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Priming of soil structural and hydrological properties by native woody species, annual crops, and a permanent pasture

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Abstract

Impermeable subsoil is a major constraint to root growth and water infiltration in most duplex soils of Australia, but can be ameliorated by channels or biopores created by dead and decomposed roots of plant species that are adapted to these soils. In the current study, we evaluated whether a 6-year phase of native woody species planted in belts created sufficient biopores to significantly improve the soil structure of a yellow Chromosol, when compared with either continuous annual crop rotations or a permanent grassy pasture. At 10 months after belt removal, we found no difference between belt-soil and cropping-soil in terms of total number of biopores, air-filled porosity, and total porosity, all of which were less than the values measured for the pasture-soil. The belt-soil, however, had significantly more large pores (diam. ≥ 2.0 mm) and marginally higher hydraulic conductivity than the other 2 treatments, indicating some improvement in permeability. The limited amelioration of the belt-soil at this time was due to (1) slow decay of the thick roots of woody species, and (2) increased bulk density arising from soil shrinkage due to prolonged drying during the years of active growth by the woody species. Following a further decomposition of roots 20 months after belt removal, however, the total number of pores of all sizes was 55% higher, and of large pores 25% higher, in the belt-subsoil than in the cropping-subsoil. At the same time, estimated hydraulic conductivity was 27% greater, and air-filled porosity 23% greater, for the belt-soil than for the cropping-soil. Preferential flow technique with a food dye solution at 20 months after belt removal also suggested a 51% increase in the macroporosity for the belt-soil compared with the cropping-soil.

Additional keywords: subsoil constraint, *Acacia* spp., *Eucalyptus* spp., *Casuarina* spp., biological drilling, porosity, hydraulic conductivity, preferential flow.

Introduction

Roots grow and function optimally where the soil has minimal physical, chemical, and/or biological constraints. An ideal soil structure for root growth and water infiltration should have an air-filled porosity of at least 15% and penetrometer resistance of <1.0 MPa at field capacity (Cockroft and Olsson 1997). This ideal soil permeability, however, is rarely attainable in agricultural soils except for soils under permanent pastures or forests (Sollins and Radulovich 1988; Lorimer and Douglas 1995). For most duplex soils in Australia, poorly permeable dense subsoil is a major cause of poor agricultural productivity, and of adverse hydrological and nutrient balance under annual crops (Jayawardene and Chan 1994). Poor permeability of these soils is primarily associated with low macroporosity, which can be ameliorated by growing adapted plant species to create channels after their roots die and decay (Elkins 1985). Biopores or pores created by roots and other soil biota are more effective than mechanical tillage in opening up the soil, especially at low down the profile. Often these pores are too large (>0.03 mm in diameter) to hold water by capillarity, but they enhance water- and air-flow, and exploration by the following generations of roots (Bouma 1981; Elkins and Van Sickle 1984; Passioura 2000). For instance, Passioura (1991) calculated the time required by roots to extract water from a given volume of soil to be proportional to the

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average distance between biopores. The conventional approach of improving macroporosity through tillage and/or the use of amendments (Olsson *et al.* 1995; Ellington *et al.* 1997) is not sustainable because the soil recompacts due to farm traffic, while pores are destroyed upon exposure to direct impact of rain/irrigation water (Jayawardene and Chan 1994).

Plants can be referred to 'primer-plants' when grown primarily to ameliorate soil conditions. Cresswell and Kirkgaard (1995) explored the potential of this concept for improving the structure of a red-brown earth by a wheat–canola (*Brassica napus* L.) rotation compared with continuous wheat cropping. They found no differences in soil macroporosity and hydraulic conductivity under the 2 systems, and concluded that an annual crop of canola had limited opportunity to significantly modify the soil structure. They hypothesised that perennial dicots whose roots reside in the soil for extended periods of time would provide a greater amelioration. An earlier study by Materechera *et al.* (1991) found that dicotyledonous species with thick roots had a greater capability for penetrating dense soils than monocotyledonous grassy species with thin roots. A successful 'primer-plant' needs to be well adapted to the prevailing environmental and soil conditions. Liang *et al.* (1999) found that acacia roots grew relatively easily through dense soils having a bulk density of 1.62, and also withstood the anaerobic conditions that prevail in impermeable soils.

In the current study, we tested the hypothesis of Cresswell and Kirkegaard (1995) that dicotyledonous perennials would be more effective than thin fibrous rooted annuals in opening up clayey subsoils. We evaluated selected physical characteristics of soil that had been under shelter-belts of a mixture of native woody species for 6 years, and compared them with those of soil under either continuous annual crop rotations or a permanent grassy pasture.

Materials and methods

Site

A field study was conducted at Rutherglen in north-east Victoria, Australia (36°08′S, 146°28′E), on an acidic light clay soil classified as eutrophic brown Chromosol (Isbell 1996) or as Dy3.32 (Northcote 1971), and it approximates Haplic Xerosol in the FAO classification. It has a duplex profile consisting of a sandy to clay-loam A-horizon about 0.2 m thick overlying a B-horizon of dense, slowly permeable, sodic, fine sandy clay loam (Table 1). The soil is acidic with an average pH ($CaCl_2$) of 5.3 (Ridley *et al.* 2001), while electrical conductivity ($EC_{1:5}$) is <0.4 dS/m. Other physical properties of the soil are given in Table 1. Rutherglen has an average annual rainfall of 598 mm, of which 397 mm occurs during the winter growing season (May–November) when average minimum temperature is 4.3°C and maximum temperature 17.0°C. Summer is generally dry, except for occasional stormy rainfall events, and hot, with average minimum temperature of 11.2°C and maximum temperature of 28.0°C.

