CSIRO PUBLISHING
Soil Research, 2018, **56**, 429–440
https://doi.org/10.1071/SR17228

Farming systems' productivity and soil organic carbon stocks following fertilisers, no-tillage or legumes on a fertility-depleted soil in a semi-arid subtropical region

R. C. Dalal[A,E,F], *W. M. Strong*[B], *E. J. Weston*[C], *J. E. Cooper*[B], *K. J. Lehane*[C], *and A. J. King*[D]

[A]Department of Science, Information Technology and Innovation, GPO Box 5078, Brisbane, Qld 4001, Australia.
[B]Department of Agriculture and Fisheries, 13 Holberton Street, Toowoomba, Qld 4350, Australia.
[C]Department of Agriculture and Fisheries, 203 Tor Street, Toowoomba, Qld 4350, Australia.
[D]Department of Natural Resources and Mines, 201 Tor Street, Toowoomba, Qld 4350, Australia.
[E]School of Agriculture and Food Sciences, The University of Queensland, St Lucia, Qld 4072, Australia.
[F]Corresponding author. Email: r.dalal@uq.edu.au

Abstract. Depleted soil nitrogen supplies in long-term continuously cultivated soil for cereal grain cropping have resulted in reduced cereal yields, low grain proteins and hence low economic returns. This has necessitated the development of alternative management practices to sustain crop yields, as well as to restore and maintain soil fertility. In the present study we examined the comparative performance of several management options over a 12-year period, including: a 4-year rotation of grass + legume pasture followed by wheat (GL–wheat); 2-year rotations of lucerne–wheat, annual medic–wheat and chickpea–wheat; and continuous conventional tillage (CT) or no-tillage (NT), without or with fertiliser N application (0, 25 and 75 kg N ha^{-1} for each crop). Average wheat grain yields were highest in the chickpea–wheat rotation, followed by the NT wheat with 75 kg N ha^{-1}; the lowest grain yields were in the CT or NT wheat treatment without fertiliser N application. Crop water use and gross margin were strongly correlated. However, there was an increasing potential for the deep leaching of nitrate-N at 75 kg N ha^{-1} application, as well as from the GL pasture initiated in 1987, but not from that initiated in 1986, emphasising the effect of variability in growing seasons. Soil organic C stocks increased under the 4-year GL pasture in the 0–0.1 m depth only, then decreased steadily following the cropping phase. The rotation of 4-year GL pasture followed by wheat cropping for 4–6 years may maintain initial soil organic C stock, but a shorter cropping phase is required to increase soil organic C and N stocks and soil fertility in the long term. Partial economic analysis of the treatments suggested that restoring or maintaining soil N fertility, either through legume-based pastures, grain legume and/or N fertiliser, provides long-term positive economic return.

Additional keywords: annual medic, chickpea, gross margin, lucerne, purple pigeon grass, Rhodes grass, soil nitrate, wheat.

Received 25 August 2017, accepted 25 January 2018, published online 4 May 2018

Introduction

The cereal growing areas of subtropical regions, such as southern Queensland and northern New South Wales, Australia, have relied largely on nitrogen mineralised from soil organic matter for crop growth for almost 100 years. Organic N (and C) in cereal cropping soils has now been depleted by up to 70%, due primarily to the removal of N in produce (mostly grains; Dalal and Mayer 1986*a*, 1986*b*) and other N losses, such as denitrification and deep leaching (Page *et al.* 2002). Sustaining cereal grain production on these soils requires increased nitrogen inputs, either through legume N_2 fixation and/or external N supply, such as fertiliser nitrogen (Strong *et al.* 1996*a*, 1996*b*; Dalal *et al.* 1998; Holford *et al.* 1998; Thomas *et al.* 2010). Therefore, the inclusion of legumes in crop rotations with cereal grain crops, and/or fertiliser application, is required to achieve not only high grain yield, but also high grain protein (Holford and Crocker 1997; Armstrong *et al.* 1999) because economic returns are based on both wheat grain yield and protein concentration; for example, for prime hard (PH) wheat (Strong *et al.* 1996*b*), the improvement in soil fertility following these practices may also result in increased economic benefits (Thomas *et al.* 2010).

Although nitrogen accretion in soil, either from legumes or N fertiliser, may increase wheat yield and protein, it may also be subjected to loss via denitrification (as gaseous N_2O and N_2) and deep leaching. Gaseous N losses, especially as N_2O, contribute to global warming (Dalal *et al.* 2003) and therefore the judicious management of N in cropping systems is required (Wang and Dalal 2015). Deep leaching of nitrate-N below the root zone contributes to groundwater pollution as well as being an economic loss. Therefore, cropping systems require an optimum balance between N supply and crop uptake, or N supply and crop water use (Dalal *et al*. 2013), for both production and economic return (Thomas *et al*. 2010).

