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Change in soil infiltration associated with leys in south-eastern Queensland

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Abstract

Cropping systems in south-eastern Queensland have led to degradation of soil physical properties and loss of infiltration capacity. Pasture leys are favoured for ameliorating soil physical properties because they add organic matter to the soil, create macroporosity, and help to re-aggregate soil. We measured change in hydraulic conductivity with period of ley for 5 major soil groups in south-eastern Queensland (Sodosols, light and heavy Vertosols, Red Ferrosols, and Red Chromosols/Kandosols). We characterised 2 soil layers that are susceptible to degradation when cropped: surface soil exposed to raindrop impact, and the layer immediately below the cultivated layer (0·1–0·2 m deep). A rainfall simulator was used to measure hydraulic conductivity of surface seals under high intensity rainfall. Disc permeameters and pressure plate apparatus were used to measure hydraulic conductivity of the soil matrix in the 0·1–0·2 m layer.

Hydraulic conductivity of both soil layers improved with period of pasture for all but the light-textured Red Chromosols/Kandosols. The estimated period of pasture required to return hydraulic conductivity to pre-cultivated levels ranged from 5 to 40 years, depending on soil type and layer. This is about 2–3 times the period of cultivation that caused the degradation. Grazing reduced the effectiveness of pasture in ameliorating surface sealing on Sodosols. Beneficial effects of a 2·5–4·5 year, ungrazed ley pasture on surface soil persisted for up to 5 years after recultivation, but were lost in the 0·1–0·2 m layer within 1 year. These rates of decline in hydraulic conductivity were faster than observed on previously uncultivated soils.

The APSIM model was used to predict the effect of measured improvements in soil hydraulic conductivity on average runoff from summer fallows. The model predicted that most benefits for fallow runoff would be achieved with 2–5 years of ley. The surface seal was the major limitation to infiltration when the soil was bare. Subsurface soil layers limited infiltration if surface sealing was reduced by ameliorating soil properties or maintaining cover on the soil surface. The results suggest that despite amelioration of soil structure with leys, appropriate tillage and cover management is still required to maintain high infiltration rates.

Additional keywords: soil structure, hydraulic conductivity, pasture leys, cropping, tillage, rainfall simulators, disc permeameters, moisture characteristic.

Introduction

Cropping to summer and winter grain and forage crops in south-eastern Queensland frequently involves tillage to control weeds and prepare soil for planting. These cropping practices have been found to degrade soil structural and chemical properties (Dalal and Mayer 1986; Cook *et al.* 1992; Bridge and

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Bell 1994; Connolly *et al.* 1997). Connolly *et al.* (1997) found that surface sealing increased with period of cultivation for a range of soils in south-eastern Queensland. Hydraulic conductivity, macroporosity, and water-holding capacity of the layer immediately below the cultivated layer (0·1–0·2 m deep) decreased in most soils. Steady infiltration rate, measured *in situ* with a rainfall simulator, also declined. Much of the change in soil hydraulic properties occurred within 10 years of first being tilled. After continuous tillage for 25–70 years, many of these soils now have significantly poorer infiltration than when first cropped.

Reduced infiltration is a problem for crop production in southern Queensland, where grain yield is commonly limited by water stress, rainfall is highly variable, and runoff may exceed 10% of rainfall (Freebairn *et al.* 1986*a*). Reduced infiltration leads to less water stored in the soil for later use by crops and often reduces crop yields. Runoff associated with low infiltration is also the driving force for soil erosion, a problem for sloping lands (Freebairn *et al.* 1986*b*; Radford *et al.* 1992).

Leys, in general, are useful for restoring and maintaining the chemical and physical properties of cultivated soils. Studies by Andrew (1965), Clarke *et al.* (1967), Bridge *et al.* (1983), and Douglas *et al.* (1992) found significant improvements in soil aggregation, aggregate stability, bulk density, and infiltration characteristics of soils under pasture, compared with their condition when tilled conventionally. Bridge and Bell (1994) recommended vigorous grass pasture to restore macropores and organic carbon to degraded Red Ferrosol soils in the south Burnett, Queensland, a recommendation supported by Cotching (1995). Pasture has been widely found to lead to increased soil organic matter (Bathke *et al.* 1992; Skjemstad *et al.* 1994; Bell *et al.* 1997) and populations of soil fauna (Marinissen and Bok 1988; Lee and Foster 1991; Radford *et al.* 1995). The activities of soil fauna, particularly earthworms, are highly beneficial for soil structure and infiltration (Lee and Foster 1991; Bell *et al.* 1997). Vigorously transpiring annual crops (e.g. mungbean, *Vigna radiata*) are commonly used to encourage cracking and 'self repair' in soils which shrink–swell (Pillai-McGarry and McGarry 1996). Legume leys or green manure crops are also often used to improve soil fertility (Dalal *et al.* 1991).

Despite the obvious benefits of leys for soil structure and infiltration, the introduction of a ley into an established cropping system can be a difficult decision for farmers. Variability in weather and commodity prices alter the priority that land managers place on the relative benefits of a ley. In addition, farmers cannot be sure of an economic benefit arising from a ley for their particular soil/climate combination. Measured indices of soil structure are difficult to interpret in terms of quantitative responses in the production system, i.e. runoff, soil water storage, and crop production. This is where models have a role in integrating soil properties, weather, and management.

