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Physical rehabilitation of degraded krasnozems using ley pastures

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Abstract

The physical fertility of krasnozems and euchrozems (Red Ferrosols) in Australia has declined substantially as a result of continuous cropping. Much of this decline is associated with reduced levels of soil organic carbon and soil compaction due to vehicle traffic when soils are too wet. We examined the impact of kikuyu (*Pennisetum clandestinum*) and Rhodes grass (*Chloris gayana*) pasture leys with various management inputs on the regeneration of physical fertility of continuously cropped krasnozems from 2 locations in the South Burnett region of southern Queensland.

Pasture leys significantly improved the physical fertility of continuously cropped soils within 2–4 years. The most significant effects were on the creation of improved surface and subsurface macroporosity, and in a reduction in surface crust formation under high energy rain due to improved aggregate stability. Final steady state infiltration rates under well-managed leys increased 4-fold compared with those in continuously cropped soil.

Pastures were unable to ameliorate compacted layers below approx. 15 cm, although significant improvements in hydraulic conductivity through these layers (and to depths of at least 70 cm) were made, presumably by creating of continuous biopores. Introduced earthworms improved pasture effectiveness in ameliorating this layer, but only to depths of 20 cm, while deep ripping during the ley phase was the most effective treatment.

Kikuyu was the more effective pasture species in overcoming soil physical infertility, particularly in terms of improving aggregate stability under rain. In addition, the ability of kikuyu to resist the compacting influence of cattle trampling during wet weather meant that rainfall infiltration efficiency was maintained during the ley phase and management options on returning to cropping were more flexible (e.g. direct drill strategies can be used). However, if pastures were ungrazed, the advantages of kikuyu in soil physical restoration were evident in only 2 years.

Additional keywords: krasnozems, Red Ferrosols, ley pastures, grazing, soil fertility, earthworms, deep ripping.

Introduction

The basalt-derived krasnozems in Australia are restricted to eastern regions, occurring in intermittent, relatively small areas from Tasmania to North Queensland (Isbell 1994). In the inland Burnett area of south-eastern Queensland, nearly 60 000 ha of these soils, representing about 50% of the total area cropped, are sown to a range of summer grain legume (peanut, soybean, and navybean) or cereal (sorghum, maize) crops, with approximately 30% of the total area

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double-cropped to winter cereals when rainfall is adequate. Virtually all crops are grown under rainfed conditions and the low district average yields represent the effect of considerable variation in both the amount and distribution of the 770 mm average annual rainfall (Meinke *et al*. 1996).

These soils degrade significantly during continuous cultivation, with long-term cropping soils (mostly 30–50 years) now characterised by hard setting, the presence of compacted layers, relatively poor rainfall infiltration, and restricted plant root access to stored soil moisture (Bridge and Bell 1994). Low organic matter levels, subsoil acidification, and nutrient depletion (especially of potassium) are also contributing to poor crop performance (Bell *et al*. 1995). An apparent increase in the incidence of soil-borne fungal pathogens has been associated with this declining chemical and physical fertility, possibly as a result of the generally low levels of soil organic carbon and hence microbial activity (Grace *et al*. 1994; Rovira 1994).

Ley pastures have been found to produce improved soil physical characteristics (e.g. more stable aggregates, increased macroporosity, reduced hard setting, etc.) in long-term cropped soil in other environments and farming systems (Douglas and Goss 1982; Chan 1989; Chan and Mead 1989; Douglas *et al*. 1992). In addition, significant improvements in soil structure as a result of soil faunal activity have been recorded, with larger soil invertebrates such as earthworms, termites, and ants being the most important contributors (Lee and Foster 1991). The review by Fraser (1994) clearly indicates that activity of these large invertebrates is favoured by permanent pasture or minimum tillage systems, and local observations suggest that, although earthworms and other macrofauna are prevalent in remnant patches of virgin scrub in the inland Burnett, numbers are negligible in continuously cropped soil.

The predominant farming system in the inland Burnett area of south-eastern Queensland prior to the 1950s had been mixed farming: dairy or beef cattle, combined with cropping of maize and other grain crops. This was followed by a change to continuous annual cropping, which persisted until the early 1980s, with peanuts being the dominant crop in the rotation. Since the mid 1980s, up to 20% of the cropped area on krasnozems has been returned to pastures (primarily for beef cattle) due to falling productivity and profitability, although much of this land may be now returning to cropping after the occurrence of a sequence of wetter seasons (G. Smith 1996, pers. comm.). There is now considerable interest in the impact of ley pastures on the sustainability of cropping in the region.

In this paper we examine the impact of grass pasture leys with varying management practices on regeneration of physical fertility of continuously cropped krasnozems in southern Queensland. In addition, we evaluate the impact of re-introducing locally adapted earthworm species during the ley phase on soil physical properties.

Materials and methods

Experimental sites

Two sites with histories of long-term continuous cropping (>50 years) were selected in the South Burnett region of south-east Queensland. Sites were designated as Goodger and North Coolabunia. Both sites were located on krasnozem soils (Uf6·31, Northcote 1979; acidic Red Ferrosols, Isbell 1993), with similar dispersed particle size distributions (22% sand, 15% silt, 63% clay). Further detail for the Goodger site is provided in Bridge and Bell (1994) and Bell *et al*. (1995).

The North Coolabunia location was sown to either Rhodes grass (*Chloris gayana*) or kikuyu (*Pennisetum clandestinum*) pasture in the spring of 1989, following a winter fallow preceded by a summer peanut crop. The Rhodes grass was established from seed and the kikuyu from transplanted runners. The Goodger site was sown to kikuyu using transplanted runners in spring–summer 1990, following a double crop during the preceding 12 months that consisted of summer soybean followed by winter wheat.

Pasture species comparisons were made at North Coolabunia by comparing adjacent contour bays sown to each species. Contours were periodically grazed during the following 5 years, beginning approximately 7 months after pasture establishment, although a series of small enclosures (approx. 15 m by 5 m) were established in the Rhodes grass area to provide ungrazed references. The original continuously cropped reference area nearby was itself sown to pasture in 1991.

The kikuyu pasture at Goodger was all ungrazed. The experimental area was divided into 2 replicate blocks within an individual contour bay that was approximately 450 m long and 30 m wide. Each replicate contained 4 plots, 50 m by 30 m, that were subject to differing management practices: (*i*) a low maintenance pasture (LI), with no inputs other than a single preplant application of basal fertiliser (200 kg/ha of a mix containing 14% N, 14·7% P, and 12·3% K); (*ii*) a vigorous pasture (FP), with annual spring (50 kg N, 30 kg P, and 50 kg K/ha) and autumn (25 kg N/ha) broadcast fertiliser applications; (*iii*) a vigorous pasture as in (*ii*), with a deep ripping/subsoiling operation 2 years into the pasture phase (FR) to assist with the disruption of pre-existing hardpans formed during cropping; and (*iv*) a vigorous pasture as in (*ii*), with repeated reintroduction of locally adapted earthworm species once the pasture was established (FW).

Subsoiling was conducted in October 1992, following a 4-month period in which only 70 mm of rain had fallen (see Table 1). A Yeoman's deep ripper with narrow tines spaced 70 cm apart was used to disrupt soil to a depth of approximately 35 cm without significant disturbance to the surface kikuyu sward. Due to the density of rhizomatous material in the top 10 cm of the profile, it was necessary to use coulters preceding each ripper tine.

Table 1. Monthly rainfall (mm) for the Goodger location during the pasture ley phase, relative to the long-term averages for the nearby Bjelke Petersen Research Station

Month	Long-term average	1990	1991	1992	1993	1994
January	96	53	182	26	107	19
February	110	40	87·5	118	94	74
March	100	83	73	125	0	101
April	44	123	0	58	0	3
May	36	132	39	60	24	35
June	35	39	29	0	31	49
July	35	42	25	17	43	18
August	24	5	0	44	0	0
September	26	4	3	26	61	14
October	64	52	77	37	21	52
November	95	73	54	54	34	22
December	98	98	132	0	155	24
Total	728	744	701·5	565	570	411

Earthworms were collected from a variety of locations in the South Burnett during late 1991, and placed in well-drained beds of moist krasnozem soil regularly supplied with composted material and crop residues. As populations increased, juvenile and adult worms of 3 species (*Fletcherodrilus unicus, Aporrectodea trapezoides*, and *Potoscolex corethurus*) were introduced to the appropriate plots on 4 separate occasions over 11 months beginning in mid February 1992. When soils were moist, worms were placed into freshly dug, 10-cm-deep holes which were systematically located throughout each plot using a grid pattern (3 m by 3 m grid). On each occasion, 4–5 worms were placed in each hole.

