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Effects of rundown in soil hydraulic condition on crop productivity in south-eastern Queensland—a simulation study

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Abstract

Declining soil organic matter levels because of cropping have been shown to reduce crop growth and yield, but the effects of changing infiltration and soil hydraulic properties on crop productivity have not been widely evaluated. Cropping systems in south-eastern Queensland have, in the past, involved intense tillage, trafficking with heavy machinery, and changed organic matter cycling, affecting soil aggregation, permeability, water-holding characteristics, and organic matter. The aim of this paper is to determine how important infiltration and soil hydraulic condition has been to the water balance, crop growth, and yield in the past, and may be in the future if management is not changed. Change in physical and chemical condition of the 5 most commonly cropped soils in south-east Queensland (Sodosols, Vertosols with ≤55% clay, Vertosols with >55% clay, Red Ferrosols and Red Chromosols/Kandosols) was measured over 0–70 years of cropping and estimated up to 200 years. The APSIM model was used to predict effects of changing soil condition in a rain-fed, fertilised, wheat-summer fallow cropping system with intense tillage. Decline in infiltration, restricted internal redistribution of water, and increased evaporation reduced water supply to the crop, causing simulated yield to decline by 29, 38, 25, 17, and 13% for the 5 soils, respectively, after 50 years of cropping. Gross margin declined at a faster rate, falling by 36, 50, 40, 20, and 21%, respectively after 50 years because of increasing fertiliser requirement to compensate for declining soil fertility. Crop productivity on most soils continued to steadily decline as period of cropping increased to 200 years. To arrest or reverse this downward trend, it is likely that substantial changes to current cropping systems will be needed, including reducing tillage and trafficking, and improving organic matter levels.

Additional keywords: infiltration, soil structure, cropping systems, sustainability, wheat, models.

Introduction

Traditionally, cropping systems in south-eastern Queensland use tillage for weed control, to prepare a seedbed, and to improve soil infiltration and aeration (Freebairn *et al.* 1986). Tillage is typically intense, breaks up the soil surface, reorganises soil aggregates and porosity, and disturbs macroporosity and beneficial soil fauna. Heavy machinery is frequently used and, at times, operated when the soil is wet and readily compressible (McGarry 1990).

As a result of these intense tillage regimes, soil condition has been degraded. Soils now tend to have reduced aggregate stability (Loch 1994) and increased tendency to crust (Connolly *et al.* 1997). Soil layers immediately below the cultivated layer (0.1–0.6 m deep) often become compacted, resulting in reduced porosity and hydraulic conductivity, and changed water-holding properties (Gupta *et al.* 1989; McGarry 1990; Connolly *et al.* 1997). Tillage often reduces the amount of vegetative cover on the soil surface, and subsequent raindrop impact on the bare, tilled soil causes aggregate breakdown and crusting (Bridge

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and Bell 1994; Loch 1994). Soil organic matter and fertility also decline with cropping, a result of a changed organic matter balance and disruption of soil aggregates (Clarke and Marshall 1937; Dalal and Mayer 1986*a*).

While degradation in the soil resource is recognised as a serious issue (e.g. GRDC 1999), there are few studies in south-eastern Queensland that relate change in infiltration capacity of soils to crop productivity. Various studies have been undertaken to evaluate interactions between soils, crop productivity, and the water balance (e.g. Radford *et al.* 1992; Thomas *et al.* 1995*a*, 1995*b*) but these rarely consider temporal change in soil condition. There have been no studies that attempt to predict change in infiltration and soil productivity into the future.

The aim of this paper is to evaluate effects of measured rundown in soil properties to date on infiltration and the water balance, and yield and gross margin, and to estimate effects of continued intense tillage into the future.

We used the APSIM model (McCown *et al.* 1996), configured with the SWIM and SURFACE modules, to simulate the 5 soils in south-eastern Queensland characterised by Connolly *et al.* (1997). The model was parameterised using soil properties (hydraulic conductivity, water-holding capacity, organic carbon, and mineralisable N) measured on soils cropped for up to 70 years. Based on observed rates of rundown and assuming continued intense tillage, we estimated change in soil properties for periods of cropping up to 200 years, and simulated the resulting impact on infiltration and the water balance, yield, and gross margin.

Experimental methods

The APSIM model

APSIM (Agricultural Productions Systems Simulator, McCown *et al.* 1996) is a cropping system model that represents the water balance (i.e. rainfall, runoff, soil water storage, crop water use, evaporation, and drainage below the root-zone) and crop growth in detail. APSIM operates on a daily time step at a small field or bay scale.

We used the SWIM (Verburg *et al.* 1996) with SURFACE modules in APSIM to represent processes of infiltration. In APSIM, SWIM operates with a variable time step, often <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 seal disturbance associated with tillage. Infiltration and runoff is a function of the permeability of the surface seal and subsurface soil layers.

The other modules used were: NWHEAT, which simulates wheat growth and yield; RESIDUE2, which decomposes residue over time, accounts for tillage disturbance, and estimates surface cover; and SOILN2, which simulates organic and mineral N dynamics.

Methods for deriving APSIM parameter values

Parameter values describing surface crusting, soil hydraulic conductivity and water-holding capacity, and soil organic carbon and chemical condition were derived from independent point measurements of soil condition. Trend in these parameters with period of cropping was determined by grouping together data from like soils with varying cropping histories. Measurements were made at 40 on-farm sites with period of cropping varying from 0 to 70 years. The sites and experimental methods are described in Connolly *et al.* (1997). Sites were mostly cropped to winter wheat, but summer sorghum or fodder crops were also grown. Crops were normally separated by a fallow period to allow accumulation of soil water. During the fallow, soils were typically tilled 2–8 times for weed control and seedbed preparation.

Hydraulic conductivity of the surface crust, K_{seal}, was derived from data measured with a rainfall simulator and tensiometers in the laboratory using methods described by Freebairn *et al.* (1991) and Connolly *et al.* (1997). 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. Wheat stubble was added to the plots by weight to give varying levels of cover. Weight of stubble varied up to 5000 kg/ha and 100% cover. Cover levels were estimated visually after rainfall. Rainfall was applied at 100 mm/h for 30-min periods to replicate plots. Up to 4 rainfall applications were applied, separated by 24 h. Infiltration rate and subseal matric potential were measured during rainfall. Hydraulic conductivity of the surface seal was calculated after surface ponding with Darcy's Law (Darcy 1856).

Saturated hydraulic conductivity of the soil matrix, K_{matrix}, was derived from unsaturated hydraulic conductivity measured with disc permeameters (Perroux and White 1988; Reynolds and Elrich 1991), saturated hydraulic conductivity measured with single ponded rings (Reynolds and Elrich 1990), and the desorption moisture characteristic measured with pressure plate apparatus (McIntyre 1974). Hydraulic conductivity measured with disc permeameters, K, includes contributions of the soil matrix, K_{matrix}, and macropores, K_{mpore} (Connolly *et al.* 1997): $K_{mpore} = K - K_{matrix}$. K_{matrix} can be calculated at any water content, θ, using Campbell's function (Campbell 1974).