The aim of this paper is to evaluate how effectively leys ameliorate the infiltration capacity of soils in south-eastern Queensland and how long the benefits of a ley persist once conventional cultivation recommences. We use an integrated measuring–modelling approach. Measurements of hydraulic conductivity are used to characterise change in infiltration capacity with leys. We then use these experimental data to choose parameters for a soil–crop model and use the model to estimate how effectively leys reduce runoff in this subsequent cultivation period.

Experimental methods

Experimental sites

Twenty sites with varying cropping histories were selected in south-eastern Queensland (Fig. 1). Soils at the sites were grouped according to the Australian Soil Classification system (Isbell 1996). Vertosols were further split based on clay content. The groupings were: Sodosols, light Vertosols (35–55% clay), heavy Vertosols (55–80% clay), Red Ferrosols, and Red Chromosols/Kandosols. Some properties for each soil group are listed in Tables 1 and 2.

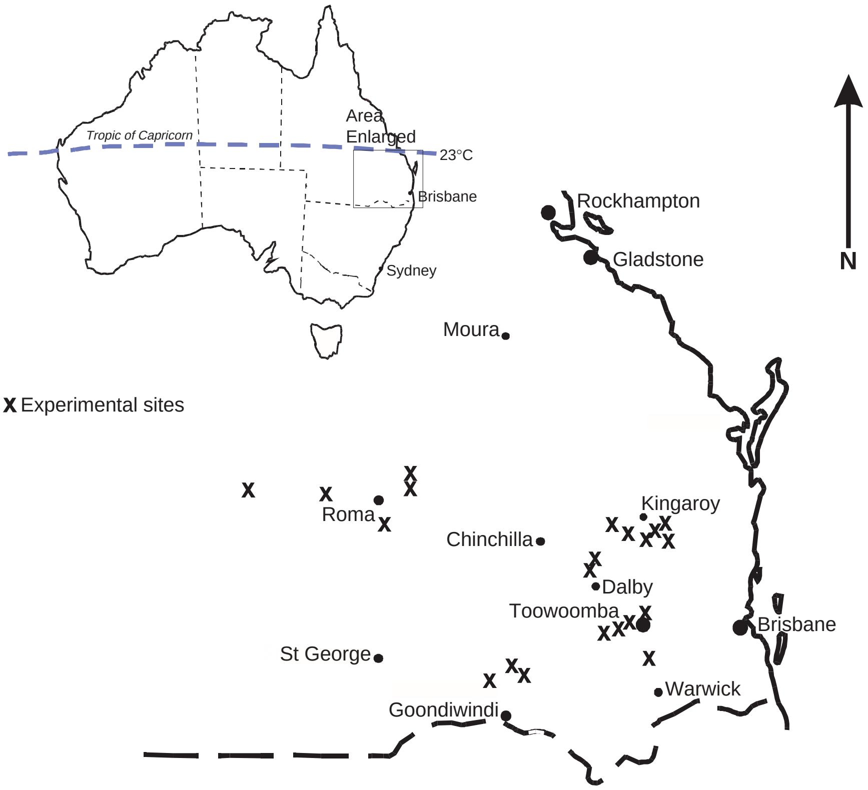

Fig. 1. Location of the experimental sites.

Each site had been cropped to summer and winter grain and fodder crops for at least 20 years prior to establishment of a ley. Pastures were a mixture of improved and native pastures containing *Cenchrus ciliaris* (buffel grass), *Bothriochloa* cv. (blue grass), *Dicanthium sericeum* (Queensland blue grass), *Chloris gayana* (rhodes grass), *Pennisetum clandestinum* (kikuyu), or *Setaria porphyrantha* (purple pigeon grass). Leys on all but one site were grazed. Stocking rates were not controlled, and at times pastures suffered considerable trampling and vegetation denudation from sheep and cattle.

Hydraulic conductivity and the moisture characteristic were measured prior to pasture establishment, and after varying periods of pasture and recultivation. Measurements were made annually for 6 years, usually between May and August.

Grazing was excluded from one site (a Sodosol, Fairlands North) to evaluate the effect of grazing on soil properties. The site had been cultivated and cropped to summer and winter grain and forage crops for 24 years prior to the exclusion of stock and establishment of pasture. After 2·5, 3·5, and 4·5 years of ley pasture, plots in the pasture were recultivated and cropped. Conventional cultivation was used, i.e. tillage with chisel implements 2–4 times during a summer fallow. Wheat (*Triticum aestivum* L. cv. Cunningham) was grown.