Table 1. Particle size analysis, volumetric soil water (θ) characteristics, and total soluble salts (TSS), electrical conductivity (EC), and sodium adsorption ratio (SAR) for the soil at the study site

Depth intervals (m)	Particle size distribution Sand (%)	Silt (%)	Clay (%)	Gravel (%)	θ (m^3/m^3) at: –300 kPa	–1500 kPa	Chemical characteristics TSS (%)	$EC_{1:5}$ (dS/m)	SAR
0.0–0.2	74	15	9	2	0.20	0.06	0.03	0.08	0.08
0.2–1.0	56	17	21	6	0.23	0.13	0.03	0.07	0.41
1.0–2.0	43	21	33	3	0.28	0.14	0.05	0.14	1.14
2.0–3.0	41	21	38	n.a.	n.a.	n.a.	0.06	0.19	1.52

n.a., data not available.

Treatments

The site was under mixed pastures of subterranean clover (*Trifolium subterraneum* L.)/annual ryegrass (*Lolium regidum* Gaudin) in the 24 years preceding September 1993 when it was ripped to 0.35 m depth and limed at 2.5 t/ha to establish an alley-cropping experiment. Four belts, each measuring 40 m long and 7 m wide, were marked in a northwest–southeast direction. These were planted to a mixture of native woody species dominated by acacia (*Acacia melanoxylon*, *A. dealbata*, and *A. pravissima*), but also containing eucalypts (*Eucalyptus botryoides, E. camaldulensis*, and *E. campara*) and casuarina (*Casuarina cunninghamiana*). Each belt contained 3 rows spaced 2.5 m apart with the seedlings spaced at 2.0 m within rows, which gave a plant density of approximately 2000 trees/ha. The belts were separated by alleys of at least 20 m wide sown to lupins (*Lupinus angustifolius*) in 1994, wheat in 1995, canola in 1996, wheat in 1997, and triticale (× *Triticosecale* Wittmack) in 1998. Prior to sowing in these years, stubbles from the preceding season were burnt in autumn and the plots were disced. On 10 March 1999, the woody plants were mechanically pulled out after treatment with a contact herbicide, and the whole paddock was sown to an oat crop (*Avena sativa* L.) in May and harvested in December (Mele and Yunusa 2001). Measurements were also made in two 10 by 4 m plots of annual ryegrass pastures marked out in an adjacent paddock, which has been under ryegrass since 1994, but previously under subterranean clovers (1974–1993) and oat fodder (1969–1974). Thus, there were 3 soil treatments: (1) belt-soil, made up of soil previously under native woody species, (2) cropping-soil, made up of soil in the alleys that were continuously cropped, and (3) pasture-soil. Both the belt-soil and cropping-soil had 3 replications each, while the pasture-soil had 2. At the start of 2000, belt-soil had been under woody species for 6 years (1993–1999) followed by 1 year of oat crop (1999).

Measurements taken 10 months after belt removal (January/February 2000)

Soil structure

Pore numbers. Between January and February 2000, stepped pits were excavated with a backhoe to 1.5 m depth in each of the 6 belts, while 2 similar pits were dug in the pasture paddock. To estimate biopore numbers in each pit, 3 metallic rings (80 mm i.d. and 50 mm length) were pushed vertically into the soil at 0.2, 0.5, 1.0, and 1.5 m depths and the surrounding soil was excavated to the bottom of the rings. The rings were then gently twisted to achieve a clean break at the base of the sampled soil and avoid smearing. These intact samples were taken to the lab, where biopores exposed on the cross-sectional soil surface were counted visually under an illuminated magnifying glass. We grouped the biopores into 3 diameter classes (<1 mm, 1–2 mm, and >2 mm) using drill bits as described by Cresswell and Kirkegaard (1995).

Bulk density and water content. In each pit, 3 intact soil samples were taken with metallic rings (40 mm i.d. and 50 mm length) from the pit face at depths 0.1 m and 0.2 m, and thereafter at 0.2-m intervals to 1.4 m; additional cores were taken from the pit bottom for the 1.6 m depth. These were quickly weighed soon after being taken and after drying at 105°C for 36 h to estimate bulk density and volumetric water content (θ) following the procedures given by Hillel (1971). Total porosity (*tp*) was calculated as (Hillel 1971):

$$tp = 1 - bd/pd \tag{1}$$

where *pd* is the specific particle density for which we used a value of 2.7, i.e. the average of 2.6 and 2.9 found for Australian soils (Turner *et al.* 1984).

Air-filled porosity. This was determined using the suction method (Reeve and Carter 1991) on intact soil cores taken with metallic rings as described above for biopore counts. Two core samples were each taken at 0.2, 0.5, and 1.0 m depths from each pit and trimmed and the volumes of gaps in the samples determined by filling with sand. The cores were then saturated using a vacuum suction desiccator and placed on a hanging column tension table to equilibrate at –5 kPa and –10 kPa water tension. They were weighed twice a week until an equilibrium weight was attained. Air-filled porosity at –5 kPa or –10 kPa was calculated as the difference between *tp* and θ at either tension. The effective diameter of pores (*d, mm*) involved in water storage at these tensions was estimated as (Hillel 1971):

$$d = 0.03/h \tag{2}$$

where *h* is the water potential in metres.