However, disc permeameters consistently over estimated K_{matrix} compared with K derived from ponded rings. When disc permeameter Ks were used in APSIM, runoff was underpredicted relative to measured runoff and drainage over predicted relative to established drainage rates. Our disc permeameter data set was much larger than our ponded ring data set, so we estimated values of K_{matrix} and K_{mpore} suitable for use in APSIM from ponded ring data, and trend with period of cropping from disc permeameter data.

The moisture characteristic, which describes soil water-holding capacity, was measured on undisturbed cores using porous ceramic plates and pressure plate apparatus (McIntyre 1974).

Organic carbon, NO_3-N, and pH were measured using techniques given in Bruce and Rayment (1982) and Rayment and Higginson (1992). Organic carbon was determined using the Walkley and Black method and multiplied by 1.3 to convert to total organic carbon.

Default parameter values describing crop and residue processes were used as far as possible, but some were derived by optimisation against observations made in crop growth studies at 3 detailed studies: Fairlands, 35 km north-east of Roma; Greenmount, 25 km south of Toowoomba; and Billa Billa, 40 km north of Goondiwindi (Table 1). References listed in Table 1 describe these studies in detail. Each site had treatments with fallows prepared using conventional and zero-tillage. Conventional tillage involved 2–8 tillage operations over the summer fallow to control weeds and prepare a seedbed. With zero-tillage, chemicals were used to control weeds and seed was sown directly into stubble from the previous crop. Several varieties of wheat were grown in plots 180 m^2 to 6 ha. Crops were generally grown using natural rainfall, but some at Billa Billa had supplementary irrigation. Varying rates of NO_3-N were applied at sowing. Yield measurements were made from quadrants or with a plot harvester.

The parameters *fbiom* and *finert*, which describe the organic matter pool, were optimised against observations of soil mineralisation at Fairlands, Billa Billa, and Greenmount. The crop parameters *wr*, *plv*, and *pld* were varied until time of anthesis, depth of root water extraction, leaf area index, and yield were adequately represented.

Table 1. Summary of the experimental sites used to test APSIM's accuracy

	Fairlands	Billa Billa	Greenmount
Location	26°29′S, 149°6′E	28°10′S, 150°15′E	27°46′S, 151°55′E
Soil type	Brown Sodosol[A], Sodic Gypsiustert[B]	Sodosol, Red Chromosol[A], Typic Natrustalf[B]	Black Vertosol[A], Udic Haplustert[B]
Experiment described by:	Freebairn *et al.* (1988)	Radford *et al.* (1992), Thomas *et al.* (1995*b*)	Freebairn and Boughton (1981)
Data used for testing APSIM	Soil water, runoff, yield	Soil water, yield	Runoff
Period of cropping (years)	26–30	18–25	26–30
Properties of the 0–0.1 m soil layer:			
Sand (%)	59	60	16
Silt (%)	7	14	21
Clay (%)	35	27	62
Total organic carbon (%)	1.3	1.2	1.90
Exch. sodium percentage	4	1	1

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

Rainfall intensity and weather information measured at Fairlands, Billa Billa, and Greenmount were used for the test simulations and when deriving the crop parameter values. For the long-term simulations, rainfall intensity was disaggregated from daily rainfall records using the model of Connolly *et al.* (1998*b*).

Model testing

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; Verburg 1996). We further tested APSIM's ability to simulate the water balance and response of crop growth to environmental inputs using experimental data from the sites at Fairlands, Greenmount, and Billa Billa (Table 1). Parameter values were determined from data measured at the sites. Model accuracy was tested by comparing measured data with predictions of crop yield, soil water, and annual runoff. Goodness of fit was indicated using coefficient of determination calculated about the line of best fit, R^2, and the line $y = x$, EF (Mayer and Butler 1993), and root mean square error expressed as a percentage of the measured mean, defined as the 'general standard deviation' in Jorgensen *et al.* (1986).

Model application

Five soil groups were simulated, representing the main soils cropped in the cereal growing areas of south-eastern Queensland. The soils were grouped based on the Australian Soil Classification system (Isbell 1996) and Vertosols were further split based on clay content. The groupings were: Sodosols, Light Vertosols (35–55% clay), Heavy Vertosols (56–80% clay), Red Ferrosols, and Red Chromosols/Kandosols. Response of these soil groups to cropping is described in Connolly *et al.* (1997, 1998*a*). Some properties for each soil group are listed in Table 2 and a summary of parameter values used to represent the soil is given in Table 3.

Table 2. The soil groups simulated, mean values of some properties (0–0.1 m deep), and the maximum age of cropping for which experimental data were available

Soil cultivated for <3 years

Soil group	Soil types: Australian Classification[A]	Soil types: Soil Taxonomy order[B]	Sand	Silt (%)	Clay	Total organic C (%)	Exchangeable sodium percentage	Maximum age of cropping (years)
Sodosols	Sodosols	Alfisols, Aridosols	58	11	32	2.2	3	28
Light Vertosols	Brown and Grey Vertosols	Vertisols	37	16	47	2.6	6	30
Heavy Vertosols	Black and Grey Vertosols	Vertisols	20	17	63	3.0	2	70
Red Ferrosols	Red Ferrosols	Oxisols, Alfisols	24	15	62	5.3	1	70
Red Chromosols Kandosols	Red Chromosols, Red Kandosol	Alfisols, Aridosols	69	15	18	1.7	3	20

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

A continuous wheat–summer fallow cropping system was simulated. In the model, fallows were managed using 'intense tillage'; disc, chisel, and scarifier tillage implements were used, with 2–8 tillage operations over the summer fallow (typically November–April). The model automatically decided when and what tillage and sowing operations occurred based on time of year and rainfall. Tillage occurred when rain in the previous 20 days was >35–70 mm and rain in the previous 3 days was <5 mm. Sowing occurred when rain in the previous 20 days was >20–25 mm and <5 mm in the previous 5 days. The wheat genotypes sown varied with location and sowing date. For the Sodosols, light Vertosols, and Red Chromosol/Kandosols, a slow variety was sown between 17 and 30 April, medium between 1 and 31 May, and quick between 1 and 30 June. Planting windows were 30 April–23 May, 24 May–7 June, and 8 June–16 July for the Heavy Vertosols, and 30 April–30 May, 31 May–19 June, and 20 June–17 July for the Red Ferrosols for slow, medium, and quick varieties, respectively.