Table 1. Soil groups used and a summary of each group's general characteristics
PAWC, plant-available water capacity

Soil group	Soil type		No. of sites	General soil characteristics
	Australian classification[A]	Soil taxonomy[B]		
Sodosols	Sodosols	Alfisols, Aridosols	3	Soils with a strong texture contrast between A and B horizons and a sodic B horizon. Tendency to weakly hardset but can form small shrinkage cracks when cultivation mixes surface soil with higher clay content subsurface soil. Common in more marginal cropping areas of south-eastern Queensland and often cropped to grain and fodder crops. Relatively low PAWC
Light Vertosols	Brown and Grey Vertosols	Vertisols	3	Clay soils with shrink–swell properties that exhibit strong cracking when dry and at depth have slickensides and/or lenticular structural aggregates; 35–55% clay. Productive soils used for grain and fodder crops. Medium PAWC
Heavy Vertosols	Black and Grey Vertosols	Vertisols	5	As for light Vertosols but more than 55% clay. Highly productive soils cropped with grain and fodder crops. High PAWC
Red Ferrosols	Red Ferrosols	Oxisols, Alfisols	7	Fine, friable, and stable structure and high infiltration capacity when uncropped; tend to degrade to a massive structure and low infiltration when continuously cropped. Widely used for peanut, sugarcane, and horticultural crops. Non-shrink–swell. Medium PAWC
Red Chromosols/ Kandosols	Red Chromosols, Red Kandosols	Alfisols, Aridosols	2	Massive structure and strongly hardsetting. Cropped with grain and fodder crops. Medium PAWC

[A] Isbell (1996).
[B] Soil Survey Staff (1975).

Table 2. Mean values (%) of some properties of the five soil groups (0–0·1 and 0·1–0·2 m deep, soil cultivated for <3 years)

ESP, exchangeable sodium percentage

Soil group	Sand	Silt	Clay	Organic C	ESP
		0–0·1 m			
Sodosols	58	11	32	1·7	3
Light Vertosols	37	16	47	2·1	6
Heavy Vertosols	20	17	63	2·0	2
Red Ferrosols	24	15	62	4·0	1
Red Chromosols/Kandosols	69	15	18	1·3	3
		0·1–0·2 m			
Sodosols	47	10	37	1·2	7
Light Vertosols	32	14	53	1·6	9
Heavy Vertosols	15	16	68	1·8	3
Red Ferrosols	28	12	60	2·0	1
Red Chromosols/Kandosols	60	13	28	0·6	5

Measurement of hydraulic conductivity

Hydraulic conductivity of the surface seal layer was measured using a rainfall simulator and tensiometers in the laboratory. Details of this method are given by Freebairn *et al.* (1991) and Connolly *et al.* (1997) and only a summary is given here. Disturbed, air-dry soil was used and the soil surface was bare of any vegetative cover. An oscillating boom rainfall simulator based on the design of Bubenzer and Meyer (1965) was used to apply rainfall to 0·3-m-square trays of soil. Rainfall was applied at 100 mm/h for 30 min to 3 replicate plots. Depth of soil was sufficient to ensure that the depth of wetting did not exceed soil depth. Infiltration rate and subseal matric potential were measured during rainfall. Hydraulic conductivity of the surface seal was calculated after surface ponding, by Darcy's law (Darcy 1856). Hydraulic conductivity measured after 30 min of rainfall, K_{seal}, is presented here.

Saturated hydraulic conductivity of the soil matrix at 0·1–0·2 m depth, K_{matrix}, was derived from unsaturated hydraulic conductivity measured with disc permeameters (Perroux and White 1988; Reynolds and Elrich 1991) and the desorption moisture characteristic measured with pressure plate apparatus (McIntyre 1974). Details of this method are given by Connolly *et al.* (1997). Hydraulic conductivity measured with disc permeameters (K) includes contributions of both the soil matrix and macropores (Connolly *et al.* 1997). K_{matrix} can be separated from the macropore component, K_{mpore}, with $K_{\mathrm{mpore}} = K - K_{\mathrm{matrix}}$. K_{matrix} can be calculated at any water content, θ, using Campbell's function (Campbell 1974). We calculate K_{matrix} at saturation, θ_{s}.

To separate matrix from macropore hydraulic conductivity, a scaling conductivity, K_{ψ}, must be measured at a matric potential low enough to exclude the contribution of macropores to infiltration. Disc permeameter measurements with a supply potential of −1 kPa were used to estimate K_{ψ}, corresponding to an average pore diameter of approximately 0·3 mm. Pores >0·3 mm were arbitrarily defined as macropores.

Statistical analysis

A linear regression was used to describe change in K_{seal} and K_{matrix} with period of pasture:

$$K_{\mathrm{seal}},\ K_{\mathrm{matrix}} = mt + b \tag{1}$$

where t is period of pasture and m is the slope of the regression. Correlation between predictions with Eqn 1 and the measured data were significant at $P < 0{\cdot}05$. Eqn 1 was used to predict the period of pasture required to restore K_{seal} and K_{matrix} to values similar to those of uncultivated soil. Values of K_{seal} and K_{matrix} for uncultivated soil were taken from Connolly *et al.* (1997).

Changes in K_{seal} and K_{matrix} with years of cultivation after a ley were described by Eqn 2 (from Connolly *et al*. 1997):

$$K_{\mathrm{seal}},\ K_{matrix}(t) = A + BR^t \tag{2}$$

where A, B, and R are fitted parameters and t is years of cultivation. The time required for K_{seal} and K_{matrix} to decrease to half their initial value (half life) was determined using Eqn 2.