Hydraulic conductivity

Hydraulic conductivity (K) was estimated from *in situ* measurements of sorptivity on the pit steps at 0.2, 0.5, and 1.0 m depths at matric potential of –10 mm (K_{-10}) and –40 mm (K_{-40}) using disc permeameters (White and Perroux 1987). The permeameters had a base diameter of 100 mm, and for every depth 2 measurements were made at each matric potential. The hydraulic conductivity was used to estimate the number of cylindrical pores with mean diameter dominating the flow as given by Coughlan *et al.* (1991):

$$N = 0.0722(K_{-10} - K_{-40})/R^4 \quad (3)$$

where R is pore radius, which in the present case was 1.875 mm, i.e. the average of 3.0 mm for K_{-10} and 0.75 mm for K_{-40} (Hillel 1971).

Soil structure measurements at 20 months after belt removal (November 2000)

Preferential flow

Preferential flow or movement of water through macropore systems that bypasses the soil matrix (Deeks *et al.* 1999) was assessed at the end of November 2000 on adjoining belt- and alley-soil. The wheat crop was mowed to a height of approximately 0.04 m and removed, but leaving the stumps in place. A steel frame (1 by 1 m) of 0.2 m height was pushed into the soil to depths of 40–80 mm in the belt, and a second frame at 5 m distance into the cropping alley. Earlier observations of crop growth and soil water found no significant influence of belts beyond 4 m distance from the belts (P. J. Haines, unpublished data). Each frame was ponded with 110 mm (110 L) of 0.06% solution (6 g/L) of food grade dye (FCF Blue, Proscience Pty Ltd, Melbourne, Australia). The frames were removed after 6 days and a 1-m-deep trench measuring 6 m by 1.1 m was dug connecting the 2 ponded squares while cutting into the squares at approximately 0.3 m from the northern end. Straight pit walls were prepared at each square and colour photographs were taken to evaluate vertical dye distribution. Horizontal surfaces were then prepared within the remnants of the ponded squares at 0.25, 0.50, and 0.75 m depths and photographed. The photographs were scanned and digitally analysed using Delta-T Scan (Delta-T Devices, Cambridge, UK) to estimate surface area stained. The degree of preferential flow was deduced from the percentage area stained by the dye (Sollins and Radulovitch 1988; Yasuda *et al.* 2001). In the first 2 days following their construction, the pits were flooded with dye solution, the depth of which was measured at several positions to estimate its volume before being emptied.

Pore numbers

This was undertaken in the pits used for the preferential flow paths by taking intact soil samples with rings at 0.2, 0.5, and 1.0 m depths as was done during the previous January/February period. At this second sampling, 4 samples were taken per depth level from each of the pits and the pores counted as described above.

Data analyses

All quantitative data collected in January/February were analysed using the REML (residual maximum likelihood) option in GENSTAT (NAG Ltd, UK) because of the unbalanced nature of the experimental design. Each data set was treated as a split-plot design with soil treatments (belt-soil, cropping-soil, and pasture-soil) as the main plots and soil depths as subplots. The hydraulic conductivity data were transformed into a log-normal scale before analysis. The predicted means from REML were compared using the standard error of the difference (s.e.d.), while the level of significance was determined by comparing the Wald statistic to chi-square values at the appropriate degrees of freedom. Data on biopore numbers taken in November were analysed using the student's t-test.

Results and discussion

Soil structure

At 10 months after the removal of the belt, there was only limited evidence of soil amelioration by the woody species. The total number of pores averaged over the 4 depths (Table 2) was similar between belt and cropping treatments, both of which had significantly fewer pores than the permanent pasture-soil. Most of the differences in pore density were in the top 0.2 m of the soil, where presumably a greater root turnover, in addition to the absence of tillage in the previous 5 years, enabled the pasture to produce more biopores than

Table 2. Total number of all pores and of large pores (≥ 2.0 mm equivalent spherical diameter, e.s.d.) counted in soils in the belt, cropping, and pasture treatments 10 months after belt removal

Depth (m)	Total number of pores (000s per m^2) Belt	Cropping	Pasture	Mean	Large pores (per m^2) Belt	Cropping	Pasture	Mean
0.20	7.96	11.20	16.09	11.73	161.4	209.9	414.6	261.0
0.50	10.23	12.74	12.22	11.72	161.4	96.9	60.5	106.3
1.00	4.75	4.04	5.84	4.87	80.7	48.4	0.0	43.0
1.50	4.62	3.33	2.48	3.48	16.1	16.1	0.0	10.8
Mean	6.89	7.83	9.14		104.9	92.8	118.0	
Subsoil[A]	6.70	6.53	7.87		86.1	53.8	21.5	
Statistics		s.e.d.	*P*			s.e.d	*P*	
Soil treatment		0.580	***			32.96	n.s.	
Depth		0.665	***			37.81	***	
Soil treatment × depth		1.527	**			86.72	**	
Subsoil		1.294	n.s.			1.96	**	

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; n.s., not significant.
[A]Average number of biopores for the 0.5, 1.0, and 1.5 m depths.

the other 2 treatments. In the subsoil below 0.2 m depth, however, there were no significant differences amongst the 3 treatments in the number of biopores formed (Table 2). Pores produced in the subsoil (below 0.2 m depth) in the belt treatment were similar to those found in the other 2 treatments. This was attributed to the slow decomposition of the woody roots to expose all the potential biopores as many intact roots were found. Usman *et al.* (2000) reported that thick roots (≥ 2.0 mm) of tree species decompose slowly because of their low soluble carbohydrate content and high C : N of >85, whereas our unpublished data show that finer roots of annual crops such as wheat generally have a C : N of around 70 (IAM Yunusa, unpublished data).

