sufficient to raise the whole 1.40 m profile to water contents approaching the DUL, while an additional 150–170 mm would have raised the whole profile to near saturation (data not shown). The 182 mm that fell during this period should clearly have been sufficient to raise pore water pressures above those recorded in Fig. 7, unless rapid rates of undetected drainage were occurring.

Combined analysis of effect of profile water content on apparent deep drainage

Throughout most of the datasets presented in this paper, there have been indications that the higher the initial profile water content the less the apparent recovery of applied rainfall measured using changes in soil water content. To test this hypothesis, the relationship between average initial water content of the profiles to 0.90 m depth at Goodger and Coolabunia and the percentage of infiltrated water recovered in that depth after 60 min of simulated rain was examined for all the experiments reported previously in Tables 1, 2, 3, and 4. The relationship is presented in Fig. 8, with a linear regression fitted to the Goodger data.

There was a significant negative correlation between initial profile water content and the percentage of infiltrated water recovered in the profile in the Goodger data, with similar trends apparent at the Coolabunia sites. Nearly 50% of the variation in rainfall recovery could be accounted for by variation in initial profile water content at Goodger, despite this relationship being derived from data collected from widely varying soil management treatments (i.e. ley pastures returned to cropping using direct drill or conventional tillage, through to continuous cropping under conventional or direct drill tillage systems).

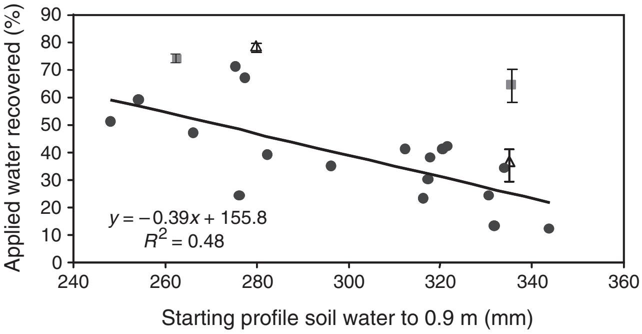

Fig. 8. Relationship between initial profile soil water content (to 0.90 m) with percent recovery of infiltrated rainfall applied during a 60-min interval. Data are from the Goodger (●) and Coolabunia (DD, ■; CT, Δ) sites, with the regression equation fitted to the Goodger data only. Coolabunia data points represent combined means of the confined and unconfined plots, with vertical bars representing the standard error of the mean recovery for each starting soil moisture.

It is interesting to note that the Coolabunia data, which represent single tillage systems/land use histories, suggest that while a similar pattern of reduced rainfall recovery with increased soil wetness occurs, the variability in recovery (indicated by the standard error bars in Fig. 8) is much greater in the wetter profiles. Such an observation would be consistent with a greater reliance on flow through macropores that were not uniformly distributed throughout wet profiles.

General discussion and conclusions

These results provide evidence of the very high internal drainage rates in the Red Ferrosols, and in so doing, highlight the risks of extensive water movement below crop root zones during periods of high rainfall (e.g. February 2003, Fig. 8). The implications of this finding for rising water tables in lower parts of the landscape are significant, and provide a mechanism to explain the presence of shallow groundwater and high salinity hazard in many of the subcatchments surrounding the Red Ferrosols in the inland Burnett (Baillie and Searle 1998).

There is good evidence of the degradation of hydraulic properties of Red Ferrosols under conventional tillage and continuous cropping (Bridge and Bell 1994) and also that this degradation can be at least partially reversed by changed management practices (Bell *et al.* 1997). The data presented in this paper show that most of this degradation and repair is happening in, or immediately below, the cultivated layer (i.e. the top 0.30 m). Below this layer, hydraulic conductivity remains high and largely unaffected by management practices. The key issue seems to be the interaction between this top 0.30 m and the high conductivity layers below.