Simulation of runoff

The APSIM model (McCown *et al*. 1996) was used to predict fallow runoff in a wheat–summer fallow monoculture. APSIM is a cropping system model and represents the complete water balance (i.e. rainfall, runoff, soil water storage, crop water use, evaporation, and drainage below the root-zone). APSIM operates on a daily time step. We used the SWIM (Verberg *et al*. 1996) with SURFACE submodels in APSIM to represent infiltration and runoff at a point. The ability of APSIM and SWIM to simulate the impact of soil properties, weather, and management on runoff has been confirmed in other studies (e.g. Bristow *et al*. 1994; Verberg 1996).

In APSIM, SWIM operates on a time step <1 day, but outputs runoff daily. SWIM and SURFACE represent the development of a surface seal associated with variable rainfall intensity, cover, and roughness and predict infiltration and runoff as influenced by a surface seal and permeability of subsurface soil layers. The other modules used in APSIM were RESIDUE2, SOILN2, and NWHEAT.

APSIM was used to simulate fallow runoff for the following 3 fallow management strategies.

(*i*) Ley then conventional tillage: cropping with 'conventional tillage' after 0–15 years of ley. Conventional tillage involved burning stubble after harvest then tillage with disc, chisel, and scarifier implements 2–5 times over a fallow to control weeds and prepare a seedbed. The soil surface was bare for most of the summer fallow. Soil hydraulic conductivity was improved with period of pasture (see relationships in Table 4). Hydraulic conductivity was not run-down with period of cropping after the ley.

(*ii*) No ley, conventional tillage: hydraulic conductivity was assumed to remain constant.

(*iii*) No ley, stubble mulch: stubble was not burnt. Tillage regime was similar to conventional tillage but maintained stubble cover on the soil surface. Surface sealing was assumed to be reduced compared with conventional tillage because the cover increased minimal conductance and reduced the rate of seal formation.

Soil physical conditions were held constant for each simulation. A separate simulation was made for each period of ley (2–15 years) and for the 2 no-ley strategies. The no-ley and 0 years ley strategies assumed that the soil had been cropped continuously for 50 years. Parameters describing the soils are given in Table 3. Parameters describing surface sealing (conductance and shape factor) were derived from measured hydraulic conductivity of the surface seal (Verberg *et al*. 1996). The smoothed Brooks–Corey function (Hutson and Cass 1987) was used to represent moisture characteristic and $K(\psi)$ relationships. Contributions of macropores to water-holding properties and hydraulic conductivity were represented with the moisture characteristic and $K(\psi)$ relationship. There were insufficient data, though, to find parameters for the model to represent the effects of livestock trampling on macroporosity.

Simulations were made with 100-year weather records and runoff was averaged for the fallow periods. Tillage and planting dates were calculated automatically in the model, depending on rainfall in the prior 10–20 days and soil water available to the plant. The model determined harvest date. Fertiliser was added at a rate so as, on average, not to limit crop growth.

The model is used to give an indication of the relative benefits of leys. The model, though, is only a representation of the physical system. The simulated rate of reduction in runoff with period of pasture is influenced by assumptions made with the model. In addition, hydraulic conductivity was not run-down with period of cropping after the ley, so results represent the maximum possible benefit likely to arise from the ley.

Table 3. Summary of APSIM parameter values used in the simulation study

PAWC, plant-available water capacity; K_{s}, saturated hydraulic conductivity of the soil matrix; K_{m}, saturated hydraulic conductivity of macropores; θ_{s}, saturated water content; ψ_{e}, air entry matric potential; b, a constant

Soil group	Sodosols		Light Vertosols	Heavy Vertosols	Red Ferrosols	Red Chromosols/ Kandosols
	Grazed	Ungrazed				
Weather record	Roma	Roma	Goondiwindi	Dalby	Kingaroy	Goondiwindi
PAWC (mm)	100	100	132	200	106	157
Surface seal						
Initial conductance (/h)	10	10	10	15	15	10
Minimal conductance (/h)	0·033–3·2	0·033–0·78	0·002–2·84	0·002–2·40	0·0128–2·30	0·01
Shape factor (m^2/J)	0·009	0·009	0·009	0·008	0·008	0·009
0·1–0·2 m layer						
θ_{s} (v/v)	0·45	0·45	0·50	0·57	0·51	0·42
ψ_{e} (cm)	−25	−25	−50	−300	−10	−20
b	8	8	18	16	10	9
K_{s} (mm/h)	0·16–0·82	0·16–0·82	0·04–0·071	0·47–1·13	8·5–22·0	0·38
K_{m} (mm/h)	0·50–8·0	0·50–8·0	0·1–7·6	0·5–8·0	20·0–51·0	1·0