A greater number of large pores having equivalent spherical diameter (e.s.d.) ≥ 2.0 mm in the belt-subsoil (Table 2) indicated some improvement in the soil macroporosity. Six years of woody species increased the number of these pores in the subsoil (below 0.2 m depths) by 60% compared with the cropping treatment and by almost 400% compared with the pasture treatment. There were few large pores in pasture subsoil because of the shallow root systems, reflected in the θ distribution (Fig. 1*c*), and this was consistent with the study on clayey soils by Barley (1953), in which no ryegrass roots were found beyond 0.7 m depth. Total pore density and the number of large pores were significantly correlated ($r = 0.86$) with each other, when data at 0.5 m depth for the pasture was excluded as an outlier. We observed fewer large pores in the current study than did Cresswell and Kirkegaard (1995) in continuous wheat or wheat–canola rotations, probably because their subsoil was less dense (bulk density of 1.65 Mg/m) than ours (1.74 Mg/m).

We found no significant difference in air-filled porosity at either –5 kPa or –10 kPa between the belt-soil and the cropping-soil 10 months after belt removal (Table 3). Porosity for these 2 soils was significantly lower than for pasture-soil, consistent with the differences in pore numbers amongst the 3 treatments at this time (Table 2). It is noteworthy that the air-filled porosity below 0.2 m was larger for the cropping-soil than for the belt-soil, probably a result of the deep taproots of lupin in 1994 and canola in 1996, although this was not evident in the pore numbers counted (Table 2). Low air-filled porosity in the subsoil of the belt treatment could be associated with high bulk density (Fig. 1*a*) and, hence, low total

Table 3. Air-filled porosity measured at two suctions and volumetric water content (θ) at –10 kPa for soils in the belt, cropping, and pasture treatments 10 months after belt removal

Depth (m)	Porosity (–5.0 kPa) (%)				Porosity (–10.0 kPa) (%)				θ (–10 kPa) (%)			
	Belt	Cropping	Pasture	Mean	Belt	Cropping	Pasture	Mean	Belt	Cropping	Pasture	Mean
0.20	11.1	6.6	13.5	10.4	14.0	9.8	16.6	13.5	27.4	29.7	27.3	28.2
0.50	3.4	5.8	4.7	4.7	6.3	8.7	8.3	7.8	34.6	34.0	34.4	34.4
1.00	0.8	2.3	0.5	1.2	2.5	4.2	3.0	3.3	37.5	37.9	40.7	38.7
Mean	5.1	4.9	6.3		7.6	7.6	9.3		33.2	33.9	34.1	
Statistics		s.e.d	*P*			s.e.d.	*P*			s.e.d.	*P*	
Soil treatment		0.91	*			0.93	**			0.86	n.s.	
Depth		0.89	**			0.90	**			0.83	**	
Soil treatment × depth		1.87	**			1.94	**			1.63	n.s.	

*$P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; n.s., not significant.

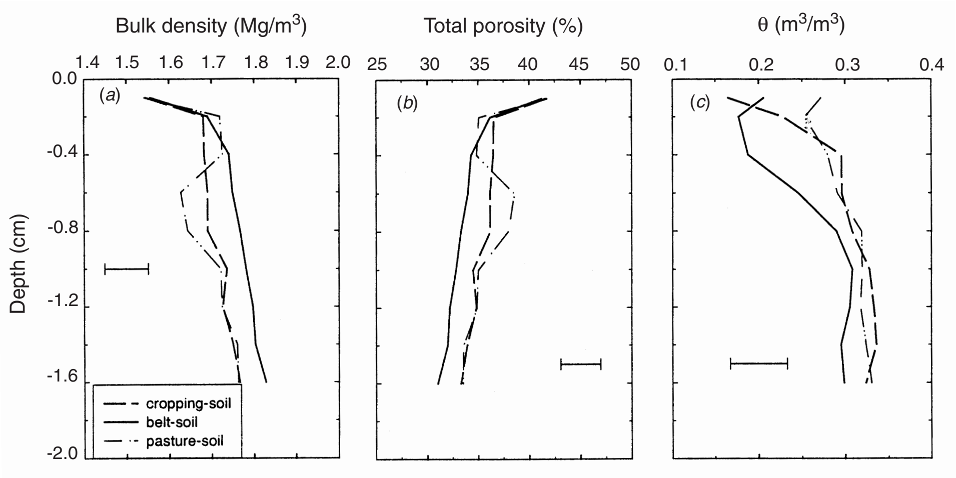

Fig. 1. Selected physical characteristics for soils either after 6 years of belt followed by 1 year of oat crop or under continuous annual crops or under permanent pasture measured 10 months after belt removal (January/February 2000): (*a*) bulk density, (*b*) total porosity, and (*c*) volumetric water content (θ). Bars are standard errors of difference.