At the end of the ley phase, each plot was split longitudinally to different tillage systems (full/conventional tillage and direct drill), thus producing subplots which were 50 m long and 15 m wide. The contour bays above and below the kikuyu area, which initial chemical and physical characterisation had shown to be homogeneous with the ley contour (Bridge and Bell 1994; Bell *et al.* 1995), were used as continuously cropped references during the period under pasture. At the end of the ley period, these were also divided into replicate plots with dimensions similar to those in the ley contour and prepared using conventional and direct drill methods.

Soil physical properties

Methods used to determine soil physical properties were reported in full in Bridge and Bell (1994). Brief details are provided here.

Bulk density

Soil bulk density was determined by collecting 3 randomly distributed cores (samples) from each plot on each sampling occasion. Cores were divided into 5-cm increments to 30 cm depth and 10-cm increments from 30 to 70 cm depth using a 10-cm-diameter thin-walled push tube and cutting box.

Aggregate stability

Bulked samples of air-dried surface soil (0–10 cm depth) were collected from each plot, crumbled by hand, and loosely packed into 8 trays with dimensions 60 cm by 60 cm by 10 cm deep. The trays were exposed to high energy simulated rain (29 $J/m^2 \cdot mm$) applied at an intensity of 105 mm/h to the unprotected soil surface for 30 min. Samples from the surface of each tray were then analysed for aggregate size distribution using a modified Yoder wet-sieving apparatus. Aggregate size classes from >5 mm diameter to <0·125 mm diameter were collected and weighed (Loch 1995).

Infiltration

Infiltration parameters were taken at both locations using a portable rainfall simulator fitted with an oscillating boom (Bubenzer and Meyer 1965) which covered an area of 1·6 m^2. Rainfall intensity was 150–175 mm/h depending on sampling occasion, with all vegetative cover carefully clipped and removed from the plot areas (high energy rainfall; 29 $J/m^2 \cdot mm$) so that there was maximum opportunity for rain-induced crusts to form. At the North Coolabunia location, pasture plot measurements were made in pairs, with treatments consisting of either (*i*) bared and undisturbed soil, or (*ii*) bared soil that had been vigorously tilled to a depth of 15–20 cm using a mattock. A rainfall intensity of 145 mm/h was used at this site.

Infiltration parameters recorded were (*i*) time to commencement of runoff, (*ii*) cumulative infiltration over 1 h, and (*iii*) the final steady state infiltration rate. Infiltration was deemed to have reached steady state when at least 100 mm of rain had fallen and the differential between rainfall and runoff remained constant. There were 3 replications in each pasture area at North Coolabunia and 2 samples in each replicate plot at Goodger.

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 10–15 cm depth at both sites in order to avoid large surface porosity caused by recent tillage or soil fauna. Shallow 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_S) to be derived. There were 8 measurements made in each pasture species area at North Coolabunia, and 4 measurements were made in each replicate plot at Goodger.

Estimates of macropore densities at both sites were calculated from the change in hydraulic conductivity with supply potential using a combination of Poiseulle's and Darcy's laws (Coughlan *et al.* 1991).

Soil moisture characteristic

The relationship between pore water pressure and water content was determined on undisturbed soil cores 10 cm in diameter by 3 cm long using suction plates and pressure plates. Pore water pressures included $-0\cdot0001$ MPa (saturation), $-0\cdot01$ MPa (field capacity), and $-0\cdot1$ MPa, while core bulk densities were combined with laboratory-determined gravimetric moisture contents to determine $-1\cdot5$ MPa (wilting point) water contents. The cores were taken from 2–7 and 12–17 layers of the profile.

Soil chemical properties

Soil chemical data were determined on finely ground, bulked samples collected from 0–5, 5–10, 10–20, and 20–30 cm depths in each plot. Soil samples were analysed using methods described by Rayment and Higginson (1992). Organic carbon (C) reported in this paper was determined using the Walkley–Black procedure, and total N was measured by Kjeldahl digestion.

Soil microbial and macrofaunal activity

Soil microbial activity was determined only at the Goodger site. On each sampling occasion, 6 cores, each 5 cm in diameter, were collected from each plot. Cores were separated into 0–5, 5–10, 10–20, and 20–30 cm increments and bulked to provide 1 sample per depth increment in each plot. Samples were immediately placed in an ice chest to be kept cool, and once out of the field, samples were stored at about 5°C until the C and N contents in the microbial biomass were estimated by the procedure of Jenkinson and Powlson (1976). The effects of treatment on microbial biomass C and N were assessed on both a concentration basis (e.g. mg C/kg soil) and on the total amount per depth increment of soil (e.g. kg N/ha in the 0–5 cm layer).

Soil sampling to monitor soil macrofauna was undertaken only at the Goodger site. On each sampling occasion, 10 square spadefuls (approx. 15 cm by 15 cm) of soil, from which above-ground vegetation had been removed, were collected in each plot to a depth of 20 cm. Soil was sorted in the field, and the recovered faunal specimens were subsequently collated and identified in the laboratory.

Sampling times

North Coolabunia

Soil samples were taken from the 0–10 cm layer of the North Coolabunia location in May 1990, shortly after pasture establishment, and from an adjacent area still under cultivation. Further samples were collected from the areas under different pasture species in March 1996. These samples were analysed for organic C content and aggregate stability under rain.

During March 1994 (approx. 4·5 years after pasture establishment), data on soil bulk density, rainfall infiltration, and subsurface hydraulic properties were collected from grazed and ungrazed Rhodes grass and grazed kikuyu areas.

Goodger

The physical properties of the trial site were extensively characterised during late summer and early autumn of 1990 (see Bridge and Bell 1994 for details), while samples for soil chemical analyses (see Bell *et al*. 1995) and an assessment of soil macrofaunal activity were taken prior to pasture establishment in November 1990.

Subsequently, samples for assessment of soil macrofaunal abundance and diversity were taken in all pasture plots at approximately 6-monthly intervals beginning in December 1991 and continuing until the area was returned to cropping in January 1995. Whilst efforts were made to ensure similar sampling times each year (e.g. late spring–early summer, and late autumn–early winter), dates varied somewhat as practicalities necessitated sampling when soil was moist. The final samplings in June 1994 and February 1995 also included samples from adjacent, continuously cropped areas.

Soil hydraulic properties (field rainfall simulations, disc permeameters) were determined in June 1992 (18 months after pasture establishment), at pasture sprayout in June 1994, and in the seedbed (either conventionally prepared, or in undisturbed sprayout condition prior to direct drilling) in late November 1994, prior to planting the first crop. An additional set of disc permeameter measurements was undertaken in September 1993.

Samples to determine the soil moisture characteristic were taken in March 1995, during the first crop after the ley (soybean). Samples were collected from both the fertilised ley pasture (FP) and continuously cropped (CC) treatments, either prepared conventionally (FP, CT and CC, CT) or undisturbed except for direct drilling of the soybean crop (FP, DD and CC, DD).

Soil bulk density samples were taken from continuously cropped or kikuyu ley plots in September 1993 (18 months after the first earthworm inoculations and 12 months after the deep ripping treatment was imposed). Further samples were taken from both areas after plots were split for direct drill or conventional tillage, shortly after the soybean crop was established in February 1995. Microbial biomass nitrogen and carbon were determined from samples taken at pasture sprayout (June 1994), and immediately after planting the soybean crop. Sampling times were influenced by soil moisture content, with sampling only undertaken when soil had been moist for at least 1 week prior to the event.