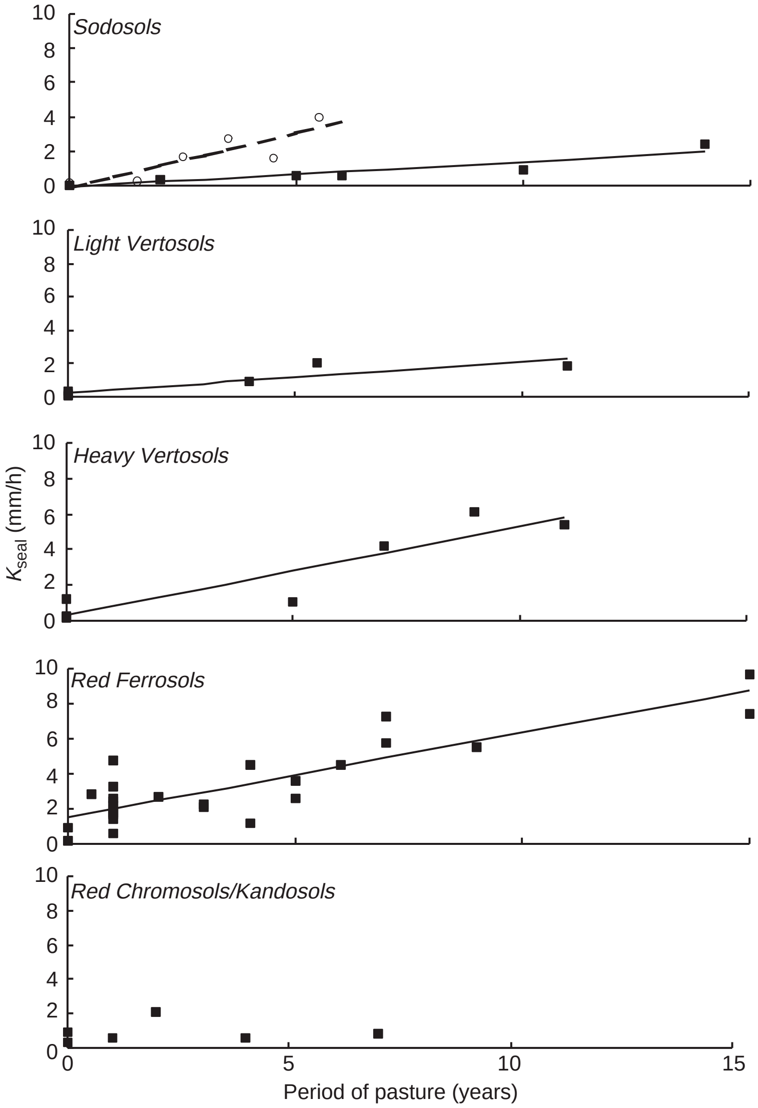

Fig. 2. Change in $K_{\rm seal}$ with period of pasture for the 5 soil groups: ■, ungrazed; ○, grazed; Eqn 1 fitted to grazed (——) and ungrazed (— —) sites.

Results and discussion

Amelioration of surface sealing

$K_{\rm seal}$ increased with period of pasture for all but the Red Chromosols/Kandosols (Fig. 2). The increase in $K_{\rm seal}$ was a reflection of increased aggregate stability under high-energy rainfall, probably due to increased concentrations of the labile fractions of soil organic matter (Bell *et al.* 1998) or greater amounts of plant residues or coarse organic matter occluded within aggregates (Golchin *et al.* 1995). The increase in $K_{\rm seal}$ with period of pasture was adequately described by Eqn 1 ($R^2 > 0{\cdot}74$, Table 4). Comparison of values of m from Eqn 1 for the various soil types suggested that rates of amelioration of grazed Sodosols and light Vertosols were similar. The rate of amelioration of heavy Vertosols was similar to Red Ferrosols, and more than twice the rate of grazed Sodosols and light Vertosols. Red Chromosols/Kandosols showed no response to pasture, a consequence of their hard-setting nature and inherent poor aggregation.

Table 4. Parameters in Eqn 1 describing change in K_{seal} and K_{matrix} with period of pasture

Soil group	m±s.e. (mm/h·year)	b±s.e. (mm/h)	R^2	K for uncultivated soil (mm/h)^A	Time to restore to uncultivated condition (years)
		K_{seal}			
Sodosols, grazed	0·15±0·02	−0·07±0·18	0·87	4·3	30
Sodosols, ungrazed	0·77±0·11	−0·14±0·61	0·77	4·3	7
Light Vertosols	0·18±0·04	0·25±0·19	0·81	7·5	39
Heavy Vertosols	0·50±0·07	0·29±0·40	0·88	6·8	19
Red Ferrosols	0·48±0·06	1·51±0·32	0·74	20·8	40
Red Chromosols	n.s.	n.s.	n.s.	2·8	n.s.
		K_{matrix}			
Sodosols, grazed and ungrazed	37·5±5·4	25·8±16·9	0·80	200	5
Light Vertosols	16·0±4·1	38·3±21·6	0·66	408	23
Heavy Vertosols	26·1±5·0	94·4±62·5	0·85	1050	37
Red Ferrosols	18·1±3·7	108·8±17·5	0·75	346	13
Red Chromosols	n.s.	n.s.	n.s.	128	n.s.

n.s., no significant relationship.

[A] From Connolly *et al.* (1997).

Grazing reduced the rate of amelioration of surface sealing on Sodosols (Fig. 2). This was probably caused by a combination of foot track trampling, changed plant growth, and changes in the dynamics of plant residue decomposition and incorporation of organic matter into the soil. Negative effects of foot track trampling on infiltration (e.g. Mulholland and Fullen 1991; Mead and Chan 1992; Bell *et al.* 1997) and soil organic matter accumulation (Murphy and Harte 1992) have been observed. The effects of changed plant growth and residue decomposition processes on infiltration, though, are not well understood and warrant further study.