porosity (Fig. 1*b*) caused by prolonged periods of drying during the years of active growth by the woody species. The dry profile was still evident almost a year after the removal of the belts (Fig. 1*c*). A slope (n) of 0.4 was estimated for the plot of specific soil volume against gravimetric water content (McGarry and Malafant 1987; Allbrook 1993) for this soil, using the clay content (Table 1) in an empirical model (Crescimanno and Provenzano 1999). A value of n <1 meant that the air-filled porosity increased as the soil dried, but continued drying resulted in a temporary collapse of the storage pores (10–30 µm), leaving macropores (>30 µm) and residual pores (<10 µm) largely intact (Allbrook 1993). These pores may recover upon rehydration, which explains the similarity in the θ (–10 kPa) for the 3 treatments (Table 3). Thus, the belt-soil would be prone to waterlogging, and the roots of the following crop would encounter dense soil, until most of the roots of woody species had decayed to increase macroporosity.

Subsequent site analysis 20 months after belt removal produced a clear indication of soil amelioration by the woody species, presumably following further decomposition of remnant thick roots. We did not find any intact remnant roots of the native species at this time, only those that were at advanced stages of decomposition. The number of large pores at 0.5 m depth was 93% greater in the belt-soil than the cropping-soil (Table 4). Many of these pores were created by the growing wheat to account for the increases in pore density for both belt and cropping treatments (pasture treatment was not measured) compared with 10 months previously. Bulk density was not measured at this time, but could be lower in the belt-soil compared with the cropping-soil, consistent with differences found between soils under annual crop and forests (Lorimer and Douglas 1995).

This improvement in permeability 20 months after acacia removal accounted for a doubling of root length density (1.47 km/m^3) on the belt-soil compared with the cropping soil in 2000 (Yunusa *et al.* 2001). Roots in the belt-soil could have grown along zones of least mechanical resistance through the biopores directly (Passioura 2000) and/or the

Table 4. Total number of all pores and of large pores (≥2.0 mm equivalent spherical diameter, e.s.d.) counted in the belt-soil and cropping-soil 20 months after belt removal

Variables	Depth (m)	Belt	Cropping	s.e.d.
Total number of pores ('000s per m^2)	0.20	19.35	13.83	3.923
	0.50	15.16	12.60	1.815
	1.00	0.80	0.97	0.475
	Mean	11.77	9.13	1.224
Pores >2.0 mm e.s.d. per m^2	0.20	791	793	142.3
	0.50	679	352	180.9*
	1.00	113	126	26.2
	Mean	528	424	63.1

*Differences between means in a row were significant ($P < 0.05$).

biopore sheath (Kirby *et al.* 2000). It is noteworthy that even in the pasture treatment the subsoil did not attain the optimum air-filled porosity of 15% suggested by Cockroft and Olsson (1997).

Hydraulic conductivity

Six years of native woody species improved the hydraulic conductivity of the subsoil measured at 10 months after the belt removal. Conductivity data for pasture-soil were not presented due to rainfall damage to the pits. Both K_{-10} and K_{-40} in the subsoil (below 0.2 m depth) were at least doubled in the belt treatment compared with cropping treatment (Table 5), a response consistent with the increases in the numbers of large pores in the belt-subsoil. Despite the shrinkage discussed above, K_{-10} in the top 1 m profile of the belt-soil was, on average, 42% greater than for the cropping-soil, which was significant at $P = 0.10$. This was because the pores controlling flow of water at K_{-10} and at K_{-40} had an average radius of 1.88 mm (Eqn 2), and were less prone to structural degradation through drying as explained above. Transmission of water was therefore, not significantly affected by the 6

Table 5. Hydraulic conductivity (mm/day) measured at matric potential of either –10 mm (K_{-10}) or –40 mm (K_{-40}) for soils in the belt, cropping, and pasture treatments 10 months after belt removal

Depth		K_{-10}			K_{-40}	
(m)	Belt	Cropping	Mean	Belt	Cropping	Mean
0.20	311	368	339	400	322	361
0.50	401	151	276	254	88	171
1.00	84	39	61	56	29	42
Mean	265	186		236	146	
Subsoil[A]	310	128		134	65	
Statistics		s.e.d.	*P*		s.e.d.	*P*
Soil treatment		75.1	n.s.		61.0	n.s.
Depth		103.0	**		80.1	**
Soil treatment × depth		177.0	n.s.		126.6	n.s.
Subsoil		72.2	*		33.0	*

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; n.s., not significant.
[A]Average number of biopores for the 0.5 and 1.0 m depths.

years of woody species. Richard *et al.* (2001) reported that relic structural pores, created by wetting–drying cycles, enhanced hydraulic conductivity in compacted soils. Calculated number of cylindrical pores controlling flow between K_{-10} and K_{-40} in the belt-soil (14.4 per m^2) was almost twice that in the cropping-soil (7.8), although the two were statistically similar. These results show that contrary to a 1-year phase of canola in rotation with wheat (Cresswell and Kirkgaard 1995), 6 years of native woody species improved the hydraulic conductivity of the soil.