Data presented here confirm that losses by deep drainage can be expected to be greater where soil rehabilitation treatments have been applied. The disc permeameter data (Fig. 3*a*) showed that the high hydraulic conductivity in the top 0.10–0.15 m of these soils (cultivated layer) at high soil water contents would be more conducive to such losses. The high final infiltration rates measured by the rainfall simulator and drip infiltrometer on the rehabilitated soils support this conclusion, together with the rapid response of tensiometers below the depth of cultivation during simulated rain (Fig. 4*a*, *b*). Collectively, the data suggest that under normal storm rainfall intensities of 25–50 mm/h, flow down these profiles would be unsaturated.

Despite the lower infiltration rates in degraded profiles, the lower hydraulic conductivities at high water contents in the cultivated layer (Fig. 3*b*) suggest that this part of the profile will become saturated under normal rainfall events. However, the saturation in these surface layers would allow water to infiltrate rapidly through the macropores in the (yet undegraded) deeper layers. This phenomenon may explain the slow response (0.42 m tensiometers in Fig. 4*c*), or apparent lack of response (the #229 sensors in Fig. 7), by water potential sensors deeper in the profile during artificial or natural rainfall events. If the sensors did not directly intersect a larger conducting macropore in the deeper parts of the profile, minimal change in the pore water pressure in the soil matrix would have been detected.

This finding has significant consequences for sustainable land use on these soil types. Runoff and soil erosion has been a major driver for the adoption of soil conservation measures such as contour banks and the interest in rehabilitation of soil physical fertility and the adoption of reduced tillage or direct drill systems (Bridge and Bell 1994; Bell *et al.* 1997). However, the lack of crop response to improved rainfall infiltration (Bell *et al.* 2001) is consistent with the observations of a large drainable porosity (Fig. 2) and high rates of deep drainage, especially when soils are wet, and suggests that a reduction in rainfall losses from erosion may well be matched by a corresponding increase in losses via deep drainage. The solution to this problem may lie in the integration of different land uses within subcatchments to utilise water that has drained below crop root-zones in different parts of the landscape (e.g. agro forestry – Claridge *et al.* 2001)

The disc permeameter data (Fig. 3), the inability to detect major changes in pore water pressures below the cultivated layer under prolonged rainfall (Fig. 7), and the high variability in the recovery of applied infiltration under simulated rain using profile water content data at Coolabunia (Fig. 8) point to bypass flow being a significant factor in deep drainage through the Red Ferrosols. Soil cracks appear to be having an effect in initially dry soils, particularly in degraded profiles, while stable macropores in rehabilitated profiles are probably the most important mechanism. Measurement of by-pass flow in the field is difficult, requiring a large array of sensors (Williams *et al.* 2000), tracers (Steenhuis *et al.* 1990), and large lysimeter trays inserted *in situ*. Further work along these lines is needed.

Acknowledgments

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References

Baillie JN, Searle RD (1998) Sustainable use of shallow groundwater in the South Burnett. Resource Management, Department of Natural Resources and Mines, DNRQ980050.

Bell MJ, Bridge BJ (2001) Management of compaction on Red Ferrosol soils used for dryland cropping—a case study. In 'Understanding Soils, Soil Data and Land Management Issues—Refresher Training Course, Course papers'. Toowoomba, 1–2 November 2000. (Eds VJ Eldershaw, KM Hey, AE McElnea, CD Smith, GI Tewes) (Australian Society of Soil Science (Queensland Branch) Inc., C/- Department of Natural Resources and Mines: Indooroopilly, Qld)

Bell MJ, Bridge BJ, Harch GR, Orange DN (1997) Physical rehabilitation of degraded krasnozems using ley pastures. *Australian Journal of Soil Research* **35**, 1093–1113. doi: 10.1071/S97005

Bell MJ, Bridge BJ, Harch GR, Want PS, Orange DN, Connolly RC (2001) Improved soil structure has unexpected effects on the water balance of cropped Ferrosol soils in the inland Burnett. In '10th Australian Agronomy Conference'. Hobart, Tasmania, January 2001. (ASA: Hobart, Tas.)