Eqn 1 was used to predict the duration of pasture required to restore K_{seal} to values similar to those found in uncultivated soil (Table 4). This simple model assumes that the rate of amelioration is constant with increasing duration of pasture. Using Eqn 1 in this way does, however, illustrate the relative gains required for each soil group to restore soil physical condition to that found in uncultivated soil. The period of grazed pasture required to restore K_{seal} to uncultivated levels varied from 18 to 40 years. This is about 2–3 times the period of cultivation that caused the degradation (Connolly *et al.* 1997); much of the loss of structure associated with cropping occurred in the first 10 years of cultivation.

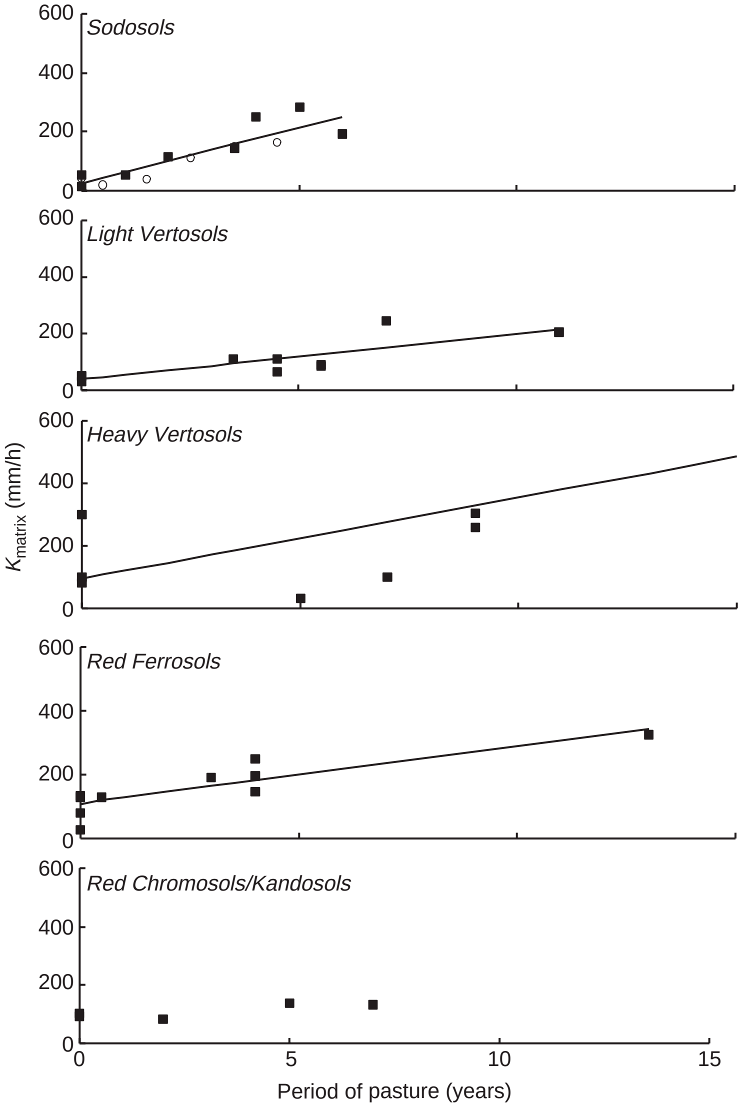

Fig. 3. Change in K_{matrix} of the $0 \cdot 1$–$0 \cdot 2$ m soil layer with period of pasture for the 5 soil groups. For the heavy Vertosols, 2 data points for 30 years of pasture are not shown: ■, ungrazed; ○, grazed; ——, Eqn 1 fitted to grazed and ungrazed sites.

Amelioration of matrix hydraulic conductivity of the 0·1–0·2 m layer

Infiltration capacity of the $0 \cdot 1$–$0 \cdot 2$ m soil layer was described with K_{matrix}–saturated hydraulic conductivity of the soil matrix. K_{matrix} excludes the contribution of larger macropores and cracks. K_{matrix} increased with period of pasture for most soils (Fig. 3) and the rate of change in K_{matrix} could be described by Eqn 1 ($R^2 > 0 \cdot 66$, Table 4). The response of this soil layer to the ley was quite different to the surface seal. For the $0 \cdot 1$–$0 \cdot 2$ m layer, Sodosols responded most quickly to the ley, and Red Ferrosols and light Vertosols were the slowest. Grazing did not influence the rate of increase in K_{matrix} (for Sodosols), at least for periods of pasture <6 years (Fig. 3). Measured data for the Red Chromosols/Kandosols represented a small sample and Eqn 1 was not significantly correlated.