Results

Pasture growth, Goodger

Above-ground biomass production in the ungrazed kikuyu pastures at Goodger responded positively to annual fertiliser application (Table 2), but additional deep ripping and earthworm introductions during the ley phase produced no significant effects. The response to fertiliser application was most evident during the mid-ley period, when the FP treatment (9690 and 14 300 kg/ha) had produced 80% and 70% more above-ground biomass than the LI treatment in years 2 and 3, respectively. Deep ripping reduced the rate of above-ground biomass production in FR in year 3 (the year following the ripping operation) to only 1770 kg/ha, which was only 35% and 60% of the increases in FP and LI, respectively. However, biomass accumulation in this treatment in subsequent seasons was unaffected. This depression was presumably due to a loss of soil moisture and damage to plant root systems resulting from the ripping operation, followed by an unusually dry 1992–93 summer growing season (Table 1).

Table 2. Above- and below-ground dry matter inputs (kg/ha) and nutrient content of above-ground dry matter (kg/ha) for the Goodger ley plots at sprayout in June 1994

Treatment	Dry matter			Nutrient content of shoots		
	Shoots	Roots and rhizomes[A]	Total biomass	N	P	K
Low input (LI)	11 060	34 930	45 990	97·1	11·6	116·1
Fertilised (FP)	16 660	33 440	50 110	174·2	22·4	223·3
Fertilised+ ripping (FR)	14 630	33 230	47 860	149·5	21·3	196·8
Fertilised+ earthworms (FW)	16 630	32 710	49 340	183·2	21·6	210·7
l.s.d. ($P = 0{\cdot}05$)	4050	n.s.	n.s.	40·1	3·6	40·6

n.s., not significant.
[A] 0–70 cm.

At sprayout in June 1994, all pasture plots contained >45 t/ha of total dry matter to 70 cm depth, with the proportion represented by tops ranging from 24% in the LI treatment to 33–34% in the FP and FW treatments (Table 2). The below-ground component was predominantly in the 0–10 cm (61%) and 10–20 cm (15%) layers of the soil profile, and consisted largely of rhizomatous material.

Nutrient content of the above-ground biomass (Table 2) was substantially increased by the annual inputs of nitrogen, phosphorus, and potassium fertilisers.

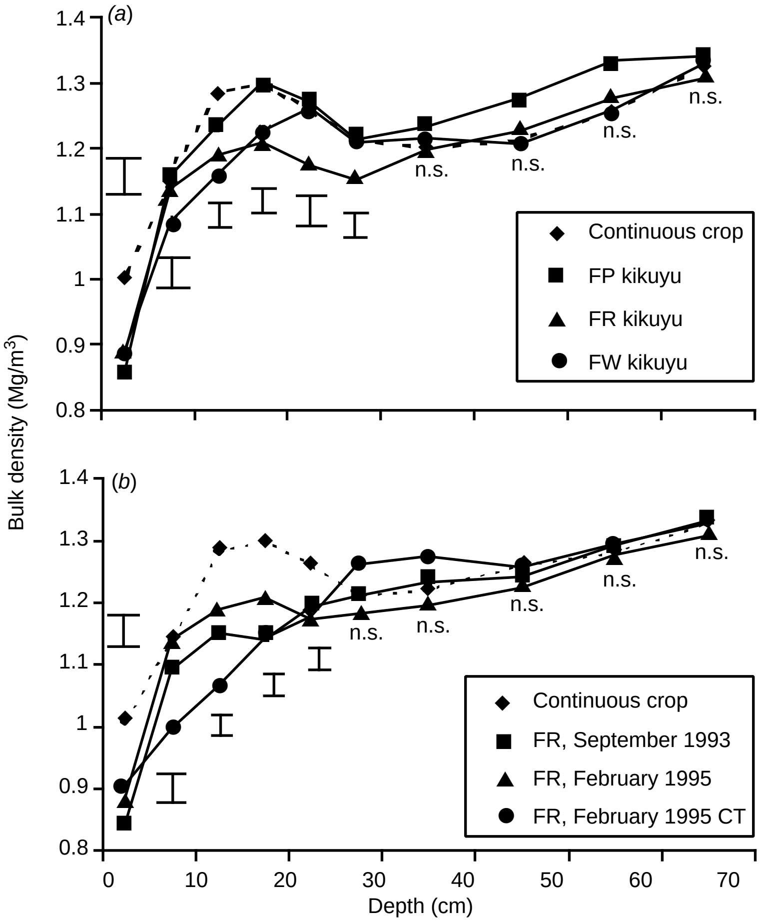

Fig. 1. (*a*) Effects of 4-year kikuyu ley treatments on soil bulk density (Mg/m^3) at Goodger, relative to that under continuous cropping. (*b*) Temporal changes in bulk density in the FR ley pasture treatment, including effects of tillage operations during seed bed preparation in the conventionally tilled subplot. In each depth interval, n.s. indicates treatments were not different statistically, while vertical bars indicate l.s.d. ($P = 0{\cdot}05$).

Bulk density

The continuously cropped treatments at Goodger were characterised by a well-developed compacted layer between 15 and 30 cm depth (Fig. 1), which was similar to the plough pan recorded by Bridge and Bell (1994) in samples taken in this and other adjoining contour bays in 1990, prior to pasture establishment. The kikuyu pasture ley treatments (LI, FP) had no ameliorating effect on the existing hard pan, while the introduced earthworms in the FW treatment produced only a slight reduction in bulk density in the 10–20 cm layers. The deep-ripped treatment (FR) successfully disrupted the original hardpan to at least 30 cm (Fig. 1*a*), with the vigorous root system in the pasture able to stabilise the ripped zone such that bulk densities at the end of the ley phase were similar to those recorded shortly after ripping (Fig. 1*b*).

It is also worth noting the effect of conventional tillage (CT) after sprayout of the FR pasture on bulk densities in both the shallow cultivated layers (0–15 cm), and the immediate subsoil (25–35 cm). Whilst tillage produced a loose seed bed for crop establishment, there were indications (although not statistically significant) of compaction at 25–35 cm depths in the soil profile, presumably due to tractor wheels during tillage operations.

The effect of trampling by cattle on the bulk density of surface soil layers under differing pasture species at the North Coolabunia site (Table 3) was clearly illustrated. There was a significantly higher bulk density in the 5–10 cm zone of the grazed Rhodes grass pasture compared with that in either the ungrazed Rhodes grass or the grazed kikuyu areas.

Table 3. Bulk density (Mg/m^3) of surface layers of grazed and ungrazed Rhodes grass and grazed Kikuyu ley pastures five years after establishment at North Coolabunia

Depth	Rhodes grass		Kikuyu	l.s.d.
(cm)	Grazed	Ungrazed	Grazed	($P = 0{\cdot}05$)
0–5	0·96	0·99	0·91	n.s.
5–10	1·24	1·14	1·11	0·08
10–15	1·28	1·22	1·14	0·11

n.s., not significant.

Soil moisture characteristic

The effects of fertilised kikuyu ley pastures (FP) and subsequent tillage on the soil water contents at pore water pressures between $-0{\cdot}0001$ and $-1{\cdot}5$ MPa are shown for the Goodger site in Fig. 2. There was a general tendency for greater drainable porosity (represented by water held at pore water pressures between $-0{\cdot}0001$ and $-0{\cdot}01$ MPa) in the tilled soils, regardless of history. However, there were few significant effects of either tillage or history on available water content (AWC, soil water held at pore water pressures between $-0{\cdot}01$ and $-1{\cdot}5$ MPa), with the exception of a slight reduction in AWC in the untilled, continuously cropped soil at 12–17 cm. This result was consistent with the observation that cores from this depth provided the highest bulk density of any of the samples tested ($1{\cdot}35{\pm}0{\cdot}06$ Mg/m^3) and were therefore likely to contain fewer storage pores.