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

K_{matrix}, saturated hydraulic conductivity of the soil matrix; K_{mpore}, saturated hydraulic conductivity of macropores; θ_s, saturated water content; ψ_e, air entry matric potential; *b*, a constant. The Brooks Corey representation of the moisture characteristic and $K(\theta)$ was used

Parameter	Sodosols	Light Vertosols	Heavy Vertosols	Red Ferrosols	Red Chromosols/ Kandosols
Weather record	Roma	Goondiwindi	Dalby	Kingaroy	Goondiwindi
			Surface seal		
Initial conductance (/h)	10	10	15	15	10
Minimal conductance (/h)	3.2–0.033	2.84–0.002	2.4–0.002	2.3–0.0128	0.01
Shape factor (m^2/J)	0.009	0.009	0.008	0.008	0.009
			0–0.1 m		
θ_s (v/v)	0.60–0.54	0.63	0.70	0.60–0.53	0.50
ψ_e (cm)	–30 to –100	–10 to –30	–15 to –50	–5 to –15	–50
b	3	3–10	10–9	7	3
K_{matrix} (mm/h)	2.0–0.5	2.0	5.0–0.5	5.0–1.0	1.0
K_{mpore} (mm/h)	3.0–0.5	5.0	10.0–0.5	450.0–10.0	1.0
			0.1–0.3 m		
θ_s (v/v)	0.47–0.40	0.52	0.63–0.53	0.57–0.46	0.42
ψ_e (cm)	–20 to –50	–25 to –60	–60	–5 to –10	–20
b	8	15–22	8–13	8–16	9
K_{matrix} (mm/h)	0.50–0.03	0.10–0.002	1.00–0.07	22.0–0.06	0.38
K_{mpore} (mm/h)	2.50–0.10	3.10–0.10	2.50–0.10	51.0–2.1	1.0
			0.3–0.6 m		
θ_s (v/v)	0.44	0.43	0.60–0.53	0.55–0.48	0.40
ψ_e (cm)	–40	–35	–300	–10	–20
b	8	17	8–9	12	8
K_{matrix} (mm/h)	0.30	0.02	0.72–0.19	1.50–0.04	0.12
K_{mpore} (mm/h)	0.50	0.10	3.00–0.25	51.0–2.1	0.10
			0.6–0.9 m		
θ_s (v/v)	0.40	0.45	0.53	0.48	0.38
ψ_e (cm)	–40	–32	–300	–40	–20
b	12	18	10	15	12
K_{matrix} (mm/h)	0.37	0.04	0.50	0.50	0.11
K_{mpore} (mm/h)	0.50	0.50	1.00	25.00	0.10
			0.9–1.2 m		
θ_s (v/v)	0.40	0.43	0.52	0.46	0.37
ψ_e (cm)	–40	–24	–150	–60	–20
b	13	25	10	18	12
K_{matrix} (mm/h)	0.37	0.04	0.50	0.50	0.08
K_{mpore} (mm/h)	0.50	0.50	0.00	25.0	0.10
			1.2–1.5 m		
θ_s (v/v)	0.40	0.43	0.50	0.43	0.36
ψ_e (cm)	–40	–24	–150	–100	–20
b	10	25	12	20	12
K_{matrix} (mm/h)	0.37	0.04	0.50	0.50	0.05
K_{mpore} (mm/h)	0.50	0.50	0.00	25.00	0.10

Table 4. Summary of parameter values used to calculate gross margin for the soil groups

Parameter	Sodosols	Light Vertosols	Heavy Vertosols	Red Ferrosols	Red Chromosols/ Kandosols
Average production costs, excluding fertiliser (AU$/ha)	47	48	53	63	64
Average number of tillages (per/year)	3.2	3.2	3.5	5.8	5.9
Average number of sprays (per/year)	0.8	0.8	1.0	0.9	0.9
Average number of sowings (% of years)	84	84	96	88	93
Minimum NO_3-N at sowing (kg/ha)	60	80	120	80	80

A long-term weather record (about 100 years) most common to the soils in each group was used (Table 3). Parameter values describing soil condition, i.e. crust conductivity, the moisture characteristic, $K(\theta)$ relationship, organic carbon, and parameters controlling N mineralisation, were input directly into the model and held constant during a simulation by resetting each year at harvest. Soil condition corresponding to 0, 5, 10, 50, 100, and 200 years of cropping was simulated. NO_3-N at sowing was maintained at a predefined minimum level (Table 4). If simulated NO_3-N was below this level at sowing, NO_3-N was reset and the deficit was considered to have been added as fertiliser.

Change in soil condition with period of cropping was determined based on the experimental data set (0–70 years of cropping) and by extrapolation for longer periods. Parameter values were derived from data at the 40 on-farm sites (Connolly *et al.* 1997), Fairlands, Greenmount, and Billa Billa, and using functions in Dalal and Mayer (1986*b*). Experimental records of changing soil physical condition were relatively short for the Sodosols, Red Chromosols/Kandosols, and Light Vertosols compared with the other soils, so our estimates of future change may be less certain. There is, of course, no way of knowing precisely how any of the soils will react in the future, so the analysis of results should be considered based on the assumption that the assumed changes with period of cropping do occur.

The experimental data indicated that tendency to form surface seals increased as period of cropping increased, with rapid changes in K_{seal} in the first 10–50 years of cropping (Fig. 1). We extrapolated beyond the experimental record assuming K_{seal} would continue to steadily decline because coarse organic matter levels in the near surface layers were likely to continue to decline with the continued intense tillage regime.

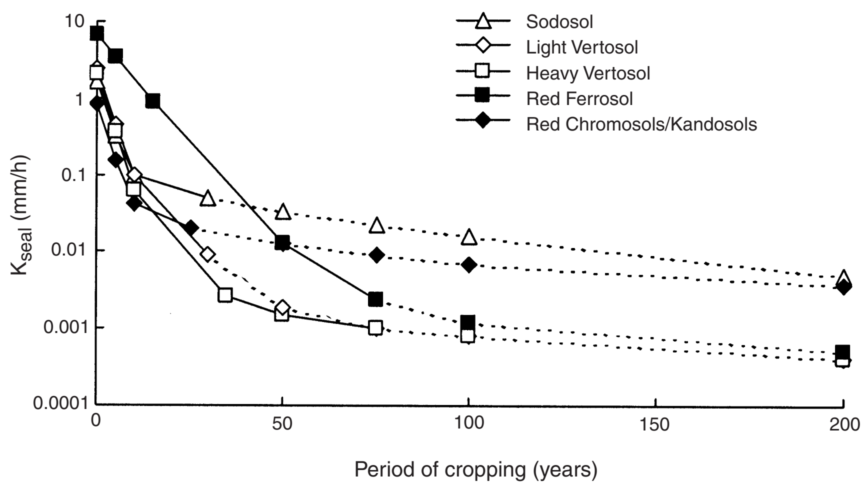

Fig. 1. Change in hydraulic conductivity of the surface seal (K_{seal}) with period of cropping, as input to the model. Solid lines indicate K_{seal} is based on experimental data; dashed lines are estimated.