Preferential flow paths

Preferential flow, deduced from percentage area stained by the dye (Fig. 2), was much greater in the belt-soil than in the cropping-soil. In the top 0.4 m of the soil profile, at least 90% of the area was stained in the belt-soil, compared with just 49% in the cropping belt. There was a large pore containing a mass of decomposing roots in the top 0.3 m of the belt-soil profile (Fig. 2*a*) from which the dye stained much of the area below when the pit was excavated. Staining was largely limited below 0.6 m depth, except for a single large pore at 0.7 m depth in the cropping belt, which stained the bottom right hand corner in Fig. 2*b*, suggesting a general decrease in macroporosity with depth. For the whole 0.8 m profile, 57% of the vertical surface was stained in the belt-soil compared with 38% in the cropping-soil. This indicated that preferential flow in the belt-soil was 51% greater than in the cropping-soil, and hence porosity due to large pores (>60 μm diameter).

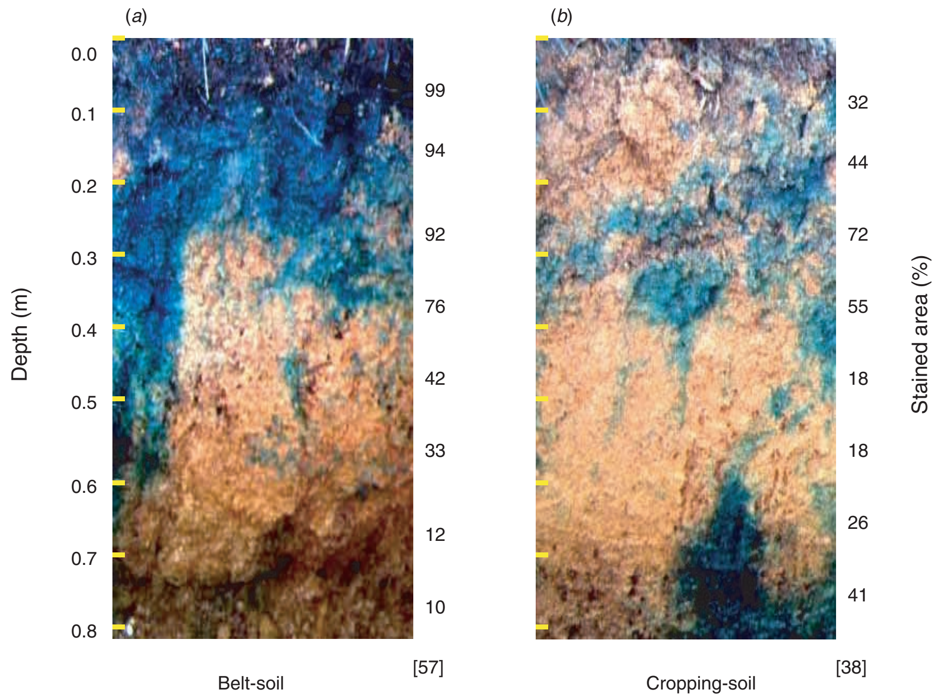

Fig. 2. Percentage of stained areas (numerals to the right of images) along the soil profiles of (*a*) belt-soil, and (*b*) cropping-soil evaluated 20 months after belt removal. Pictures taken from pits dug 1 week after dye application, numerals in brackets are mean percentages of the stained area for the whole 0.8 m depth.

Differences in the distribution of the stained area along the pit walls were consistent with the horizontal surface areas stained in the 2 treatments. The horizontal surface areas stained at 0.2, 0.5, and 0.75 m depths were 63, 51, and 40%, respectively, in the belt-soil, compared with 56, 16, and 17% in the cropping-soil. These stained areas were significantly correlated with the density of pores having diameters >2.0 mm (x):

$$\text{Stained area (\%)} = 0.055x + 12.6 \qquad (r^2 = 0.72,\ n = 8) \tag{4}$$

A large amount of dye solution collected at the pit bottom to a total depth of 0.25 m over 2 days. Assuming a rectangular shape for the pit (6.0 by 1.1 m), the drained solution was approximately 1650 L, far in excess of the dye solution applied. It was not possible to ascertain the origin of this water that mixed with the dye solution because the belts were not hydrologically isolated. It indicated, however, the magnitude of antecedent water stored in the macro-pores. Trojan and Linden (1998) calculated that macropores created by earthworms stored up to 10 mm of water in a 2-m soil profile that would be lost through evaporation, drainage, or leakage into the soil matrix.

Relationships between soil variables

In order to assess whether the number of large pores can be a reliable predictor for other variables of soil permeability, regressions were developed based on the number of large pores (≥ 2.0 mm) and either hydraulic conductivity or air-filled porosity (Fig. 3). Relationship between air-filled porosity at either –5 or –10 kPa and number of large pores was curvilinear (Fig. 3*b*), suggesting that some of the numerous pores at 0.2 m depth could be superficial and not deep enough to significantly increase porosity. Outliers from 0.2 m depth in the belt-soil were excluded from the regressions due to huge variability in the number of pores counted at this depth.

These regressions could provide first approximations for hydraulic conductivity and porosity on this soil type where direct measurements are not available. For example, the numbers of large pore at 10 months after belt removal (Table 2) suggested a K_{-10} of 205 mm/day and K_{-40} of 145 mm/day for the pasture subsoil. Using data in Table 4, K_{-10} would have increased to 1190 mm/day and K_{-40} to 949 mm/day for the belt-soil in November 2000; the corresponding values for the cropping-soil were 939 and 745 mm/day, respectively. Air-filled porosity at field capacity of the subsoil (θ at –10 kPa) would have attained 16% in the belt treatment compared with 13% in cropping treatment. Estimated K_{-10} and K_{-40}, however, seemed unrealistically large in the light of what we measured earlier in the year (Tables 3 and 5), and demonstrated the limitation of using regressions to extrapolate beyond the limits of the original data. Improvements of 27% in hydraulic conductivity and of 23% in porosity for the belt-soil compared with the cropping-soil nonetheless showed the benefit of a short phase of woody perennials in ameliorating physical subsoil constraint of poor permeability.