Soil macrofaunal activity

Soil macrofauna were monitored at 6-monthly intervals throughout the ley phase. While the data on species diversity are not presented in detail here, it should be noted that there were no real differences in species distribution between ley treatments, with the exception of the occasional presence of earthworms (*Fletcherodrilus unicus* and *Aporrectodea trapezoides* only) at densities of 1–3 individuals/m^2 in the FW treatment.

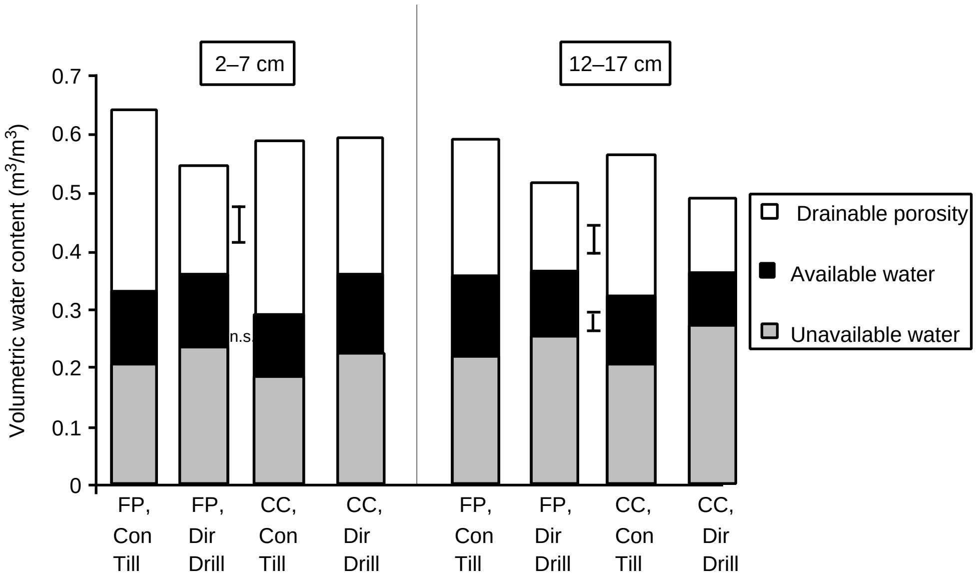

Fig. 2. Soil water contents (m^3/m^3) at pore water pressures between $-0 \cdot 0001$ and $-1 \cdot 5$ MPa determined from undisturbed soil cores taken from the 2–7 and 12–17 cm depths in the profile for a subset of treatments at Goodger. Vertical bars represent l.s.d. ($P = 0 \cdot 05$) for either the available water content (held between $-0 \cdot 01$ and $-1 \cdot 5$ MPa) or the drainable porosity (water held between $-0 \cdot 0001$ and $-0 \cdot 01$ MPa), while n.s. indicates no significant differences.

Both species richness (the number of species encountered within plots of a given treatment) and overall macrofaunal density (total number of individuals/m^2), which were at very low levels under continuous cropping, increased rapidly to reach a plateau after $1 \cdot 5$–$2 \cdot 0$ years under ley pastures (data not shown). Burrowing macrofauna (those capable of producing water-conducting macropores to depths of at least 10–15 cm, Fig. 3) were considered to be the macrofaunal component most likely to affect soil hydraulic properties, and represented 30–55% of all soil macrofauna in the ley treatments at any sampling time. Scarab larvae dominated this group throughout the ley phase (60–90% of all burrowing macrofauna at all samplings), with the melolonthines (predominantly the peanut scarabs *Heteronyx piceus* and *Heteronyx rugosipennis*) the most prevalent subfamily. Other scarabs in the Rutelinae and Dynastinae subfamilies occurred in lesser numbers. Other burrowers of significance included False Wireworms (family Tenebrionidae), burrowing bugs (family Cydnidae, *Cydnus* sp.), and the occasional Brown Field Cricket (*Lepidogryllus* sp.), with the False Wireworms the most prevalent after the scarab larvae. Macrofaunal populations in general, and burrowing macrofauna in particular, were drastically reduced by tillage at the end of the ley phase (Fig. 3).

Interestingly, although the continuously cropped treatments were only monitored during the last 8 months of the ley phase, the total soil macrofaunal densities were only 10–15% of that under pasture leys before tillage. Within this smaller population, the burrowing macrofauna (predominantly scarab larvae) represented a much lower proportion of individuals than under grass ley (0–18% compared with 30–55%).

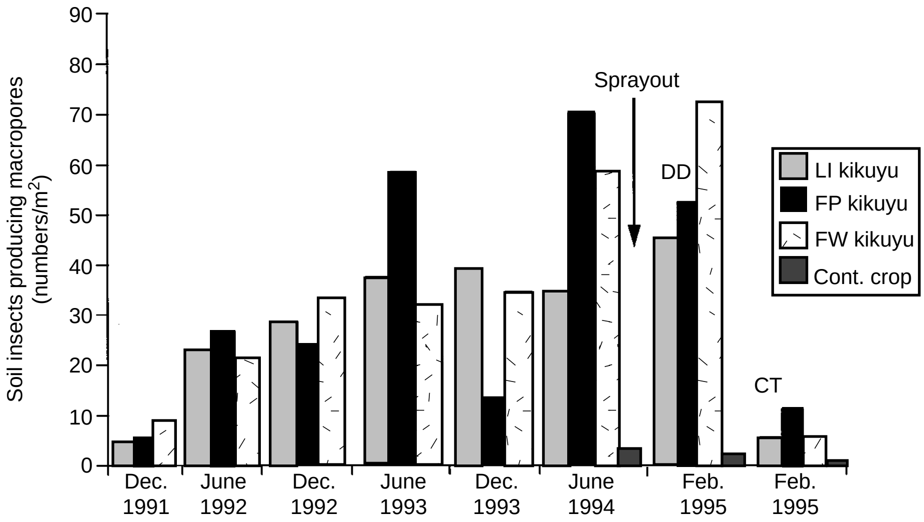

Fig. 3. Density of soil macrofauna at the Goodger site which were capable of producing continuous macropores in plots managed as kikuyu pasture leys or continuously cropped. The final sample date includes both undisturbed direct drill plots and those conventionally cultivated prior to crop establishment.

Table 4. Hydraulic conductivity and macropore density as determined by disc permeameters at 10–15 cm depth at the Goodger and North Coolabunia sites. Goodger treatments are designated CC (continuous cropping), FP (fertilised kikuyu pasture), FR (deep ripped kikuyu pasture), and FW (kikuyu pasture with earthworms)

Supply potential (cm H_2O)	Hydraulic conductivity (mm/h)				Equiv. pore diam. (mm)[A]	Macropore density (pores/m^2)			
					Goodger (Year 4 of ley)				
	CC	FP	FR	FW		CC	FP	FR	FW
0**	24	159	201	150	5·0				
					**	0·1	1·0	1·2	1·0
−1·5**	19	88	117	88	2·0				
					**	0·5	7·7	10·3	6·5
−2·5*	17	45	59	51	1·2				
					*	10·4	31·1	33·7	35·8
−3·5 n.s.	8	18	30	20	0·8				
					North Coolabunia (Year 5 of ley)				
		Grazed Kikuyu	Grazed Rhodes	Ungrazed Rhodes		Grazed Kikuyu	Grazed Rhodes	Ungrazed Rhodes	
0 n.s.		132	141	105	5·0				
					n.s.	0·8	1·0	0·8	
−1·5 n.s.		73	74	52	2·0				
					n.s.	7·4	7·2	5·1	
−2·5 n.s.		31	33	23	1·2				
					n.s.	14·0	16·2	13·5	
−3·5 n.s.		19	19	11	0·8				

* $P < 0·05$; ** $P < 0·01$; n.s. not significant for differences between paired means.
[A] Arbitrarily selected upper limit as pore size based on visual assessment.