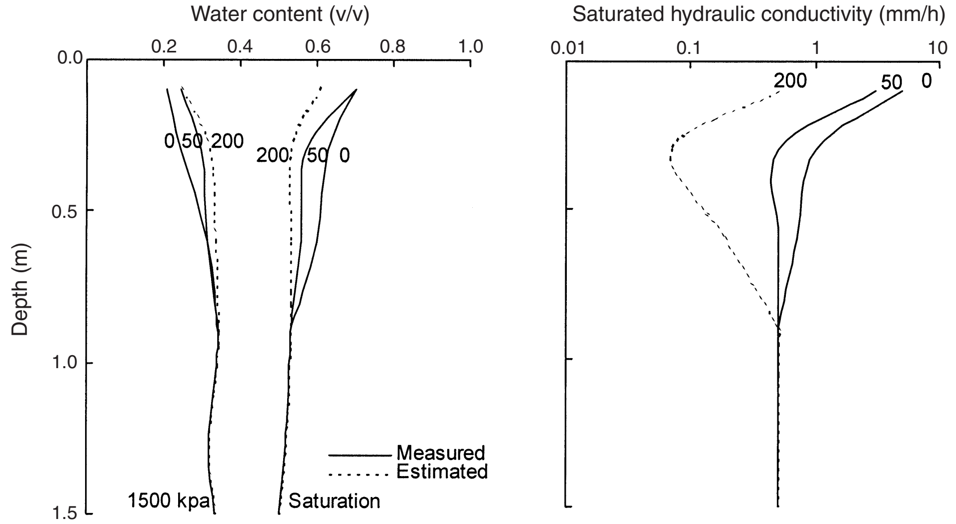

Fig. 2. An illustration of change in water-holding properties and permeability with period of cropping input to the model. Soil group is Heavy Vertosols. Numbers refer to years of cropping.

Parameter values describing water-holding properties and hydraulic conductivity of soil to a maximum depth of 0.6 m were changed to simulate cumulative effects of wheel track compaction, smearing, and tillage disturbance (e.g. Fig. 2). Effects of compaction were assumed to reach deeper into the soil profile on soils with higher clay contents, particularly the Vertosols and Red Ferrosols. Degradation in soil water-holding properties and hydraulic conductivity was predicted to steadily worsen as period of cropping increased, but change was most rapid in the first 10–50 years of cropping. An important effect of changed water-holding characteristics was changed evaporation; the 'air entry' point on the moisture characteristic tended to increase with increasing period of cropping and APSIM predicted more evaporation, despite lower hydraulic conductivities.

The decline in organic carbon with period of cropping input to the model was based on Dalal and Mayer's (1986*b*) functions, fitted to the measured record (0–70 years of cropping) then extrapolated to 200 years cropping (Fig. 3).

The relative contribution of crusting to infiltration and runoff was simulated by comparing average annual runoff with and without a crust restriction.

The economic analysis

The economic analysis assumed a single grain price (grain protein was not simulated) and fertiliser was applied each sowing to raise soil NO_3-N to a minimum level. Cost of production was calculated each year based on the simulated number of tillages and tillage type, fertiliser requirement at sowing, and other costs (Tables 4 and 5). Herbicide was only applied in years when a crop was planted. If no crop was planted, tillage was used to control weeds until the following year.

Results and discussion

Model accuracy

The model successfully simulated the response of the soil–crop system to environmental and management influences (Fig. 4, Table 6). General standard deviation was <100 for all variables tested, an indication of accurate predictions as defined by Hedden (1986). Variability in predicted wheat yield about the line $y = x$ was consistent, indicating the model was accurate over the range of experimental data. Soil water at Fairlands was slightly

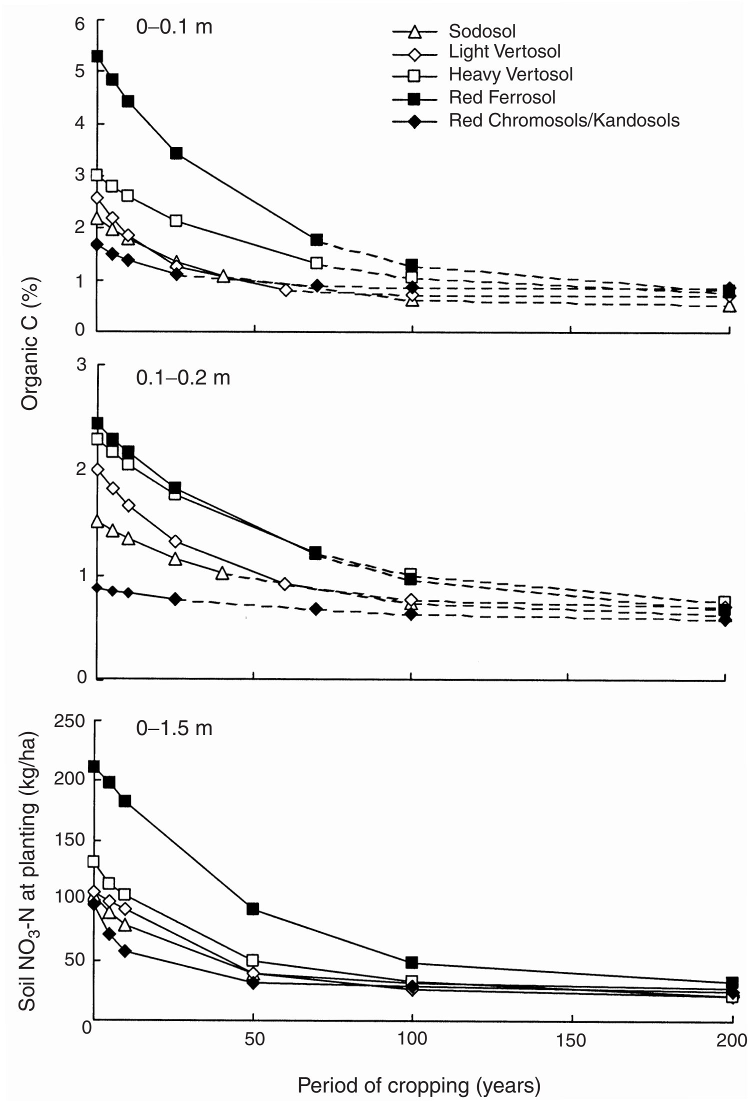

Fig. 3. Organic carbon for surface soil layers input to the model and the resulting simulated fallow mineralisation (median soil NO_3-N summed over the soil profile at sowing). Solid lines indicate organic carbon based on experimental data; dashed lines are estimated.

Table 5. Summary of costs used to calculate gross margin

Operation	Cost	Operation	Cost
Disc tillage ($/ha)	7.00	Herbicides ($/ha)	13.50
Chisel tillage ($/ha)	5.00	Harvest ($/ha)	6.00
Scarifier tillage ($/ha)	3.98	Grain price ($/t)	175.00
Plant ($/ha)	21.30	Fertiliser ($/kg)	0.90