Summary and conclusions

This study provides some support for the hypothesis of Cresswell and Kirkegaard (1995) that tap-rooted perennials would be more effective than annuals in opening up a dense subsoil through creation of biopores. It also demonstrated the feasibility of the 'primer-plant' concept as an approach for ameliorating physical subsoil constraints. The soil amelioration by the woody species was not immediately obvious until most of thick roots

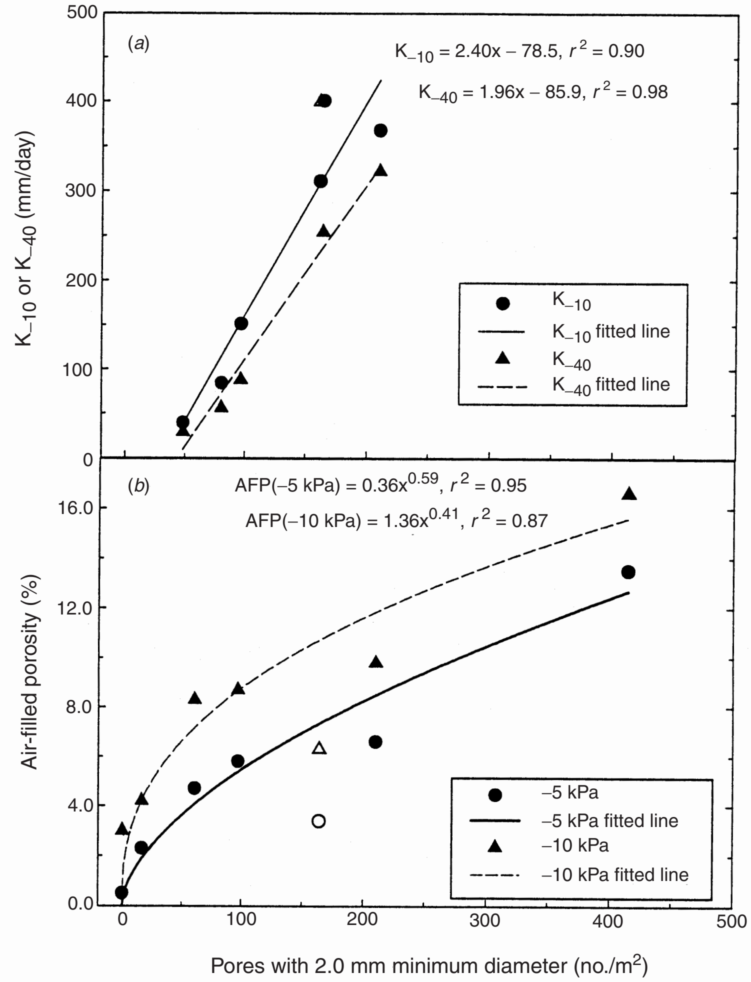

Fig. 3. Relationships between number of pores having diameters ≥2.0 mm and either (*a*) hydraulic conductivity, or (*b*) air-filled porosity 10 months after belt removal. In (*a*) there were no hydraulic conductivity data for pasture treatment; open symbols in both graphs are outliers excluded from the regressions due to large variability (see text).

decayed to expose all the potential biopores 20 months after the belt removal. The woody species were effective in opening up the subsoil because of their ability to create more large pores (≥ 2 mm wide) than did either the permanent pasture or annual crops. These large pores constituted <5% of the total number of pores counted, but had significant influence on soil structure and hydrology. These results have significant implications for crop production in terms of sustainability and profitability. The dry soil at the start of the first cropping season following belt removal reduced yield of the following oat crop by 40% in 2001, but prevented deep-drainage (Mele and Yunusa 2001). The adverse effect of the belt on crop yield was expected to be short-lived, but would be followed by increases in yields once the soil was reasonably recharged.

This study only dealt with changes in soil physical properties at this stage; changes in soil nutritional and microbial characteristics, and detailed response of the following annual crops to these modifications are subjects of ongoing studies. Future studies should include evaluation of other species, shorter perennial phases, and lower plant densities for woody species than used here.

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References

Allbrook RF (1993) Shrinkage of some New Zealand soils and its implications for soil physics. *Australian Journal of Soil Research* **31**, 111–118.

Barley KP (1953) The root growth of irrigated perennial pastures and its effect on soil structure. *Australian Journal of Agricultural Science* **4**, 283–291.

Bouma J (1981) Soil morphology and preferential flow along macropores. *Agricultural Water Management* **3**, 235–250.

Cockroft B, Olsson KA (1997) Case study of soil quality in south-eastern Australia: management of structure for roots in duplex soils. In 'Developments in soil science 25'. (Eds EG Gregorich, MR Carter) pp. 339–350. (Elsevier: Amsterdam)

Coughlan KJ, McGarry D, Loch RJ, Bridge B, Smith GD (1991) The measurement of soil structure—some practical initiatives. *Australian Journal of Soil Research* **29**, 869–889.

Crescimanno G, Provenzano G (1999) Soil shrinkage characteristic curve in clay soils: measurement and prediction. *Soil Science Society of America Journal* **63**, 25–32.