Soil macroporosity

The hydraulic conductivity and macropore densities for depths equivalent to the bottom of the cultivated layer (10–15 cm), as calculated from the disc permeameter data for the Goodger and North Coolabunia sites, are presented in Table 4. At Goodger, all ley treatments had higher hydraulic conductivity at all supply potentials except $-3\cdot5$ cm H_2O. This was due to significant increases in macropores of all size classes from $0\cdot8$ to $5\cdot0$ mm, although the relative increases were largest in the $1\cdot2$–$2\cdot0$ and $2\cdot0$–$5\cdot0$ mm ranges (i.e. the largest pore sizes). At North Coolabunia, there were no significant effects of pasture species or grazing on either hydraulic conductivity or macropore density below the immediate surface and the zone of tillage.

The results indicate that whilst differences in bulk density were observed among ley treatments (Fig. 1*a* and Table 3), these differences did not necessarily correspond to differences in measured macroporosity—either at the soil surface (Goodger only; data not shown) or immediately below the layers of high rhizome density—and/or effects of cattle trampling. Data were not available for all treatments deeper in the profile, where bulk density profiles (Fig. 1) suggested greatest ley treatment differentiation. However, disc permeameter measurements were undertaken at various layers in the profile in either continuously cropped or FP treatments at Goodger. Estimates of K_S at various depths in each treatment (Fig. 4) suggest that, while the greatest effects of the ley pasture were in the upper layers of the profile, significant improvements in conductivity were recorded to depths of at least 70 cm.

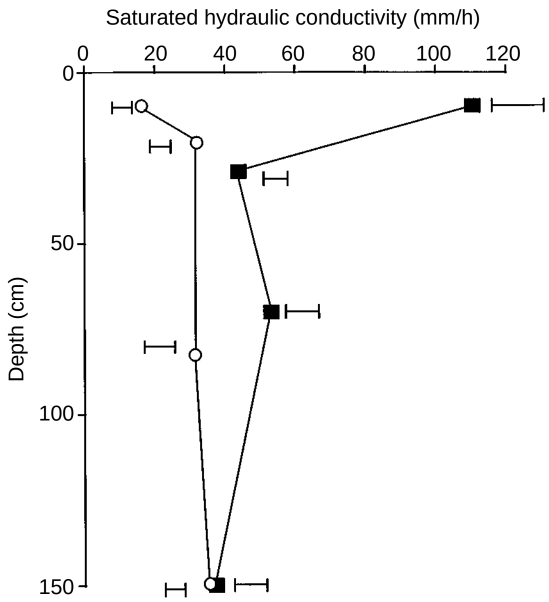

Fig. 4. Effects of a fertilised kikuyu ley pasture (■) on saturated hydraulic conductivity down the profile for a continuously cropped soil (○) at Goodger. Vertical bars indicate standard errors of means for each treatment at each depth ($n = 8$).

Organic carbon and microbial biomass

The pasture ley treatments resulted in relatively minor changes in soil organic carbon levels at the time of sowing of the first post-ley crop, with the only significant differences between histories occurring in the 0–5 cm layer (Table 5). Tillage at the end of the ley phase had the effect of producing a more uniform distribution of organic C down the profile, and negated any advantages of the ley treatments in the 0–5 cm layer. When treatment-induced changes in bulk density (Fig. 1) were considered, there were no statistically significant changes in total organic C in the top 30 cm of the profile due to management, although values ranged from 42·0 to 48·2 t C/ha in the LI and FW treatments, respectively. Comparable values in the virgin scrub adjoining the experimental area (Bridge and Bell 1994) were about 25% higher than those in the FW treatment, while under continuous cropping total organic C ranged from 40·9 (conventional tillage) to 49·7 (direct drill) t C/ha. Most of the apparent variation in profile carbon between tillage systems under continuous cropping was due to effects of higher bulk densities under direct drill.

Table 5. Soil organic carbon (%) and microbial biomass nitrogen (mg/kg) of selected treatments after kikuyu ley or continuous cropping at Goodger

NT, no till; Cult., cultivated

Depth cm	LI kikuyu ley		FP kikuyu ley		FR kikuyu ley		FW kikuyu ley		Continuous crop		l.s.d. ($P = 0{\cdot}05$)
	NT	Cult.	NT	Cult.	NT	Cult.	NT	Cult.	NT	Cult.	
					Walkley–Black organic carbon (%)						
0–5	1·68	1·35	1·76	1·56	1·88	1·35	1·86	1·65	1·44	1·31	0·38
5–10	1·42	1·44	1·44	1·65	1·58	1·44	1·64	1·77	1·47	1·33	n.s.
10–20	1·19	1·31	1·28	1·61	1·34	1·37	1·45	1·57	1·45	1·26	n.s.
20–30	0·94	0·95	0·95	1·16	1·10	1·03	1·04	1·25	1·23	1·12	n.s.
					Microbial biomass nitrogen (mg/kg)						
0–5	44·1	38·6	75·2	68·9	71·8	65·2	62·4	74·1	39·8	43·7	16·4
5–10	33·0	30·0	57·4	47·4	52·8	39·6	46·6	56·8	35·5	38·6	15·6
10–20	14·3	20·6	33·0	40·9	23·6	25·7	36·2	25·5	25·2	18·0	11·5
20–30	10·8	11·3	10·2	22·5	9·7	15·8	15·5	24·1	7·8	14·2	n.s.

This lack of short-term impact of pasture leys on soil organic C levels, despite the large quantities of above- and below-ground dry matter returned to the system, may be partly due to the very dry weather since the end of the pasture ley sprayout in June 1994 (Table 1). Only 100 mm of rain fell in the first 6 months after sprayout (and subsequent tillage in some treatments), so much of the old pasture was present as undecomposed dry matter at the time of soil sampling and would have been removed prior to the determination of Walkley–Black organic carbon.

Microbial biomass, as indicated by microbial biomass N (Table 5), showed a greater response to the fertilised pasture ley treatments (FP, FR, and FW) than organic carbon. Whilst the LI and CC treatments did not differ significantly ($P > 0{\cdot}05$), the fertilised kikuyu ley treatments contained higher microbial biomass N contents in the 0–5 cm layer (regardless of tillage system) and less predictably in the 5–10 cm layer. When adjusted for differences in bulk densities, the continuous crop and LI treatments (80·2 and 72·2 kg microbial N/ha, respectively) were characterised by significantly lower levels of microbial activity than in the FR (99·0 kg microbial N/ha), or FW and FP (117·3 and 126·0 kg microbial N/ha, respectively) treatments.

Aggregate stability

Ley pastures were shown to have a major effect on the stability of surface soil aggregates exposed to high energy rain (Table 6), with the effect dependent on the duration of the ley phase. Data from North Coolabunia showed that the initial summer growing season for each ley pasture species had no effect on either the proportion of aggregates <0·125 mm in diameter or the proportion >0·5 mm in diameter after exposure to 30 min of high intensity rain. However, subsequent samples taken about 6 years after pasture establishment show that the proportion of aggregates <0·125 mm in diameter was reduced from 20% under continuous cropping to 14·5% and 10·6% for Rhodes grass or kikuyu pastures, respectively. Similarly, the proportion of particles >0·5 mm in diameter increased with time in the ley, rising from 51·4% under continuous cropping to 68·2% and 74·5% after 6 years under Rhodes grass and kikuyu, respectively. In both cases, kikuyu pastures produced more stable aggregates than Rhodes grass, with similar observations made in other locations in the Burnett (R. J. Loch and M. J. Bell, unpubl. data 1996).

Table 6. Effects of ley pasture species and ley duration on the aggregate distribution (%) of air-dried surface soil from North Coolabunia after wetting by rainfall at 90 mm/h

Pastures were sown in October 1989

History	<0·125 mm	>0·5 mm
Continuous cropping	19·7	51·4
Grazed Rhodes grass ley, May 1990	19·3	48·1
Grazed Kikuyu grass ley, May 1990	21·9	51·2
Grazed Rhodes grass ley, Feb 1996	14·5	68·2
Grazed Kikuyu grass ley, Feb 1996	10·6	74·5
l.s.d. ($P = 0\cdot05$)	3·5	5·9

Infiltration of simulated rain

The effects of pasture leys and pasture ley management on selected infiltration parameters are shown for both the Goodger (Fig. 5) and North Coolabunia (Fig. 6) locations. At Goodger, final steady state infiltration rates (FIR) in continuously cropped areas were very consistent during the experimental period, averaging 28(±1·6) mm/h unless the soil had been recently tilled. After 2 years of undisturbed kikuyu ley, regardless of management inputs, this rate had at least doubled, and in the case of the FW treatment, FIRs had increased 4-fold (Fig. 5). Cumulative infiltration after the 1-h simulation period showed similar treatment effects, although the differences between ley treatments were less pronounced than those shown for FIR in Fig. 5. Cumulative infiltration during the hour ranged from 124 mm (FW) to 109 mm (LI), while the total in the continuously cropped soil was only 55 mm.