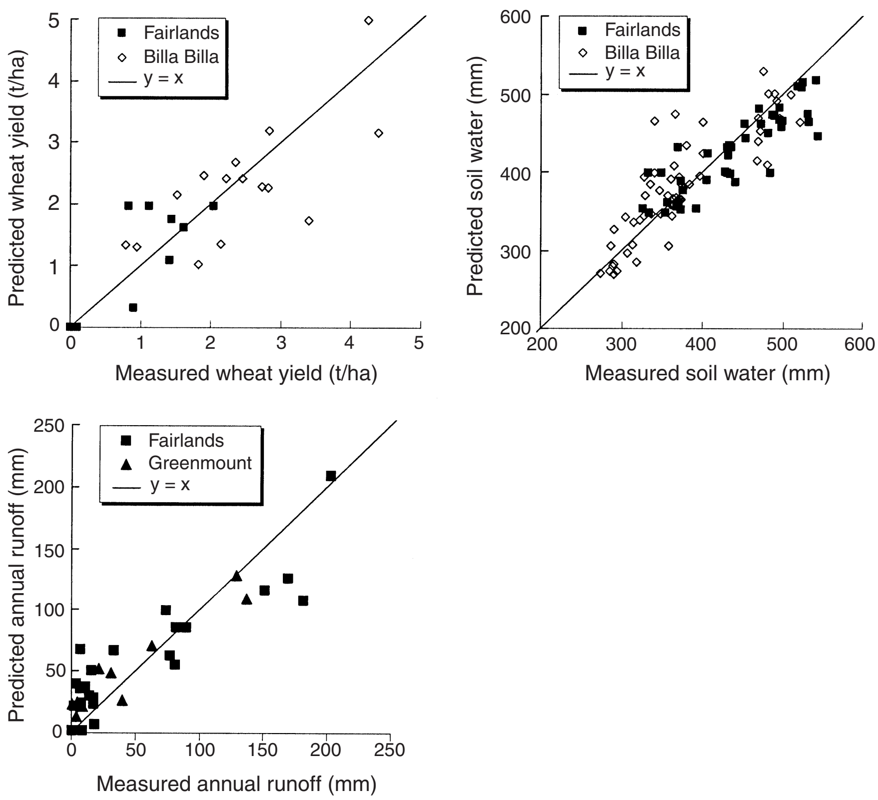

Fig. 4. Measured and simulated wheat yield, soil water (summed to 1.5 m deep), and annual runoff for the 3 test sites simulated with APSIM. Goodness of fit statistics are given in Table 6.

underpredicted for high water contents, but correlation for the full range of water contents and across both sites was high, indicating the water balance (i.e. runoff, evaporation, transpiration, and drainage) was well represented. Runoff was reliably simulated, though some over prediction at Fairlands in years with <25 mm of runoff reduced the slope of the line of best fit.

Effect of degradation on the soil water balance

Rundown in soil physical condition with cropping markedly affected the simulated water balance in the first 50 years of cropping and effects worsened with continued intense tillage

Table 6. Summary of goodness of fit of simulated with measured data

Slope and intercept of a linear regression between simulated and measured data ± standard error; R^2, coefficient of determination calculated about the line of best fit; *EF*, coefficient of determination calculated about the line $y = x$

	Slope	Intercept	R^2	*EF*	General standard deviation
Wheat yield	0.87 ± 0.08	0.18 ± 0.16	0.79	0.78	39
Profile soil water	0.76 ± 0.04	94.4 ± 17.8	0.76	0.76	9
Runoff	0.69 ± 0.06	21.8 ± 4.3	0.83	0.79	53

(Table 7). Crusting and compaction of subsurface soil layers reduced infiltration and movement of water deeper into the soil and increased runoff. Change in soil water-holding properties and permeability lead to increased evaporation. Evaporation was always the largest component of the water balance, but cropping caused increases of as much as 35%. Accordingly, transpiration tended to decline as period of cropping increased.

Crusting was an important contributor to runoff, as indicated by the proportion of simulated runoff with no crust compared with a crust (Fig. 5). Effects of crusting on runoff increased on most soils in the first 50 years of cropping. Reduced permeability of sub-surface soil layers, exhibited by a reduction in the proportion of runoff due to crusting, tended to become more important as period of cropping increased, particularly on the Sodosols and Red Ferrosols. Crusting was only briefly the main limitation to infiltration on

Table 7. The simulated soil water balance (% of average annual rainfall) for selected periods of cropping

Component of the water balance	Period of cropping (years)	Sodosols (%)	Light Vertosols (%)	Heavy Vertosols (%)	Red Ferrosols (%)	Red Chromosols/ Kandosols (%)
Runoff	0	12	14	2	0	12
	50	15	19	7	10	15
	200	24	19	9	22	15
Drainage	0	9	7	18	34	1
	50	2	0	8	22	1
	200	1	0	7	11	1
Evaporation	0	54	54	49	44	65
	50	66	62	62	50	62
	200	61	65	67	53	64
Transpiration	0	25	25	31	22	21
	50	16	16	23	18	20
	200	15	13	17	15	20

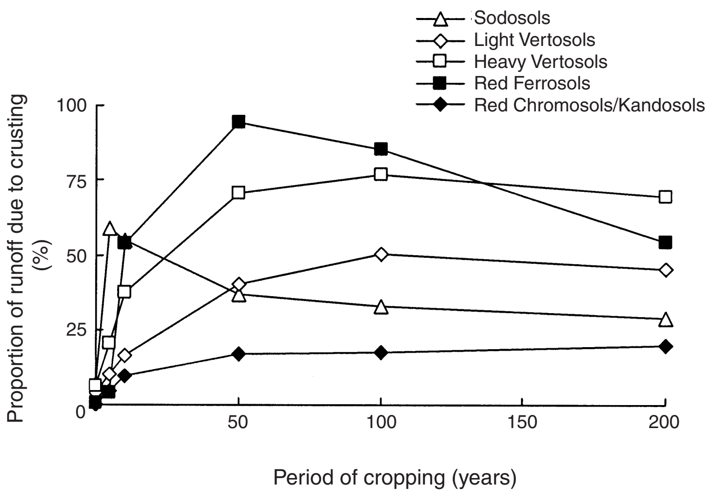

Fig. 5. Average annual runoff with no crusting expressed as a proportion of runoff with crusting. Increasing effects of compaction cause the proportion to drop off as period of cropping increases.

the Sodosols; subsurface limitations became more important after 10 years. On the Red Chromosols/Kandosols, crusting was less important compared with the low subsurface permeability of these soils. Crusting was important on the Light Vertosols, but infiltration was equally limited by the naturally low permeability of subsurface soil layers, particularly deep in the soil profile.

The increasing importance of subsurface restrictions to infiltration suggests that, in the future, greater effort should be made to control wheel traffic and tillage. However, if compaction is reduced without maintenance of surface cover and good soil structure, crusting will remain a limitation to infiltration.

Reduced infiltration, internal redistribution of soil water, and increased evaporation reduced movement of water deeper into the soil profile (e.g. Fig. 6). Water was slower to accumulate in deeper layers and lost more quickly to evaporation in surface layers.