Eqn 1 was used to predict the time required for K_{matrix} to increase to pre-cultivation levels (Table 4). The predicted time required to restore K_{matrix} to uncultivated values varied from 5 years for Sodosols to 23–37 years for the Vertosols. This is a somewhat surprising result, as although Vertosols exhibit shrink–swell characteristics and have a so-called capacity to 'self repair' (Beckman and Thompson 1960), they took longer than the Sodosols to ameliorate. It is not surprising that the Red Ferrosols did not respond quickly; they have little shrink–swell capacity and amelioration is mostly the result of soil faunal activity (Bell *et al.* 1997). It is not apparent why the Sodosols, also with little shrink–swell capacity, had the quickest rate of amelioration.

Persistence of ley-induced amelioration on a Sodosol

One Sodosol site was re-cropped, using conventional fallow management, after varying periods of ley (Fig. 4*a*). From Eqn 2, 50% of the gain in K_{seal} was lost in about 6 months to 1 year after re-cropping, depending on the period of ley. At this rate of decline, K_{seal} would return to pre-ley levels in 4–5 years. This rate of decline was faster than for previously uncultivated soils (Connolly *et al.* 1997).

K_{matrix} decreased rapidly in the first half-year of cropping after the ley to a value no greater than before the ley (Fig. 4*b*). Duration of the ley, although increasing K_{matrix} prior to re-cropping, did not appear to change this rate of decline once cropping recommenced.

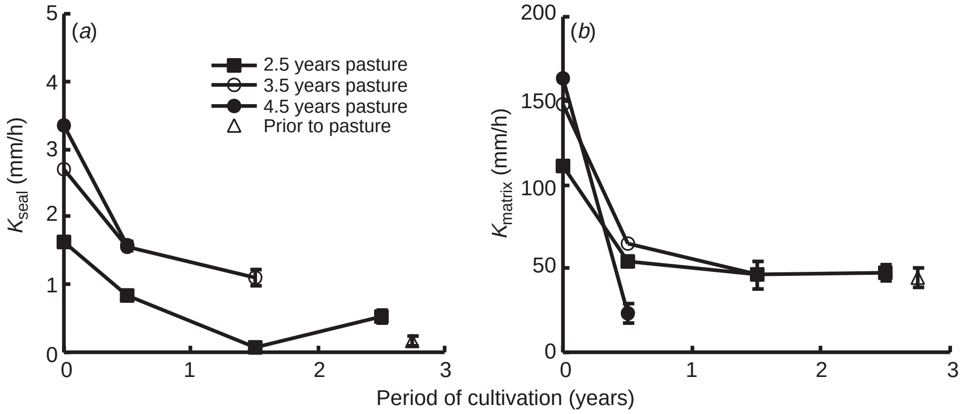

Fig. 4. Change in (*a*) K_{seal} and (*b*) K_{matrix} with years of cropping after a ley pasture rotation. The soil is a Sodosol and was cropped for 24 years prior to a ley pasture of 2·5, 3·5, and 4·5 years. Error bars are ±1 s.e.

Such rapid rates of decline in hydraulic conductivity, compared with previously uncultivated soil, suggest that improvements in soil structure brought about by leys are relatively fragile. Alternatives to intensive cultivation, such as direct drilling or zero-tillage, may reduce the rate of decline because these systems reduce wheel-track compaction and soil disruption. Frequent rotations, perhaps with green manure or other crops that increase soil organic matter and plant residue levels, may also usefully benefit infiltration (Bathke *et al.* 1992; Bell *et al.* 1997).

Simulated effect of ley-induced amelioration on summer fallow runoff

The simulated effect of period of ley on average fallow runoff after re-cropping is shown in Fig. 5. Conventional fallow management was simulated so the soil surface was mostly bare. Note that hydraulic conductivity was not run-down with period of cropping after the ley. Simulated fallow runoff was reduced on 4 of the 5 soils as a result of increased hydraulic conductivity of the surface seal and the 0·1–0·2 m deep soil layer. Much of this reduction in runoff was achieved with only 2 years of ley because the simulated results were very sensitive to change in hydraulic conductivity of the surface seal when the hydraulic conductivity was already low. Such a quick reduction in runoff is favourable for land managers wishing to incorporate regular leys into existing cropping systems. However, leys longer than 2 years may be required if favourable infiltration is to be maintained during the subsequent cropping phase.

For periods of ley >5 years, soil layers deeper in the profile represented the major limitations to fallow runoff. Deeper layers are less easily ameliorated with a ley than layers close to the surface (Bell *et al.* 1997), so change in runoff for these longer periods of ley were less noticeable.

No consistent effect of period of ley on surface sealing or subsurface hydraulic conductivity was evident in measured data for the Red Chromosols/Kandosols (Figs 2 and 3, respectively). Accordingly, simulations suggested that leys were not an effective strategy for reducing runoff with these soils.

Fallow runoff for the Vertosols was reduced by a greater proportion than for the Sodosols. For the heavy Vertosols this was partly because subsurface soil layers were more permeable than the Sodosols, causing less restriction to infiltration once surface sealing was reduced. Light and heavy Vertosols, however, were also more responsive to the ley than the Sodosols because of their greater water storage capacity (PAWC in Table 3). Reduction in runoff with period of ley on the Red Ferrosols was mostly a result of reduced surface sealing.