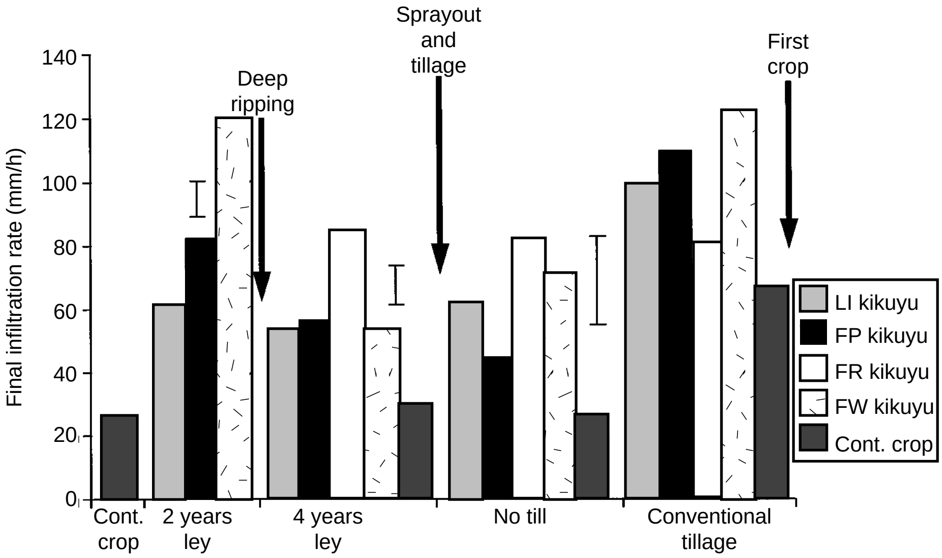

Fig. 5. Effects of kikuyu ley pastures on final steady state infiltration rates of high energy, simulated rainfall at Goodger. Measurements were made prior to pasture establishment (1990), 2 years and 4 years after ley establishment, and just prior to sowing the first crop 6 months after pasture sprayout. Vertical bars indicate l.s.d. ($P = 0{\cdot}05$) for samplings undertaken after 2 and 4 years of kikuyu ley, and immediately prior to sowing the first crop.

After 4 years of ungrazed ley, however, the infiltration benefits were generally lower unless a pasture renovation of some form (in this case, deep ripping in FR) had been undertaken. This was especially evident in the FW treatment, where the FIR after 4 years of ley was only 45% of that after 2 years. Despite the apparent degradation of the ungrazed ley system without renovation, in all cases the FIRs of the ley treatments were still at least double that under continuous cropping. Again, treatment effects on cumulative infiltration during the hour-long simulations mirrored those shown for FIR, with totals ranging from 115 mm (FR) to 54 mm in the continuously cropped treatment.

Six months after pasture sprayout (and tillage in the case of the plots prepared conventionally), the most significant change had been the improvement in FIR in all non-ripped ley plots (and that of the continuously cropped area) in response to tillage. While tillage had no effect on FIR in the FR treatment, tillage increased FIR by 60% (LI) to 150% (FP) of the levels recorded in untilled ley plots, and by 140% in the continuously cropped area. Effects of tillage on cumulative infiltration during the simulation period were also positive but less substantial, especially in the ley treatments, ranging from 10% (FR) to 50% (FP) in the ley plots, up to 100% under continuous cropping.

Effects of grazing, tillage, and ley species on FIR at North Coolabunia are shown in Fig. 6. Undisturbed, the grazed kikuyu sward allowed simulated rain to infiltrate at rates equivalent to 300% and 160% of those in the grazed and ungrazed Rhodes grass, respectively. Vigorous soil disturbance to a depth of 15–20 cm reduced FIR in the grazed kikuyu by 40% and in the ungrazed Rhodes grass by 25%. However, tillage increased FIR by 85% in the grazed Rhodes grass area. Similar trends were evident in cumulative infiltration during the simulation period, with values ranging from 119 mm in the undisturbed grazed kikuyu, to 47 mm in the undisturbed grazed Rhodes grass.

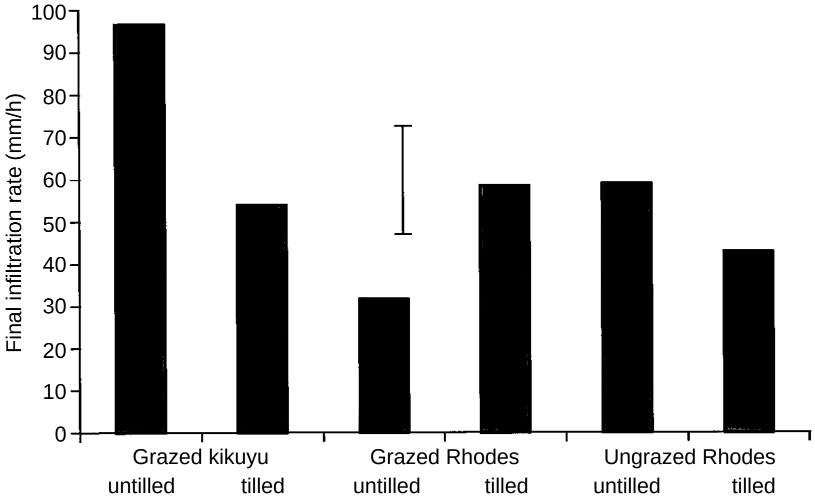

Fig. 6. Effects of pasture species, exclusion of grazing animals, and tillage on cumulative infiltration of high energy, simulated rainfall at North Coolabunia 5 years after pasture establishment. Rainfall intensities of 170 mm/h were used. Vertical bars indicate l.s.d. ($P = 0{\cdot}05$).

The negative effects of tillage obtained here for the kikuyu sward contrast with the positive effects obtained at Goodger. However, it is worth noting that the FIR values obtained at Goodger in the absence of tillage (Fig. 5) were only 60% of those at North Coolabunia, and may reflect the influence of the well-developed plough pan at that site (Fig. 1).

Discussion

Bridge and Bell (1994) noted that the continuously cropped krasnozem soils of the inland Burnett, characterised by deep compaction, low levels of organic carbon, and non-swelling properties, had little capacity for self-repair under the current land use system. Of perhaps greatest significance for the viability of rainfed cropping enterprises was the observation that continuous cropping had produced soils which were now much less capable of allowing high intensity storm rain to infiltrate. This was due to a combination of surface crust formation and restricted conduction of infiltrated rain down the soil profile. By using weather records from the last 60 years and the QNUT crop model (Hammer *et al.* 1996), simulation modelling techniques have been used to quantify the impact of this reduction in rainfall use efficiency on productivity of rainfed peanut crops (M. J. Bell and G. C. Wright, unpubl. data). Soils with a reduced infiltration capacity similar to the current continuously cropped soil (Fig. 5) produced a 25% reduction in average peanut yield and a doubling of the occurrence of non-viable crops (from 13% to 26% of all seasons) when compared with soils with unrestricted infiltration similar to that in the virgin condition (Bridge and Bell 1994). The data collected in the studies reported in the present paper clearly show that ley pastures can make a significant improvement in the physical fertility of such soils during a relatively short period (2–4 years).