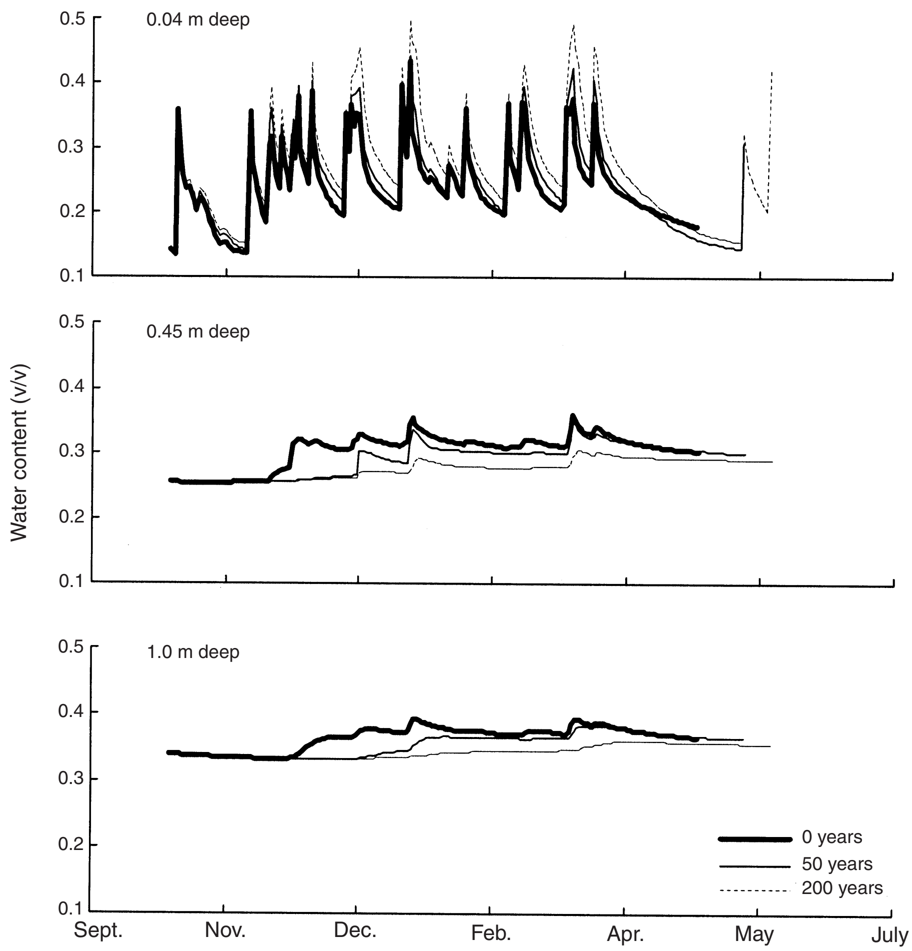

Fig. 6. Typical change in soil water during a cropping cycle for selected depths and periods of cropping for Red Ferrosols. Volumetric water content of soil 0.04 m deep is greater for longer periods of cropping because the moisture characteristic has changed.

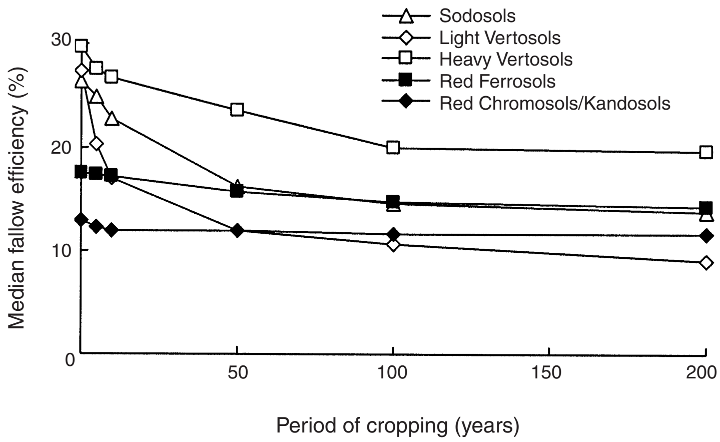

Fig. 7. Simulated change in fallow efficiency with period of cropping.

Accordingly, drainage below the root-zone was reduced and evaporation increased (Table 7).

Evaporation tended to increase as period of cropping increased because water-holding characteristics and permeability of soil in near-surface layers changed. Infiltrated rainfall moved more slowly through compacted soil layers so was more readily lost to evaporation. In addition, the 'air entry' potential on the moisture characteristic increased causing predicted evaporation to increase.

The changed water balance meant that the soils became less efficient at retaining rainfall during fallows. Simulated fallow efficiency (soil water stored over the fallow expressed as a percentage of fallow rainfall) decreased in most soils as period of cropping increased (Fig. 7). The Vertosols and Sodosols were most adversely affected, consistent with increased runoff and evaporation. Red Ferrosols were not substantially affected because the water-holding capacity of these soils is low and readily recharged even when soil permeability has been run down. Fallow efficiency of the Red Chromosols/Kandosols did not change with period of cropping because their water balance was relatively unchanged.

Water-holding capacity of the soils with high clay contents (Vertosols and Red Ferrosols) declined with increasing period of cropping, reflecting observed changes to the moisture characteristic (Fig. 8). Typically, water content at 1500 kPa increased and water contents between saturation and 'air entry', corresponding to the range in which macropores are most active in carrying water, decreased (e.g. Fig. 2).

Changes in the water balance, fallow efficiency, and soil water-holding properties reduced the amount of soil water available at sowing for the Vertosols and Sodosols (Fig. 8). Reduction was most severe in the Light Vertosols; the amount of water in the soil at sowing declined by 56% after 50 years of cropping. The Heavy Vertosols and Sodosols lost about 20% in that time.

The proportion of rainfall used by the crop (transpiration) declined with increasing period of cropping in all but the Red Chromosols/Kandosols (Table 7). Transpiration is a product of soil water and N supply, and is a fairly reliable indicator of yield (French and Schultz 1984*a*, 1984*b*; Fig. 9). A tendency toward reduced transpiration and yield can be seen in Fig. 9 as period of cropping increases, mostly because of increased water stress

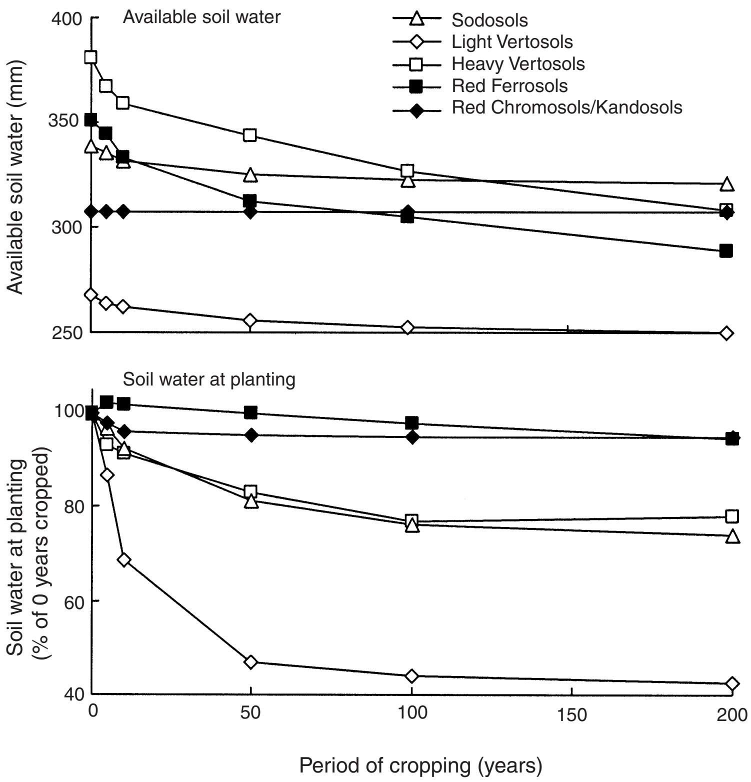

Fig. 8. Change with period of cropping in water-holding capacity (difference between water content at saturation and 1500 kPa matric potential) summed for the profile, a model input, and simulated median soil water at sowing, expressed as a percentage of available soil water at 0 years cropping.

resulting from declining infiltration and water-holding capacity and increasing evaporation. Amount of soil N mineralisation probably restricted yield in wetter years, but N stresses were minimised by resetting soil N at sowing. Variability within a soil condition in Fig. 9 is due to the timing of water and N stresses.