Continuous cereal grain cropping of soils in the region has resulted in the loss of up to 70% of their initial organic C (and N; Dalal and Mayer 1986*a*, 1986*b*). This can be ascribed primarily to aggregate disruption from tillage operations (Dalal *et al*. 1991), reduced addition of organic materials, including crop C inputs (Dalal *et al*. 1995), and increased soil erosion (Cook *et al*. 1992). Cropping systems that involve no-tillage (NT) practices may reduce aggregate disruption, and the inclusion of pasture in rotations could lead to increased organic material inputs to soil (Dalal *et al*. 1995). Therefore, both practices may reduce continuing soil organic C loss, or even increase soil organic C, in cereal farming systems (Dalal *et al*. 1995; Hossain *et al*. 1996*a*; Studdert *et al*. 1997; Holford *et al*. 1998; Thomas *et al*. 2010; Chan *et al*. 2011; Salvo *et al*. 2014). Increases in soil organic C, with concomitant increases in soil N, will improve soil fertility and may result in more sustainable crop production and hence increased economic return in this region.

In the present study we examined the comparative effects of pasture–wheat rotation, including long-term pasture (4 years) or short-term pasture (1 year), grain legume, chickpea–wheat rotation and conventional till (CT) or NT wheat cropping, with and without fertiliser application, on a fertility-depleted Vertosol over a 12-year period. The objectives of the study were to: (1) evaluate the comparative effects of alternative management strategies, including pasture legumes, a food grain legume, fertiliser application and reduced tillage on wheat yields and gross margins; and (2) assess the effects of these practices in restoring or maintaining soil organic C on a fertility-depleted Vertosol.

Materials and methods

Site details

The long-term field experiment was established at Warra (26°47′S, 150°53′E) in southern Queensland on a soil that had been cultivated for cereal cropping since 1935. The site originally had predominantly brigalow (*Acacia harpophylla*) and belah (*Casuarina cristata*) vegetation. The soil was a grey Vertosol (Typic Chromustert) that had lost 70% of organic C (from 2.23% to 0.68%) and total N (from 0.203% to 0.06%) from the 0–0.1 m layer after 50 years of continuous cereal cropping (Dalal and Mayer 1986*a*, 1986*b*; Dalal *et al.* 1995). The soil description, mean monthly maximum (27°C) and minimum (12°C) temperatures, mean monthly rainfall and growing season rainfall at the field site (1987–98) have been reported by Weston *et al.* (2002) and Dalal *et al.* (2004*a*). The soil contained 56% clay, 17% silt and 27% sand at 0–0.1 m depth; it was alkaline at 0–0.1 m depth (pH 8.6) trending to strongly acidic (pH 4.9) at 0.9–1.2 m depth. The average annual rainfall from 1986 to 1998 at the Warra site was 597 mm. During the experimental period, annual rainfall at the site varied from 396 mm in 1986 to 778 mm in 1998 (Fig. 1).

Experimental design and pasture and crop establishment

The experimental setup, treatments, pasture and agronomic practices, stubble and tillage management, weed control, soil, pasture and crop monitoring and sampling procedures have been described in detail by Dalal *et al.* (1995). Briefly, 17 treatments were established in a randomised block design having four replicates in plots that were each 25 m long and 6.75 m wide. Five major farming systems were examined: (1) 4-year grass + legume (GL) pasture–wheat (*Triticum aestivum* L. cv. Hartog) rotation (GL–wheat); (2) legume ley–wheat rotation, 2-year rotation of lucerne (*Medicago sativa* L. cv. Trifecta)–wheat or medics (*Medicago scutellata* L. Mill cv. Sava and Kelson and *Medicago truncatula* Gaertn. cv. Jemalong, Cyprus, Paraggio and Sephi)–wheat; (3) food grain legume–wheat, 2-year rotation of chickpea (*Cicer arietinum* L. cv. Barwon)–wheat; (4) continuous CT wheat, with fertiliser N application at 0, 25, and 75 kg N ha^{-1} (CT wheat 0N, CT wheat 25N and CT wheat 75N, respectively); and (5) continuous NT wheat, with fertiliser N application at 0, 25, and 75 kg N ha^{-1} (NT wheat 0N, NT wheat 25N and NT wheat 75N, respectively). All treatments received a basal rate of 10 kg ha^{-1} phosphorus as superphosphate, fortified with copper and zinc annually.

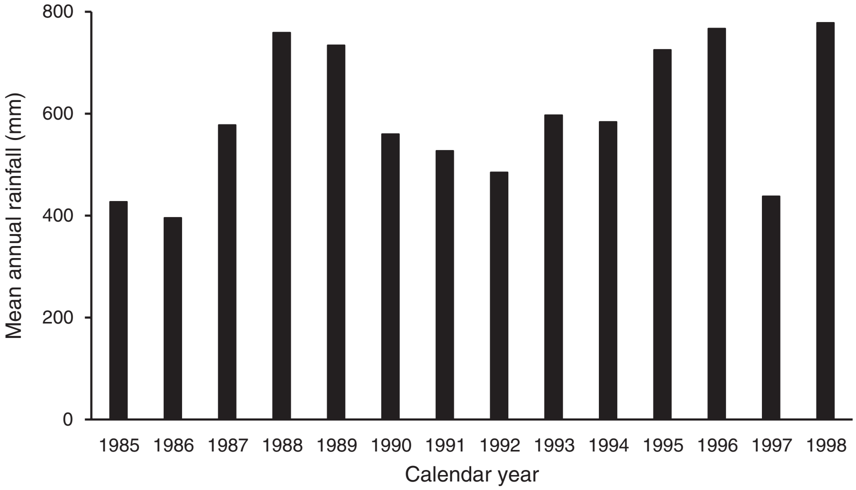

Fig. 1. Mean annual rainfall distribution from 1986 to 1998 (experimental period).