Bell MJ, Moody PW, Connolly RD, Bridge BJ (1998) The role of active fractions of soil organic matter in physical and chemical fertility of Ferrosols. *Australian Journal of Soil Research* **36**, 809–819. doi: 10.1071/S98020

Bridge BJ, Bell MJ (1994) Effect of cropping on the physical fertility of krasnozems. *Australian Journal of Soil Research* **32**, 1253–1273. doi: 10.1071/SR9941253

Bridge BJ, Ross PJ (1985) A portable microcomputer-controlled drip infiltrometer. II. Field measurement of sorptivity, hydraulic conductivity and time to ponding. *Australian Journal of Soil Research* **23**, 393–404.

Bridge BJ, Sabburg J, Habash KO, Ball JAR, Hancock NH (1996) The dielectric behaviour of clay soils and its application to time domain reflectometry. *Australian Journal of Soil Research* **34**, 825–835. doi: 10.1071/SR9960825

Bubenzer GD, Meyer LD (1965) Simulation of rainfall and soils for laboratory research. *Transactions of the American Society of Agricultural Engineers* **8**, 73–75.

Claridge J, Williams KJ, Grundy MJ, Wilkinson K, Bell MJ, Storey R, Ryan P, Ward D (2001) The use of modelling tools to investigate catchment water balance and eucalypt plantations in the Burnett. Final Report—June 2001: Enhanced Resource Assessment 2001–02, Queensland Department of Natural Resources and Mines, Brisbane.

Hasegawa S, Eguchi S (2002) Soil water conditions and flow chracteristics in the subsoil of a volcanic ash soil: findings from field monitoring from 1997 to 1999. *Soil Science and Plant Nutrition* **48**, 227–236.

Isbell RF (1993) A classification system for Australian soils (third approximation). CSIRO Australia Division of Soils Technical Report 2/1993.

Kraszewski A (1980) Microwave aquametry—a review. *The Journal of Microwave Power* **15**, 209–220.

Loch RJ (1994) Structure breakdown on wetting. In 'Proceedings, 2nd International Symposium on Sealing, Crusting, Hardsetting Soils: Productivity and Conservation'. 7–11 February 1994. (University of Queensland: Brisbane, Qld)

McCown RL, Hammer GL, Hargreaves JNG, Holzworth DP, Freebairn DF (1996) APSIM: A novel software system for model development, model testing and simulation in agricultural research. *Agricultural Systems* **50**, 255–271. doi: 10.1016/0308-521X(94)00055-V

Perroux KM, White I (1988) Designs for disc permeameters. *Soil Science Society of America Journal* **52**, 1205–1215.

Phene CJ, Allee CP, Pierro JD (1989) Soil matric potential sensor measurements in real-time irrigation scheduling. *Agricultural Water Management* **16**, 173–185. doi: 10.1016/0378-3774(89)90001-2

Philip JR (1957) The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. *Soil Science* **84**, 257–264.

Reynolds WD, Elrick DE (1991) Determination of hydraulic conductivity using a tension infiltrometer. *Soil Science Society of America Journal* **55**, 633–639.

Ross PJ, Bridge BJ (1985) A portable microcomputer-controlled drip infiltrometer. I. Design and operation. *Australian Journal of Soil Research* **23**, 383–391. doi: 10.1071/SR9850383

Steenhuis T, Staubitz W, Andreini M, Surface J, Richard T, Paulsen R, Pickering N, Hagerman J, Geohring L (1990) Preferential movement of pesticides and tracers in agricultural soils. *Journal of Irrigation and Drainage Engineering* **116**, 50–66.

Verberg K, Ross PJ, Bristow KL (1996) SWIM v2.1 User Manual. Divisional Report No. 130, CSIRO Division of Soils, Canberra, Australia.

Watson KK (1967) A recording field tensiometer with rapid response characteristics. *Journal of Hydrology* **5**, 33–39.

Williams A, Scholefield D, Dowd J, Holden N, Deeks L (2000) Investigating preferential flow in a large intact soil block under pasture. *Soil Use and Management* **16**, 264–269.

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