Effect of on soil productivity

Simulated rundown in soil physical and chemical conditions reduced crop yields (Fig. 10) and gross margins (Fig. 11) and increased cropping risk. Water stress as a result of reduced infiltration and a changed water balance was the main factor causing yield decline. Crop productivity decreased most sharply in the first 50 years of cropping; median yield declined by 29, 38, 25, 17, and 13% for the Sodosols, Light Vertosols, Heavy Vertosols, Red Ferrosols, and Red Chromosols/Kandosols, respectively. Yield continued to decline steadily on most soils for periods of cropping up to 200 years, indicating rundown in crop productivity is likely to continue from current levels if management does not change.

Gross margin declined at a faster rate than yield because carbon levels ran down quickly and nitrogen fertiliser costs increased (Fig. 12). After 50 years of cropping, median gross margin declined by 36, 50, 40, 20 and 21% for the 5 soil groups. Only 5–10 years of

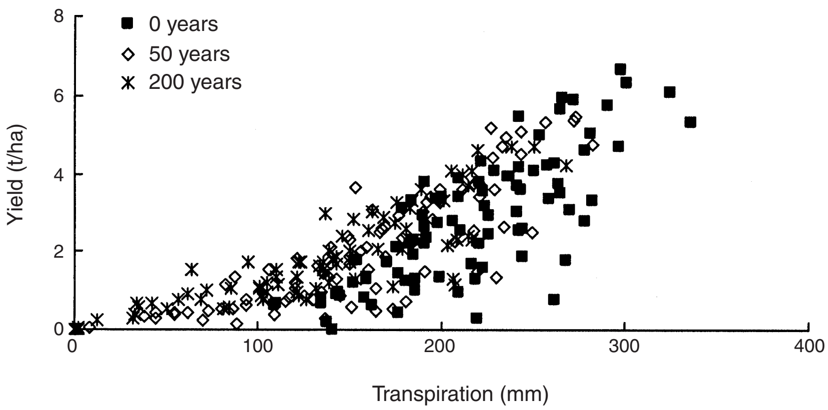

Fig. 9. Relationship between simulated crop transpiration and yield for different periods of cropping for the Heavy Vertosols.

cropping on the Vertosols and Red Chromosols/Kandosols reduced organic carbon levels to such an extent that fertiliser was required to maintain target NO_3-N levels at sowing. (Minimum NO_3-N levels at sowing are given in Table 4). Fertiliser was required after about 10 years on the Sodosols and 50 years on the Red Ferrosols. Cost of fertiliser became a major component of production costs as period of cropping increased, particularly for the Heavy Vertosols.

Risk of cropping increased with period of cropping (Fig. 11) because crop water supply was reduced. Nearly 25% of crops on all but the Red Chromosols/Kandosols were predicted to have a negative gross margin after 50–70 years of cropping. Profitability in higher yielding years (75 and 95 percentile) also ran down sharply. Gross margin for the Red Chromosols/Kandosols was relatively stable because cropping did not have a large impact on the water balance.

Implications for management

Decline in soil condition is recognised as a problem by the farming community and a number of alternative management strategies, such as conservation tillage and improved crop rotations, have been developed (Freebairn and Boughton 1985; Freebairn *et al.* 1986; Wylie 1987; McGarry 1988; Tullberg and Lahey 1990). Management strategies that aim to address problems related to infiltration typically involve maintaining stubble cover on the soil surface to reduce crusting and erosion, reducing trafficking to reduce further compaction of the soil, or making best use of the natural shrink–swell characteristics of Vertosols to 'break-up' compacted soil layers. However, adoption of these management practices is complicated by economic constraints, problems controlling weeds using herbicides only, problems with pests and disease, and a requirement for tillage to break up hardset or crusted layers, particularly when cover levels are low (Rees and Platz 1979; Radford *et al.* 1992). As a result, tillage is still widely used, though its intensity has probably declined (ABARE 1999).

Even though the simulations represent a worst case scenario, i.e. continued intense tillage, they indicate that further decline in crop productivity is possible. To arrest further decline, it is highly likely that substantial changes need to be made to our existing cropping systems. It is generally acknowledged that soil organic carbon levels need to be increased,

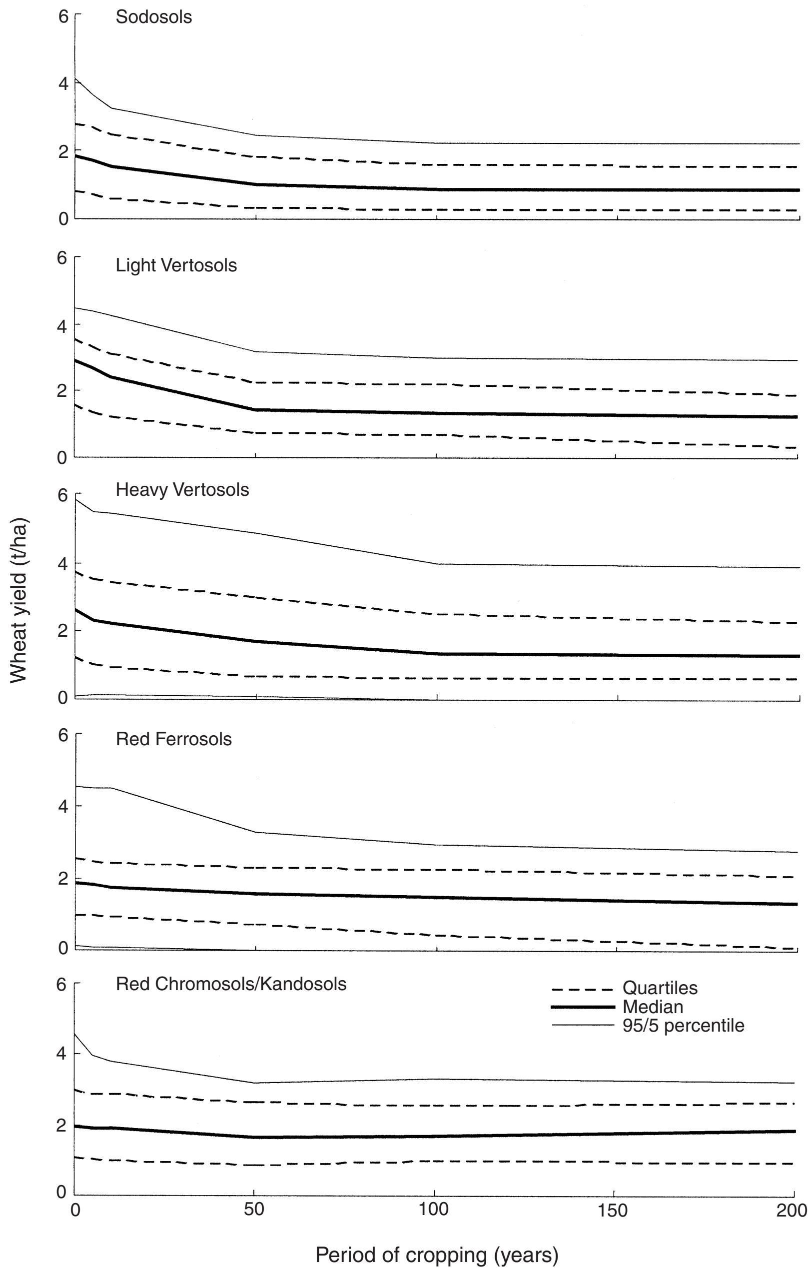

Fig. 10. Simulated change in annual wheat yield with period of cropping. The 5 percentile line for the Sodosols, Light Vertosols, and Red Chromosols/Kandosols is hidden by the axis.