The GL pasture was a mix of lucerne, medic and grasses (*Setaria incrassata* Stapf cv. Inverell and *Chloris gayana* Kunth cv. Katambora). These were established in January 1986, 1987 and 1988, and were grown for 3.75 years (hereafter referred to as GL86, GL87 and GL88, respectively). In the lucerne–wheat and medics–wheat rotations of short duration, lucerne and medics were undersown with wheat during May–July (depending on sowing rainfall) at rates of 2 and 5 kg ha^{-1} respectively, with the wheat seed rate the same as that for the CT-wheat treatment. However, annual medics were sown only once because of their self-generating nature. For the chickpea–wheat rotation, chickpea was sown at a rate of 60 kg ha^{-1} using phytophthora (*Phytophthora megasporium*)-tolerant lines or cv. Barwon. Chickpea was sown at the same time as wheat in other treatments. All short-duration (2-year) rotations consisted of both phases each year.

For the CT wheat treatments, conventional tillage operations, usually two to four, were performed using tined implements to a depth of ~100 mm during the fallow period (December–April) for weed control and seed bed preparation. Wheat was sown at a depth of ~50 mm in rows 250 mm wide at a rate of 40 kg ha^{-1} in May–June in all years, except in 1990 and 1993, when wheat was sown at a rate of 50 kg ha^{-1} in July. Fertiliser was applied as urea at sowing at rates of 0, 25 and 75 kg N ha^{-1} and was placed at a depth of ~50 mm in alternate mid-rows. In the NT wheat treatments, weeds were controlled by herbicide spray (1.2 L glyphosate and 1.2 L 2,4-D amine ha^{-1}) two to four times during the fallow period. The rates of sowing and fertiliser N applications for the NT wheat were same as that for the CT wheat.

Pasture management

Detailed descriptions of pasture managements are given by Weston *et al.* (2002), Dalal *et al.* (2004*a*) and Strong *et al.* (2006). Briefly, the pasture yields were measured by forage harvesting to a height of 0.1 m at 3-monthly sampling intervals (December, March, June and September) for the grasses and lucerne, and in June and September for the annual medics. The harvested plant material was dried at 75°C in a forced-draught oven, weighed and ground to pass through a 1-mm sieve and the N concentration of the material determined by Kjeldahl analysis (Crooke and Simpson 1971). The pastures were terminated in early October by blade ploughing at a depth of 0.10–0.15 m to coincide with maturity of the annual medics and to provide a similar opportunity for soil water recharge as would occur for the continuous cropping treatment during the summer fallow. Weeds during the fallow period were controlled by tillage to a depth of ~0.1 m (two or four events), as for the continuous CT cropping.

Crop management

The wheat grain yields were measured by machine harvesting an area ~1.75 m × 23 m in the central area of each plot. The grain yields were adjusted to 12% moisture content. Wheat grain and straw N concentrations were determined by Kjeldahl analysis (Crooke and Simpson 1971). Wheat grain protein concentration was calculated from grain N concentration using 5.7 as the nitrogen-to-protein conversion factor (Tkachuk 1966).

Soil sampling and analysis

For the soil water and nitrate concentrations, each plot was sampled to a depth of 1.5 m using a 50-mm diameter tube attached to a hydraulic sampler in May (before sowing) and November (after harvest) each year. Two soil cores taken from each plot were bulked in 0.1-m layers to a depth of 0.3 m and in 0.3-m layers below 0.3 m depth. The soil samples were collected and sealed in airtight bags and stored at 4°C until analysis. Soil moisture content was determined gravimetrically by drying the soil samples at 105°C for 48 h. For the determination of nitrate concentration, the soil was dried at 35°C under draught and ground to <2 mm; nitrate was extracted using 10 g soil in 100 mL of 2 M KCl solution and the extract analysed colourimetrically for nitrate (Best 1976). The volumetric soil water content and amount of soil nitrate for each depth interval was obtained using bulk density adjusted for the soil moisture content for that depth interval (Strong *et al.* 1996*b*). The amount of crop water use was calculated from the amount of presowing water (usually in May) at a depth of 0–1.2 m plus in-crop rainfall minus the amount of water at harvest (usually in November) at a depth of 0–1.2 m. Potential deep leaching of nitrate-N was estimated from the amount of nitrate-N at a depth of 1.2–1. 5 m in different treatments, including the 0N treatment during the experimental period. The Newman (1966) line intersection method was used to estimate root lengths from core soil samples dispersed ultrasonically, and root biomass was calculated from the root length and root weight (3 mg m^{-1} root length) in a given volume of soil at each depth (Dalal *et al.* 1995).