The benefits of pasture leys, and the effects of ley management, can be considered in terms of 3 major influences. Firstly, pastures improve soil organic matter status so that soil structural stability and friability are improved, presumably in addition to an improved ability to supply nutrients for crop growth. This improvement in stability will minimise surface crust formation (Loch 1995) and allow a high proportion of incident rain to infiltrate. Secondly, pastures provide increased macroporosity so that rainfall that infiltrates into the soil can readily penetrate to deeper layers in the soil profile for subsequent use by crops. In combination with the effects on stability, this will result in the potential to increase rainfall interception efficiency in a water-limited cropping environment. Thirdly, if pastures can overcome compaction and/or hard setting, restrictions to both the soil's capacity to store water and the ability of roots to access those stored reserves from deeper in the profile may be overcome.

Increased rainfall interception efficiency

Given the continued predominance of summer cropping and conventional tillage systems employed in the Burnett, soils with minimal stubble cover are commonly exposed to high intensity rain during the spring and early summer period, before crop canopies are well developed. We have shown that ungrazed ley pastures can have a large, positive impact on the infiltration characteristics of krasnozem soils exposed to high energy rain in as little as 2 years (Fig. 5). This effect was due to a combination of improved aggregate stability under rain (Table 6), resulting in reduced surface crust formation, and greater hydraulic conductivity through the old plough pan due to an increase in macropore density (Table 4).

The increase in surface aggregate stability occurred under both ley species (Table 6) but required years to develop, presumably due to the time required to re-aggregate and stabilise the often fine soil of the cultivated layer. Soil faunal activity, root density, and rhizosphere activity are the primary agents of aggregate formation in these soils, while soil organic matter plays the dominant role in aggregate stabilisation (Hirst *et al*. 1992; Dalal and Bridge 1996). Whilst the relative contribution of increased aggregate stability to improvements in FIR at either location was unclear, it was interesting to note that the greater aggregate stability under kikuyu than under Rhodes grass at North Coolabunia was consistent with higher FIRs in the uniformly tilled soil (54 *v*. 43 mm/h; Fig. 6). Similar data showing differences in aggregate stability between these 2 species have been reported by Loch (1995), and observed in other locations in the inland Burnett (M. J. Bell and R. J. Loch, unpublished data). The relative advantage of kikuyu over Rhodes grass is probably due to the dense rhizomatous mat formed in the surface layers of the profile (Table 2) compared with that under the more tussocky Rhodes grass sward. This rhizomatous layer (0–10 cm) has been shown to produce significant increases in organic carbon and microbial biomass (Table 5), factors which are very important in aggregate formation and stabilisation (Tisdall and Oades 1982; Edgerton *et al*. 1995; Dalal and Bridge 1996). Whilst data on microbial activity are not available for North Coolabunia, organic carbon values from the samples used to determine aggregate stability reflect this species advantage for kikuyu (2·3%) over Rhodes grass (1·9%).

The increase in rainfall infiltration apparent after only 2 years of ungrazed kikuyu at Goodger was large, but the apparent decline in FIR from Year 2 to Year 4 of the ungrazed ley (Fig. 5), particularly in FW but also evident in all other treatments except FR, has implications for ley pasture management. No pasture treatments achieved full ground cover until just prior to the Year 2 measurements being undertaken, so the dense rhizomatous mat which characterises the top 10–15 cm of the soil profile under a well-developed kikuyu sward (Murtagh 1973*a*; Table 2) would not yet have been well developed. Similarly, soil moisture conditions during the preceding summer and autumn were quite reasonable (Table 1), so earthworm and other soil macrofaunal activity may have made a significant contribution to macroporosity and hence FIR, as suggested in Fig. 5. Indeed, the soil fauna sampling taken 6–8 weeks prior to the Year 2 infiltration measurements in September 1992 (Fig. 3) was one of the few in which earthworms were recovered prior to pasture sprayout in the FW treatment, although densities measured at that stage were low (approx. 1 adult worm/m^2).

The 12 months preceding pasture sprayout and seedbed preparation in mid–late 1994, when the year 4 infiltration measurements were taken, were quite dry: conditions which would have severely limited the activity of earthworms (Fraser 1994) and other burrowing soil fauna (Lee and Foster 1991). At the same time, reduced rates of above-ground biomass accumulation due to intense interplant competition in the ungrazed kikuyu sward would cause increased dry matter accumulation in rhizomes (Murtagh 1973*b*), and this explains the very high rhizome density observed in the top 10 cm of the profile (Table 2). The combination of limited macrofaunal activity and high densities of live rhizomes may have reduced effective macropore density and hence reduced FIR, except where macroporosity had been artificially produced by deep ripping in the FR treatment. The apparent slight increase in FIR noticeable in the undisturbed ley plots 6–8 months after sprayout (when rhizomes had begun to decay), combined with the positive response to tillage in all plots except FR (which already had reasonable macroporosity in the surface layers, albeit artificially created), supports this hypothesis.

It was interesting to note that, although improvements in conductivity after kikuyu were evident as deep as 70–80 cm at Goodger (Fig. 4), the most significant improvements were in shallower layers where soil macrofauna (Fig. 3) were most abundant and where the bulk of the root and rhizome activity (Table 2) was concentrated. This very large decrease in pasture impact below the top 10–15 cm in a soil which had a well-developed compaction layer to at least 25 cm may also have contributed to the strong response to tillage/disturbance at the end of the ley phase (Fig. 5). The ploughing and other tillage operations used to remove the pasture in the conventionally tilled subplots resulted in thorough disturbance to depths of 20–25 cm (Fig. 1*b*). This tillage, like the deep ripping during the ley phase in FR, would have removed some of the deeper impediments to infiltration more thoroughly than the actions of soil fauna or roots and rhizomes alone.

The high FIRs evident under the undisturbed, grazed kikuyu at North Coolabunia (Fig. 6) suggest that the apparent kikuyu pasture rundown evident at Goodger did not occur at this site. As locations were in reasonable proximity to one another, differences in seasonal rainfall were likely to be minimal. However, the impact of grazing on sward characteristics would have been significant. Regular defoliation, combined with a return of litter and manure to the soil surface, would have resulted in continual decay and regeneration of rhizomes and provided a rich source of decaying organic matter for burrowing soil macrofauna. Macropore densities in the shallow rhizomatous layer would probably have been relatively high compared with the ungrazed situation at Goodger and, whilst not measured in this study, are the likely reason for the higher FIR at North Coolabunia in the undisturbed condition. Further, disruption of this web of continuous macropores is the likely reason for the fall in FIR with tillage at this site. It is worth noting that, once below the densely rhizomatous zone at both Goodger and North Coolabunia, macropore densities were similar (Table 6) and estimates of K_S were uniformly high relative to continuously cropped areas.

The low rates of rainfall infiltration under undisturbed grazed Rhodes grass (Fig. 6), which were associated with surface compaction (Table 3) and which could be overcome by tillage, were presumably caused by trampling of grazing animals when the soil was wet. Similar observations of effects of compaction on macroporosity and rainfall infiltration have been made in other studies (e.g. Douglas *et al*. 1992, wheel traffic effects; Greene *et al*. 1994, livestock trampling), and the reasons for similar effects not being evident in the kikuyu area lie in the contrasting growth habits of the 2 grass species. As noted earlier, kikuyu forms a spongy mat of rhizomatous material, which provides good ground cover, and also a resilient mat to resist the impact of cattle trampling. Rhodes grass, on the other hand, is a tufted, stoloniferous species which can become quite tussocky under grazing during dry conditions (Reid 1990). It is therefore not surprising to see trampling effects on bulk density in shallow soil layers (Table 3), and lower rates of rainfall infiltration through these layers (Fig. 6), in grazed Rhodes grass but not kikuyu. These trampling effects will impact on both pasture renovation practices during a ley period and the preferred method of returning ley areas to cropping (i.e. direct drill systems may not be appropriate).

Amelioration of compaction layers

Our data show that pastures alone are not very effective at ameliorating compacted zones in old cultivation in this dry environment (Fig. 1*a*), although soil macrofauna (especially earthworms) can make a significant contribution in the shallower layers. Deep ripping during the pasture phase, whilst having a detrimental effect on pasture growth during the season of application, was successful at disrupting the existing pan to at least 30 cm (Fig. 1*a*), and in maintaining the benefits of deep ripping, at least until the return to cropping 2·5 years later. Subsequent studies (M. J. Bell and B. J. Bridge, unpublished data) are examining the impact of the tillage system on the rate of reappearance of this hard pan.