Cresswell HP, Kirkegaard JA (1995) Subsoil amelioration by plant roots—the process and the evidence. *Australian Journal of Soil Research* **33**, 221–239.

Deeks LK, Williams AG, Dowd JF, Scolefield D (1999) Quantification of pore size distribution of solutes through isolated blocks. *Geoderma* **90**, 65–86.

Elkins CB (1985) Plant roots as tillage tools. In 'International Conference on Soil Dynamics, Proceedings'. Auburn. Vol III. pp. 519–523. (ICSD Conference, Office of Continuing Education: Auburn, AL)

Elkins CB, Van Sickle K (1984) Punching holes in plowpans. *Solutions,* July/August, 38– 41.

Ellington A, Badawy NS, Ganning GW (1997) Testing gypsum requirements for dryland cropping on a Red-Brown Earth. *Australian Journal of Soil Research* **35**, 591–607.

Hillel D (1971) 'Soil and water—physical principles and processes.' First edn (Academic Press, Inc.: Sydney)

Isbell RF (1996) 'The Australian soil classification.' (CSIRO Publishing: Melbourne)

Jayawardene NS, Chan, KY (1994) The management of soil physical properties limiting crop production in Australian sodic soils—a review. *Australian Journal of Soil Research* **32**, 13–44.

Kirby, JM, Pierret A, Moran CJ, Pankhurst, CE (2000) Imaging of soil structure–root interactions. In 'Proceedings of 4th International Conference on Soil Dynamics'. Adelaide. (CD-ROM)

Liang J, Zhang J, Chan GYS, Wong MH (1999) Can differences in root responses to soil drying and compaction explain differences in performance of trees growing on landfill sites? *Tree Physiology* **19**, 619–624.

Lorimer MS, Douglas LA (1995) Effect of management practices on properties of a Victorian red brown earth. I. Soil physical properties. *Australian Journal of Soil Research* **33**, 851–857.

McGarry D, Malafant KWJ (1987) The analysis of volume change in unconfined units of soil. *Soil Science Society of America Journal* **51**, 290–297.

Materechera SA, Dexter AR, Alston AM (1991) Penetration of very strong soils by seedling roots of different plant species. *Plant and Soil* **135**, 31–41.

Mele PM, Yunusa IAM (2001) Cereal yields associated with changes in soil characteristics following six years of acacia. In 'Proceedings of the 10th Australian Agronomy Conference'. Hobart. http://www.regional.org.au/. (Accessed: 27 August 2001)

Northcote KH (1971) 'A factual key for the recognition of Australian soils.' 3rd edn (Rellim Technical Publications: Glenside, S. Aust.)

Olsson KA, Crockroft B, Rengasamy P (1995) Improving and managing subsoil structure for high productivity from temperate crops on beds. In 'Subsoil Management Techniques'. (Eds BA Stewart, NS Jayawardene) Advances in Soil Science. pp. 35–65. (Lewis Publishers: Boca Raton, FL)

Passioura JB (1991) Soil structure and plant growth. *Australian Journal of Soil Research* **29**, 717–728.

Passioura JB (2000) Broad-acre agriculture: A root's eye view. In 'Proceedings of 4th International Conference on Soil Dynamics'. Adelaide. CD-ROM

Reeve MJ, Carter AD (1991) Water release characteristic. In 'Soil analysis: Physical methods'. (Eds KE Smith, CE Mullins) pp. 111–160. (Marcel Dekker, Inc.: New York)

Richard G, Cousin I, Sillon JF, Bruand A, Guerif J (2001) Effect of compaction on the porosity of a silty soil: influence on unsaturated hydraulic properties. *European Journal of Soil Science* **52**, 49–58.

Ridley AM, Christy B, Dunin FX, Haines PJ, Wilson KF, the late Ellington A (2001) Lucerne in crop rotations on the Riverine Plains 1. The soil water balance. *Australian Journal of Agricultural Research* **52**, 263–277.

Sollins P, Radulovich R (1988) Effects of soil physical structure on solute transport in a weathered tropical soil. *Soil Science Society of America Journal* **52**, 1168–1173.

Trojan DD, Linden DR (1998) Macroporosity and hydraulic properties of earthworm-affected soils as influenced by tillage and residue management. *Soil Science Society of America Journal* **62**, 1687–1692.

Turner AK, Willat ST, Wilson JH, Jobling GA (1984) 'Soil water management.' First edn (IDP: Canberra)

Usman S, Singh SP, Rawat YS, Bargali SS (2000) Fine root decomposition and nitrogen mineralisation patterns in *Quercus leucotrichophora* and *Pinus roxburghii* forests in central Himalaya. *Forest Ecology and Management* **131**, 191–199.

White I, Perroux KM (1987) Use of sorptivity to determine field soil hydraulic properties. *Soil Science Society of America Journal* **51**, 1093–1101.

Yasuda H, Berndtsson R, Persson H, Bahri A, Takuma K (2001) Characterizing preferential transport during flood irrigation of a heavy clay soil using the dye Vitasyn Blau. *Geoderma* **100**, 49–66.

Yunusa IAM, Mele PM, Haines PJ (2001) Increased root growth due to 'plant-priming' of subsoil structure. In 'Proceedings of 3rd International Conference on Land Degradation'. Rio de Janeiro. CD-ROM

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