For determination of soil organic C and total N, five soil samples from each plot were collected at a depth of 0–0.1 m and occasionally at depths of 0.1–0.2 and 0.2–0.3 m in November–December after the pasture or crop harvest using a 50-mm diameter tube sampler, a procedure similar to that reported by Dalal *et al.* (1995). The samples were bulked, sealed in plastic bags and stored at 4°C until analysis. The soil sample was dried at 35°C in a forced-draught oven, ground to pass through a <2-mm sieve and mixed thoroughly. A subsample was further ground to <0.25 mm for colourimetric determination of organic C by the Walkley–Black method (Sims and Haby 1971), as well as determination of total N, including NO_3-N, by the modified Kjeldahl method (Dalal *et al.* 1984). Soil organic C and N stocks were calculated from soil organic C and N concentrations multiplied by the corresponding bulk density and depth of sampling. The bulk density values in different treatments were not significantly different ($P < 0.05$); therefore, no adjustment in the soil organic C and N stocks was required for equivalent soil mass.

Gross margin and net return on crop water use

The gross margins of wheat from different treatments were compared with farm-gate income derived from the grain price of wheat yield at different protein concentrations less the variable costs (tillage for CT, sowing, fertilisers, herbicides and harvest) at commercial on-farm rates (Department of Primary Industries 2000). Wheat grain transportation costs were taken as A$10 t^{-1} from the farm gate to the Warra silo (16 km away), and A$22 t^{-1} from the Warra silo to the Brisbane port. Wheat grain prices for the Australian Standard Wheat

(ASW), prime hard (PH) variety (PHV) and PH wheat based on protein concentrations at the Brisbane port were provided by the Australian Wheat Board. Net return on crop water use was calculated from the gross margin divided by the crop water use (A$ $ha^{-1} mm^{-1}$) for each treatment to provide a potential benchmark for the comparative bioeconomic productivity of different treatments.

Statistical analysis

The significance of differences between treatments was assessed using analysis of variance (ANOVA; Research Experiment Management System, Queensland Department of Primary Industries, Brisbane, Qld, Australia), and time trends in soil parameters and the relationship among various parameters were examined using regression analysis (Snedecor and Cochran 1967). Soil organic C and total N values were normalised with regard to the CT wheat treatment according to Dalal and Mayer (1986*b*) and Dalal *et al.* (1995).

Results

Wheat grain yield

The wheat grain yield varied from 4.78 t ha^{-1} in the NT wheat 75N treatment in 1988 to 0.49 t ha^{-1} in the medics–wheat treatment and 0.5 t ha^{-1} in the lucerne–wheat treatments in 1995 (Table 1). The chickpea–wheat rotation performed better or equal to any other rotation or the continuous CT wheat 75N or NT wheat 75N treatments from 1988 to 1995, and significantly better than the CT wheat 0N treatment during the 1988 and 1998 cropping seasons. The wheat yields increased following fertiliser N application (75 kg ha^{-1}) in all years except in 1995, when grain yields were lower than without fertiliser N, due primarily to the dry season (48 mm pre-anthesis rainfall). Similar effects on grain yield were observed with the GL86–wheat, GL87–wheat, GL88–wheat, lucerne–wheat and medic–wheat rotations.

When all phases of the rotations for wheat production were compared (1992–98), average yields were highest in the chickpea–wheat and the NT wheat 75N treatments (2.53 t ha^{-1}) and GL87–wheat (2.49 t ha^{-1}), but lowest in the CT wheat 0N and NT wheat 0N treatments (1.9 t ha^{-1}; Fig. 2). Although the mean grain yield of the lucerne–wheat rotation (1.9 t ha^{-1}) was similar to the latter treatments, the mean grain yields of the medics–wheat (2.31 t ha^{-1}), CT wheat 75N (2.32 t ha^{-1}) and NT wheat 25N (2.31 t ha^{-1}) treatments were not significantly different from that of the NT wheat 75N treatment. Among the GL pastures, the GL86–wheat and GL87–wheat performed similarly (Fig. 2). Average yields of the GL88–wheat rotation were not compared because it was reverted back to pasture from 1996 to 1998.

Wheat grain protein concentration

The wheat grain protein concentrations varied from 8% in the CT wheat 0N treatment in 1989 to 16.3% in the medics–wheat treatment in 1993 (Table 2). Average protein concentrations (1992–98) were highest in the GL87–wheat treatment (13.7%), although this was not significantly different from that in the CT wheat 75N (13.5%), medics–wheat (13.3%), GL86–wheat (13%) and NT wheat 75N (13%) treatments (Fisher's l.s.d., grain protein, 0.89%; $P = 0.05$). As expected, the lowest protein concentrations occurred in the NT wheat 0N (9.2%) and CT wheat 0N (9.5%) treatments.

Table 1. Wheat grain yield in different farming systems

Data show mean yields for both phases of 2-year rotations of lucerne–wheat, medic–wheat and chickpea–wheat, as well as conventional tillage (CT) and no-tillage (NT) continuous wheat fertilised at a rate of 0, 25 and 75 kg N ha^{-1} (CT wheat 0N, CT wheat 25N and CT wheat 75N, NT wheat 0N, NT wheat 25N and NT wheat 75N, respectively). GL86–, GL87– and GL88–wheat, grass + legume (GL)–wheat rotation, with pastures established in 1986, 1987 and 1988, respectively