In general, our observations suggest that infiltration benefits after pasture leys may be very short-lived if potential compacting events are not managed correctly. In addition to the negative effects of trampling, measurements of hydraulic conductivity near the surface in ley plots at Goodger at the end of the first crop (data not presented) showed a 10-fold reduction in K_S where soil had been subject to vehicle traffic during the season, compared with the untrafficked inter-row. The early runoff from rainfall simulator plots was always from the trafficked section of the plot, so minimising compaction would seem to be vital for both achieving benefits of ley pasture and preserving those benefits over time.

Effects of pasture leys on the capacity of soils to store moisture for subsequent crop growth were disappointing. The fertilised kikuyu ley had no effect on drainable porosity, nor on AWC, and this was consistent with the general lack of significant effects on bulk density shown in Fig. 1. Indeed, the only factor affecting AWC at the Goodger site was tillage, and in this instance it was likely due to the re-creation of storage pores in the upper layers of the severely compacted plough pan in the continuously cropped soil. However, Bridge and Bell (1994) showed while crop water extraction was reduced by about 30–40% on continuously cropped soil compared with newly cropped soil, laboratory moisture characteristic data in cores from the top 30 cm showed little effect of continuous cropping on AWC. These differences were attributed to restrictions to root proliferation in the profile, especially as soil strength in the most compacted zones of the profile increased greatly as soils dried out. It remains to be seen whether the continuous biopores created in the various pasture ley treatments will improve root access to deeper layers of the soil profile.

Conclusions

Ley pastures have been shown to be a useful tool in the restoration of the physical fertility of krasnozem soils degraded by continuous cropping. However, the impact of the pasture ley can be significantly affected by ley management (ley pasture species, ley duration, and grazing management), as well as by the tillage method used to return the ley area to cropping. The most significant effects of the ley phase were on improvements in aggregate stability of surface soil layers, and on creation of a network of continuous macropores which allowed high intensity rainfall to infiltrate rapidly down the soil profile. Management both during and after the ley phase should look to maximise and preserve these benefits.

Acknowledgments

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References

Bell, M. J., Harch, G. R., and Bridge, B. J. (1995). Effects of continuous cultivation on Ferrosols in subtropical southeast Queensland. I. Site characterisation, crop yields and soil chemical status. *Australian Journal of Agricultural Research* **46**, 237–53.

Bridge, B. J., and Bell, M. J. (1994). Effect of cropping on the physical fertility of krasnozems. *Australian Journal of Soil Research* **32**, 1253–73.

Bubenzer, G. D., and Meyer, L. D. (1965). Simulation of rainfall and soils for laboratory research. *Transactions of the American Society of Agricultural Engineers* **8**, 73–5.

Chan, K. Y. (1989). Friability of a hardsetting soil under different tillage and land use practices. *Soil and Tillage Research* **13**, 287–98.

Chan, K. Y., and Mead, J. A. (1989). Water movement and macroporosity of an Australian Alfisol under different tillage and pasture conditions. *Soil and Tillage Research* **14**, 301–10.

Coughlan, K. J., McGarry, D., Loch, R. J., Bridge, B. J., and Smith, G. D. (1991). The measurement of soil structure—some practical initiatives. *Australian Journal of Soil Research* **29**, 869–89.

Dalal, R. C., and Bridge, B. J. (1996). Aggregation and organic matter storage in sub-humid and semi-arid soils. *In* 'Structure and Organic Matter Storage in Agricultural Soils. III. Series: Advances in Soil Science'. pp. 263–307. (Lewis Publishers: Boca Raton, FL.)

Douglas, J. T., and Goss, M. J. (1982). Stability and organic matter content of surface soil aggregates under different methods of cultivation and in grassland. *Soil and Tillage Research* **2**, 155–75.

Douglas, J. T., Koppi, A. J., and Moran, C. J. (1992). Alteration of the structural attributes of a compact clay loam soil by growth of a perennial grass crop. *Plant and Soil* **139**, 195–202.

Edgerton, D. L., Harris, J. A., Birch, P., and Bullock, P. (1995). Linear relationship between aggregate stability and microbial biomass in three restored soils. *Soil Biology and Biochemistry* **27**, 1499–501.

Fraser, P. M. (1994). The impact of soil and crop management practices on soil macrofauna. *In* 'Soil Biota: Management in Sustainable Farming Systems'. (Eds C. E. Pankhurst *et al.*) pp. 125–32. (CSIRO Aust.: East Melbourne.)

Grace, P. R., Ladd, J. N., and Skjemstad, J. O. (1994). The effect of management practices on soil organic matter dynamics. *In* 'Soil Biota: Management in Sustainable Farming Systems'. (Eds C. E. Pankhurst *et al.*) pp. 162–71. (CSIRO Aust.: East Melbourne.)

Greene, R. S. B., Kinnell, P. I. A., and Wood, J. T. (1994). Role of plant cover and stock trampling on runoff and soil erosion from semi-arid wooded rangelands. *Australian Journal of Soil Research* **32**, 953–73.

Hammer, G. L., Sinclair, T. R., Boote, K. J., Wright, G. C., Meinke, H., and Bell, M. J. (1996). A peanut simulation model. I. Model development and testing. *Agronomy Journal* **87**, 1085–93.

Hirst, K. M., Imhof, M. P., and Weston, B. A. (1992). The effect of land management on the structure of intensively cropped soils in west Gippsland. Department of Agriculture, Victoria. Research Report Series No. 138.

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

Isbell, R.F. (1994). Krasnozems—a profile. *Australian Journal of Soil Research* **32**, 915–29.

Jenkinson, D. S., and Powlson, D. S. (1976). The effects of biocidal treatments on metabolism in soil. V. A method for measuring soil biomass. *Soil Biology and Biochemistry* **8**, 209–13.

Lee, K. E., and Foster, R. C. (1991). Soil fauna and soil structure. *Australian Journal of Soil Research* **29**, 745–75.

Loch, R. J. (1995). Structure breakdown on wetting. *In* 'Sealing, Crusting and Hardsetting Soils: Productivity and Conservation'. (Eds H. B. So *et al.*) (Australian Society Soil Science: Brisbane.)

Meinke, H., Stone, R. C., and Hammer, G. L. (1996). SOI phases and climatic risk to peanut production: A case study for northern Australia. *International Journal of Climatology* **16**, 783–9.

Murtagh, P. J. (1973*a*). Environmental adaptation of kikuyu. *In* 'Kikuyu—A Research Report'. p. 2. NSW Department of Agriculture Monograph No. 10.

Murtagh, P. J. (1973*b*). Management of kikuyu pastures. *In* 'Kikuyu—A Research Report'. p. 20. NSW Department of Agriculture Monograph No. 10.

Northcote, K. H. (1979). 'A Factual Key to the Recognition of Australian Soils.' 4th Edn. (Rellim: Glenside, S. Aust.)

Perroux, K. M., and White, I. (1988). Designs for disc permeameters. *Soil Science Society of America Journal* **52**, 1205–15.

Rayment, G. E., and Higginson, F. R. (1992). 'Australian Laboratory Handbook of Soil and Water Chemical Analyses.' (Inkata Press: Sydney.)

Reid, R. L. (1990). 'The Manual of Australian Agriculture.' 5th Edn. pp. 242–9. (Butterworths: Sydney.)

Reynolds, W. D., and Elrick, D. E. (1991). Determination of hydraulic conductivity using a tension infiltrometer. *Soil Science Society of America Journal* **55**, 633–9.

Rovira, A. D. (1994). The effect of farming practices on the soil biota. *In* 'Soil Biota: Management in Sustainable Farming Systems'. (Eds C. E. Pankhurst *et al.*) pp. 81–87. (CSIRO Aust.: East Melbourne.)

Tisdall, J. M., and Oades, J. M. (1982). Organic matter and water stable aggregates in soils. *Journal of Soil Science* **33**, 141–63.

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