but to do so requires that greater amounts of organic matter be returned to the soil than with many existing cropping systems, including conservation cropping (Tisdall and Oades 1980; Dalal *et al.* 1995; Bell *et al.* 1997). Rotation into ley pastures may need to become a regular component of cropping systems to maintain or improve organic matter levels, change

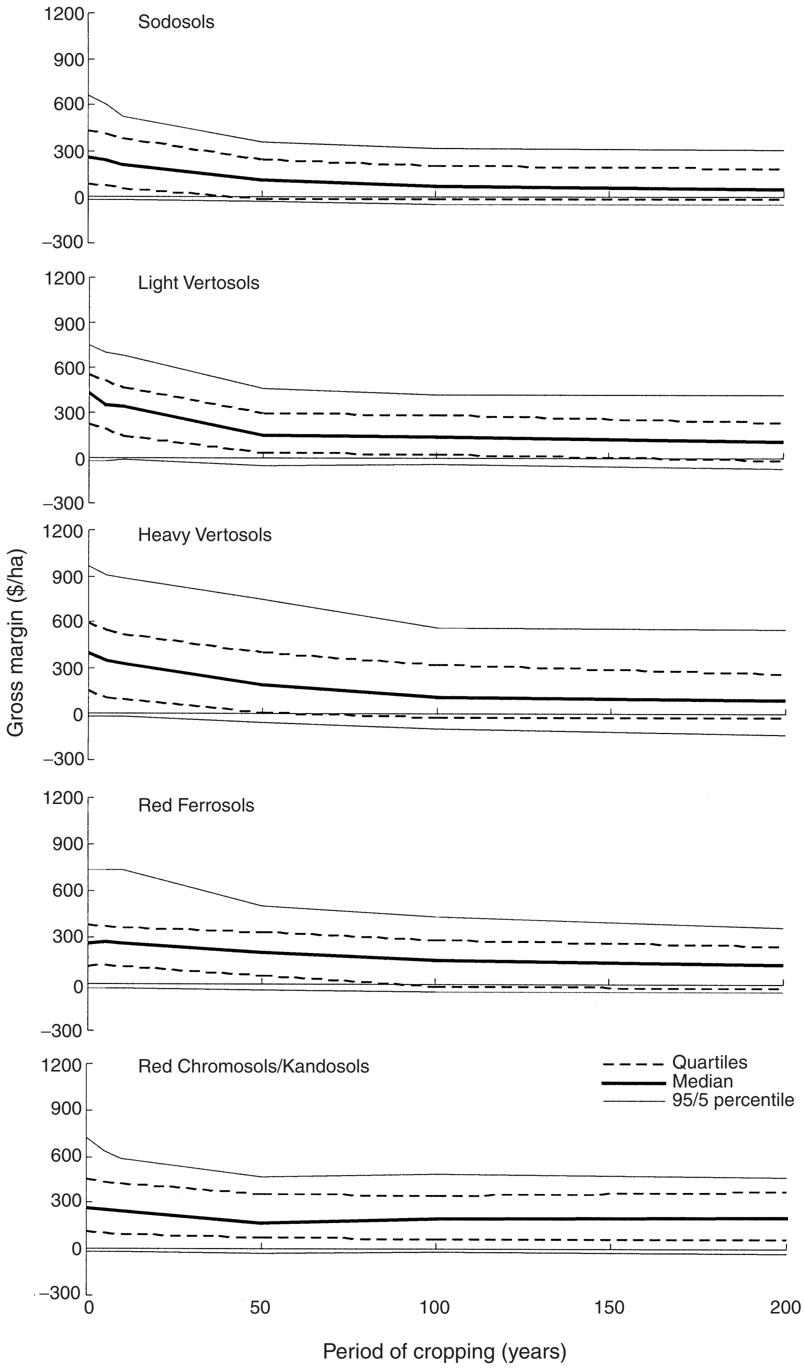

Fig. 11. Simulated change in annual gross margin with period of cropping.

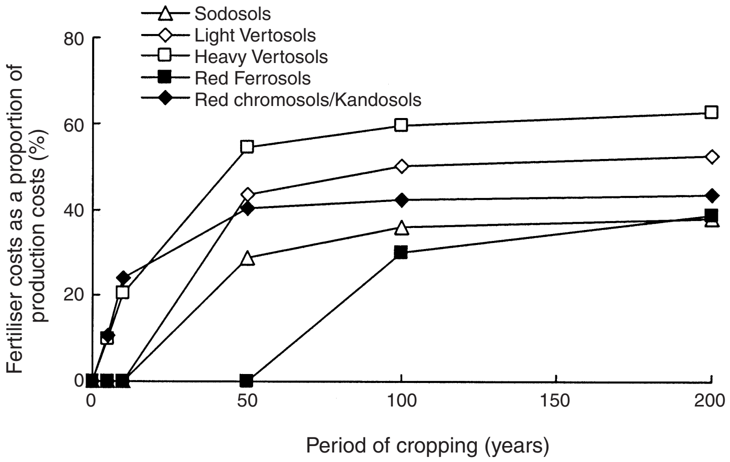

Fig. 12. Change in the cost of nitrogen fertiliser with increasing period of cropping, expressed as a proportion of all production costs.

organic matter composition, or increase soil aggregate stability and macroporosity (Lorimer and Douglas 1995; Bell *et al.* 1997; Connolly *et al.* 1998*a*). Tillage and trafficking will almost certainly need to be reduced from current levels if compaction is to be reduced. Most importantly, new management strategies will need to overcome many of the problems that have restricted the spread of conservation tillage systems, i.e. disease, pests, weeds, and economic constraints.

Conclusions

Changed infiltration and soil hydraulic condition because of cropping has substantially increased runoff and evaporation, reduced efficiency of utilisation of rainfall, and reduced crop yields and profitability for most soils cropped in south-eastern Queensland. Declining soil fertility has reduced crop profitability further.

If management does not change, crop productivity in the future is likely to continue to decline because of a declining water supply. To arrest this decline, substantial reductions in the amount and intensity of tillage and trafficking will be needed, the amount and composition of organic matter in the soil will need to improve, and good soil structure will need to be restored to surface soil layers.

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