Farming system	Wheat grain yield (t ha^{-1})									
	1988	1989	1990	1992	1993	1994	1995	1996	1997	1998
GL86–wheat	GL	GL	3.38^{A}	3.71^{A}	1.84^{A}	1.46^{A}	0.74^{A}	3.61	2.54	2.03
GL87–wheat	GL	GL	GL	4.03^{A}	1.96^{A}	1.59^{A}	0.74^{A}	3.78	2.78	2.57
GL88–wheat	GL	GL	GL	3.65^{A}	1.83^{A}	1.56^{A}	0.79^{A}	GL	GL	GL
Lucerne–wheat	2.82	1.85^{B}	3.43^{B}	3.40^{B}	1.29^{B}	1.70^{B}	0.50^{B}	2.62^{B}	2.44^{B}	1.93^{B}
Medic–wheat	2.94	2.70^{B}	3.59^{B}	3.84^{B}	1.33^{B}	1.34^{B}	0.49^{B}	4.12^{B}	2.79^{B}	2.18^{B}
Chickpea–wheat	4.62^{C}	2.88^{C}	3.59^{C}	4.23^{C}	2.20^{C}	1.60^{C}	1.76^{C}	3.02^{C}	2.55	1.87
CT wheat 0N	3.08^{C}	2.07^{C}	2.23^{C}	3.48^{C}	1.88^{C}	1.02^{C}	1.20^{C}	2.27^{C}	2.11^{B}	1.40^{B}
CT wheat 25N	4.39	2.57	2.84	3.68	2.03	1.42	1.06	3.19	2.31	1.66
CT wheat 75N	4.65	2.31	3.41	3.75^{D}	1.88^{D}	1.51^{D}	0.88^{D}	3.68^{D}	2.35	2.19
NT wheat 0N	2.56	2.08	2.52	3.92^{D}	2.03^{D}	0.95^{D}	1.33^{D}	1.83^{D}	2.08	1.42
NT wheat 25N	3.77	2.82	3.14	4.25	2.53	1.19	1.37	3.07	2.14	1.62
NT wheat 75N	4.78	2.46	3.35	4.65^{D}	2.17^{D}	1.48^{D}	1.15^{D}	3.57^{D}	2.61	2.06
Mean	3.73	2.42	3.15	3.88	1.91	1.40	1.00	3.16	2.45	1.88
l.s.d. ($P < 0.05$)	0.56	0.27	0.28	0.58	0.18	0.20	0.18	0.34	0.37	0.38

[A] Data from Strong *et al.* (2006).
[B] Data from Dalal *et al.* (2004*b*).
[C] Data from Dalal *et al.* (1998).
[D] Data from Dalal *et al.* (2013).

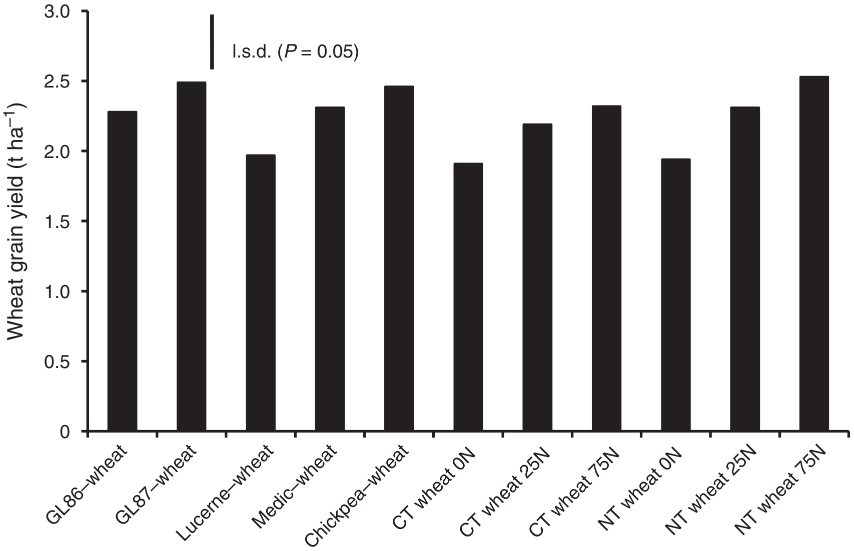

Fig. 2. Mean wheat grain yields (1992–1998) of the farming systems, namely grass + legume (GL)–wheat rotation for pastures established in 1986 and 1987 (GL86–wheat, GL87–wheat) and both phases of 2-year rotations of lucerne–wheat, medic–wheat and chickpea–wheat, as well as conventional tillage (CT) and no-tillage (NT) continuous wheat fertilised at a rate of 0, 25, and 75 kg N ha^{-1} (CT wheat 0N, CT wheat 25N, CT wheat 75N, NT wheat 0N, NT wheat 25N and NT wheat 75N, respectively).