The simulated impact of grazing on the effectiveness of a ley in reducing runoff from a Sodosol was not substantial (Fig. 5), even though grazing was shown to reduce the rate of amelioration of the surface seal (Fig. 2). This reflects the sensitivity of the model to small changes in hydraulic conductivity of the seal when hydraulic conductivity is low. In practice, grazing may have a larger effect on runoff, because we did not have sufficient data to parameterise the model to represent the effects of trampling on macroporosity in the surface (0–0·2 m deep) soil layers.

In the absence of a ley, stubble mulching was effective in reducing runoff compared with conventional tillage because stubble mulch maintained more cover on the soil surface (Fig. 6). Runoff for a 5-year ley followed by conventional tillage (i.e. bare) was generally reduced by a similar amount to stubble mulch with no ley. Stubble mulching is therefore a representation of the immediate benefit obtainable from maintenance of surface cover, whereas the ley represents the benefit that can be achieved through amelioration of soil physical properties.

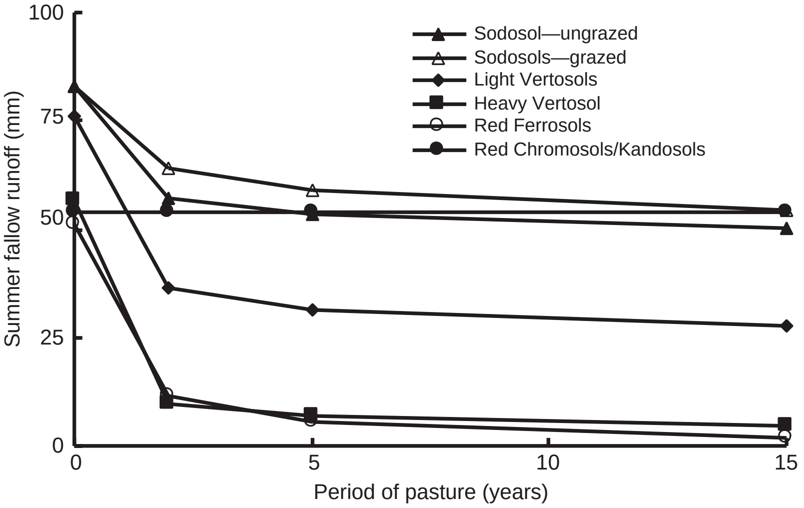

Fig. 5. Simulated effect of period of pasture on average fallow runoff from a subsequent wheat–summer fallow monoculture. Runoff was simulated with the APSIM model. Fallows were managed with conventional tillage.

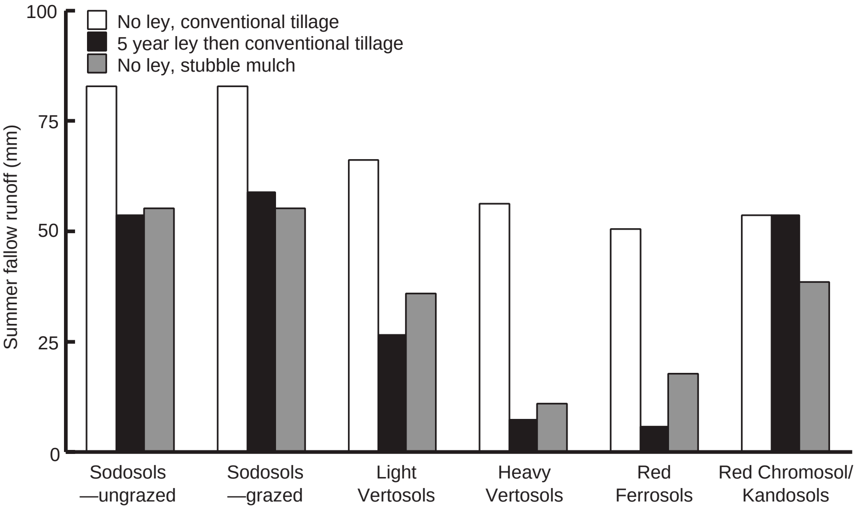

Fig. 6. Simulated fallow runoff for conventional tillage and stubble mulch with no ley, compared with a 5-year ley followed by conventional tillage.

Conclusions

Leys led to improved hydraulic conductivity of the surface seal (K_{seal}) and the $0 \cdot 1$–$0 \cdot 2$ m deep soil layer (K_{matrix}) in all but the Red Chromosol/Kandosol soils. The rate of improvement in hydraulic conductivity with period of pasture varied with soil layer, and was affected by grazing and soil type. The rate of improvement, however, was relatively slow compared with the rate of change in hydraulic conductivity when the soils were first cropped.

The improvement in hydraulic conductivity was fragile. Pasture effects on K_{seal} persisted into the subsequent cropping phrase, but effects on K_{matrix} did not. Alternatives to intense tillage need to be considered to minimise the rate of degradation in hydraulic conductivity once the soil is re-cropped after the ley.

When hydraulic conductivity was increased as the result of a ley, simulated runoff was reduced in summer fallows after the ley was re-cropped, even if the soil was bare. On bare soils, the surface seal was the most important restriction to infiltration. In general, subsurface soil layers were only a restriction to infiltration when surface sealing was reduced, either by amelioration of soil properties with leys, or by maintenance of cover on the soil surface.

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