Table 2. Wheat grain protein at 12% grain moisture in different farming systems

Data show mean yields for both phases of 2-year rotations of lucerne–wheat, medic–wheat and chickpea–wheat, as well as conventional tillage (CT) and no-tillage (NT) continuous wheat fertilised at a rate of 0, 25 and 75 kg N ha^{-1} (CT wheat 0N, CT wheat 25N and CT wheat 75N, NT wheat 0N, NT wheat 25N and NT wheat 75N, respectively). GL86–, GL87– and GL88–wheat, grass + legume (GL)–wheat rotation, with pastures established in 1986, 1987 and 1988, respectively

Farming system	Wheat grain protein (%)									
	1988	1989	1990	1992	1993	1994	1995	1996	1997	1998
GL86–wheat	GL	GL	13.0^{A}	13.2^{A}	14.9^{A}	12.4^{A}	14.4^{A}	12.2	11.9	12.1
GL87–wheat	GL	GL	GL	13.2^{A}	15.3^{A}	14.1^{A}	14.7^{A}	13.2	13.1	12.6
GL88–wheat	GL	GL	GL	11.7^{A}	14.7^{A}	10.8^{A}	14.1^{A}	GL	GL	GL
Lucerne–wheat	7.9	15.7^{B}	13.0^{B}	11.6^{B}	16.1^{B}	11.4^{B}	16.0^{B}	10.6^{B}	11.7^{B}	11.9^{B}
Medic–wheat	7.9	13.2^{B}	12.1^{B}	12.7^{B}	16.3^{B}	12.1^{B}	15.6^{B}	12.6^{B}	11.8^{B}	11.9^{B}
Chickpea–wheat	9.4^{C}	10.1^{C}	9.4^{C}	12.4^{C}	11.8^{C}	10.1^{C}	12.1^{C}	10.1^{C}	11.0	11.2
CT wheat 0N	8.3^{C}	8.0^{C}	8.3^{C}	10.8^{C}	9.6^{C}	8.7^{C}	11.8^{C}	10.2^{C}	9.0^{B}	10.6^{B}
CT wheat 25N	8.9	9.0	8.8	13.0	13.2	9.7	13.1	11.0	9.4	11.4
CT wheat 75N	13.0	14.5	11.8	13.4	15.1	13.4	14.1	13.3	12.4	12.7
NT wheat 0N	7.8	8.1	8.6	9.6	9.0	8.7	11.0	9.7	8.6	11.1
NT wheat 25N	8.5	9.4	9.1	10.7	11.1	9.6	13.0	11.3	9.7	11.5
NT wheat 75N	10.4	13.5	11.6	12.3	14.6	12.5	13.6	13.2	11.9	12.8
Mean	9.5	11.3	10.6	12.1	13.5	11.1	13.6	11.6	11.0	11.8
l.s.d. ($P < 0.05$)	1.0	0.9	0.8	1.0	0.6	1.0	0.6	0.9	1.1	1.0

[A] Data from Strong *et al.* (2006).
[B] Data from Dalal *et al.* (2004*b*).
[C] Data from Dalal *et al.* (1998).

Gross margin and net return on crop water use

In addition to grain yield, wheat grain prices are based on protein concentration within the wheat classification (ASW, PHV, PH), which affects the economic returns from different treatments. The average gross margin for the period 1992–98 was highest (A$338 ha^{-1}) for the GL87–wheat treatment and lowest for the NT wheat 0N treatment (Table 3). For the experimental period, the CT wheat 75N, GL86–wheat, medics–wheat, NT wheat 75N and chickpea–wheat treatments had similar gross margins. Gross margins calculated for the period 1992–98 varied by more than one order of magnitude. During the experimental period, the chickpea–wheat treatment

Table 3. Range and mean values of crop water use, gross margin and net return of water use in different farming systems (1992–98)

Data show mean yields for both phases of 2-year rotations of lucerne–wheat, medic–wheat and chickpea–wheat, as well as conventional tillage (CT) and no-tillage (NT) continuous wheat fertilised at a rate of 0, 25 and 75 kg N ha^{-1} (CT wheat 0N, CT wheat 25N and CT wheat 75N, NT wheat 0N, NT wheat 25N and NT wheat 75N, respectively). GL86–, GL87– and GL88–wheat, grass + legume (GL)–wheat rotation, with pastures established in 1986, 1987 and 1988, respectively

Farming system	Crop water use (mm)		Gross margin (A$ ha^{-1})		Net return/water use (A$ ha^{-1} mm^{-1})	
	Range	Mean	Range	Mean	Range	Mean
GL86–wheat	154–275	222	13–622	276	0.09–2.92	1.21
GL87–wheat	154–286	227	14–686	338	0.09–2.89	1.42
GL88–wheat	138–207	186	21–455	217	0.15–2.19	1.08
Lucerne–wheat	127–255	210	–25–414	192	–0.19–2.15	0.87
Medics–wheat	146–310	229	–28–571	272	–0.19–2.56	1.08
Chickpea–wheat	192–270	230	73–561	240	0.36–2.31	1.02
CT wheat 0N	159–262	213	–2–412	149	–0.01–1.96	0.69
CT wheat 25N	174–278	224	28–591	227	0.14–2.62	1.02
CT wheat 75N	188–281	221	14–611	283	0.07–2.83	1.25
NT wheat 0N	184–247	217	–32–434	130	–0.17–1.90	0.57
NT wheat 25N	170–263	219	–21–485	190	–0.11–2.09	0.86
NT wheat 75N	167–281	227	14–559	254	0.08–2.36	1.06
Mean		221		229		1.01
l.s.d. ($P = 0.05$)		8		55		0.22

had the minimum variability in gross margin (minimum A\$73 ha^{-1} in 1995 and maximum a A\$561 ha^{-1} in 1992). For all treatments, the minimum gross margins were recorded in 1994–95 and the maximum gross margins were recorded in 1992 following the long-term fallow period (December 1990–May 1992). A wheat crop was not sown in 1991 due to insufficient sowing rainfall.

Negative gross margins were also recorded in some years for certain treatments (Table 3). For example, the NT wheat 0N, NT wheat 75N and CT wheat 0N treatments in 1994 recorded negative gross margins of –32, –21 and –2 A\$ ha^{-1} respectively. The lucerne–wheat and medics–wheat treatments also recorded negative gross margins in 1995 of –25 and –28 A\$ ha^{-1} respectively.

The net return for the amount of water used by the wheat crop varied from –0.19 A\$ ha^{-1} mm^{-1} for the lucerne–wheat and medics–wheat treatments in 1995 to 2.92 A\$ ha^{-1} mm^{-1} for the GL86–wheat treatment in 1992. The average net return for each 1 mm of water used was highest for the GL87–wheat treatment during the period 1992–98 (Table 3). For this period, the average gross margin and crop water use were significantly correlated ($R^2 = 0.63$, $P < 0.01$; Fig. 3), except for the 1993 season.

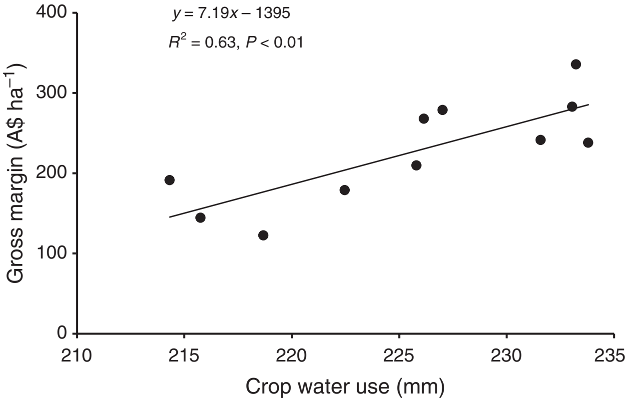

Fig. 3. Relationship between crop water use and gross margin for the period 1992–98.

Soil organic C and total N

Across the 12-year experimental period, the first 8 years of soil organic C and total N concentration values were reported by Dalal *et al.* (1995). During the pasture phase, soil organic C stocks generally increased in the GL86–wheat, GL87–wheat and GL88–wheat treatments compared with the CT wheat 0N treatment (Fig. 4*a*). Soil organic C increased significantly during the pasture phase (0–4 years) and the following year after pasture root residue incorporation (5th year) during tillage operations to prepare the land for the wheat crop phase. However, during the remaining wheat crop phase (6 years), organic C declined until it reached similar concentrations to that at the start of the experiment.

There were no consistent effects of the short-term lucerne–wheat, medic–wheat, chickpea–wheat rotations, or tillage and N fertiliser application on soil organic C stocks over the 12-year period. In general, organic C decreased in soil under these treatments for the duration of the experiment, although it decreased, on average, by only 0.04 t ha^{-1} $year^{-1}$ (0.5 t C ha^{-1} over the 12-year period).

Root biomass was estimated in December 1989 for the GL86 and GL87 pastures and for all other treatments in December 1990 (Dalal *et al.* 1995). For the 0–1.2 m soil profile, root biomass was highest in the GL pastures at the end of the pasture phase (9.8, 10.7 and 9.2 t ha^{-1} in the GL86, GL87 and GL88 pastures respectively), lowest in the chickpea

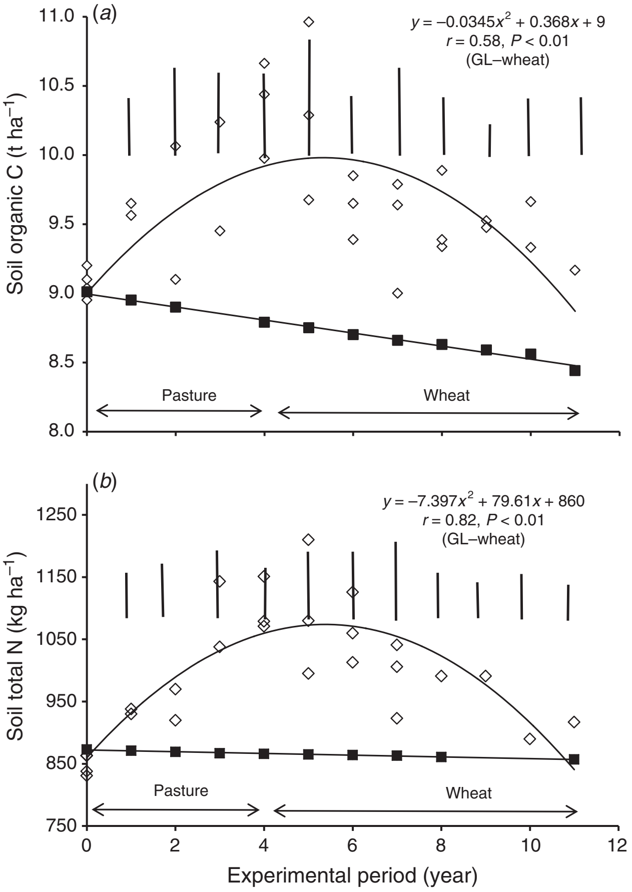

Fig. 4. Effects of grass + legume (GL) pasture on (*a*) organic C stocks and (*b*) total N stocks during the pasture phase (1986–89, 1987–90 and 1988–91) and following cereal cropping from 1990 to 1998. (◇), pasture–wheat rotation, GL–wheat (GL86–wheat, GL87–wheat, GL88–wheat); (■), conventional tillage continuous wheat fertilised at a rate of 0 kg N ha^{-1} (CT wheat 0N). Soil organic C and total N concentration values up to 1994 (i.e. the first 8 years) are given in Dalal *et al.* (1995). Bar heights show l.s.d. values at $P < 0.05$.

(2.03 t ha^{-1}) and wheat (1.65–2.2 t ha^{-1}) cropping systems and intermediate in the lucerne (4.3 t ha^{-1}) and medics phase (3.94 t ha^{-1}). The proportion of total root biomass in the 0–0.1 m depth was 20–30% in GL pasture, 30–35% in the lucerne and medics pastures, 47% in chickpea crops and up to 35% in wheat crops.

Over the course of the experiment, soil total N stocks for the pasture phases followed a similar trend to those of soil organic C (Fig. 4*b*). Total N stocks increased significantly during the pasture phase under the GL86–wheat, GL87–wheat and GL88–wheat treatments and reached a maximum value by Year 5 when plots were converted to wheat cropping (Fig. 4*b*). During the wheat cropping phase, total soil N stocks decreased each year, until after 6 years of wheat cropping they were similar to those under continuous wheat cropping. However, other treatments showed inconsistent effects on total soil N stocks. For example, the Lucerne 1988–wheat (L88-wheat) and Medic 1988–wheat (M88-wheat) only had higher total soil N stocks during the legume phase in Years 5 and 6, and the CT wheat 75N and NT wheat 75N treatments only had higher total soil N stocks in Year 6 compared with the CT wheat 0N treatment.

Deep leaching of nitrate

Potential nitrate leaching in the soil from different treatments was assessed from the amount of nitrate-N in the 1.2- to 1.5-m depth interval at the end of the experiment (after 12 years). The soil NO_3-N values were highest in the GL87–wheat rotation (42 kg N ha^{-1}; Fig. 5*a*). The CT wheat 75N (25 kg N ha^{-1}) and the NT wheat 75N (22 kg N ha^{-1}) treatments contained similar amounts of NO_3-N, which were higher than the CT wheat 0N and NT wheat 0N (6 kg N ha^{-1}) treatments. Nitrate-N in the lucerne–wheat (11 kg N ha^{-1}) and the chickpea–wheat (9 kg N ha^{-1}) treatments was not significantly higher than that in the CT wheat 0N treatment, whereas nitrate-N content in the GL86–wheat and medics–wheat treatments was higher than in the CT wheat 0N treatment, but similar to that in the lucerne–wheat and the chickpea–wheat rotations.

Nitrate-N in at a depth of 1.2–1.5 m accumulated steadily over the experimental period, especially in the last 4 years following three below-average crop growing seasons (1993–95). This demonstrated that nitrate-N mineralised from soil and/or added through fertiliser could accumulate if it was not used by the crop, and subsequently leach deep in the soil profile. This is shown for the GL86–wheat, CT wheat 0N and CT wheat 75N treatments (Fig. 5*b*).

Discussion

Grain yield and protein concentration

Nitrogen supply is critical for optimising crop yields in most environments (Strong *et al.* 1996*b*; Campbell *et al.* 2007). In the present study, the highest grain yields were obtained in the chickpea–wheat rotation and the NT wheat 75N treatment due to a balance between plant-available water and nitrogen supply. In comparison, in the lucerne–wheat rotation yield was depressed despite adequate N supply because of inadequate plant-available water. Similarly, in the CT wheat 0N and NT wheat 0N treatments, yield was depressed due to insufficient N for optimum yields, despite adequate plant-available water (Dalal *et al.* 1997, 2013). These data corroborate the findings of Holford and Crocker (1997) for similar rotations on a Vertosol.

Nitrogen supply to wheat is also important for increasing grain protein concentrations (Strong *et al.* 1996*b*). Without N either from a legume or fertiliser N, protein concentrations in the CT wheat 0N and NT wheat 0N treatments remained generally low throughout the experimental period (1988–98) in this N-depleted soil (Dalal and Mayer 1986*b*). Nitrogen supply from either the legumes (chickpea, legume pasture) or fertiliser enhanced protein concentrations by as much as 5% (Table 3; Strong *et al.* 1996*b*, 2006; Dalal *et al.* 1998, 2004*b*; Weston *et al.* 2002). Herridge *et al.* (1995), Hossain *et al.* (1996*b*), Marcellos *et al.* (1998) and Dalal *et al.* (1998) observed additional N supply following a chickpea crop of 28–51 kg N ha^{-1}. Nitrogen supply from pasture legumes was much higher, up to 100 kg N ha^{-1} year^{-1} (Hossain *et al.* 1996*b*; Holford and Crocker 1997; Holford *et al.* 1998; Weston *et al.* 2002; Dalal *et al.* 2004*b*; Strong *et al.* 2006), and there was a

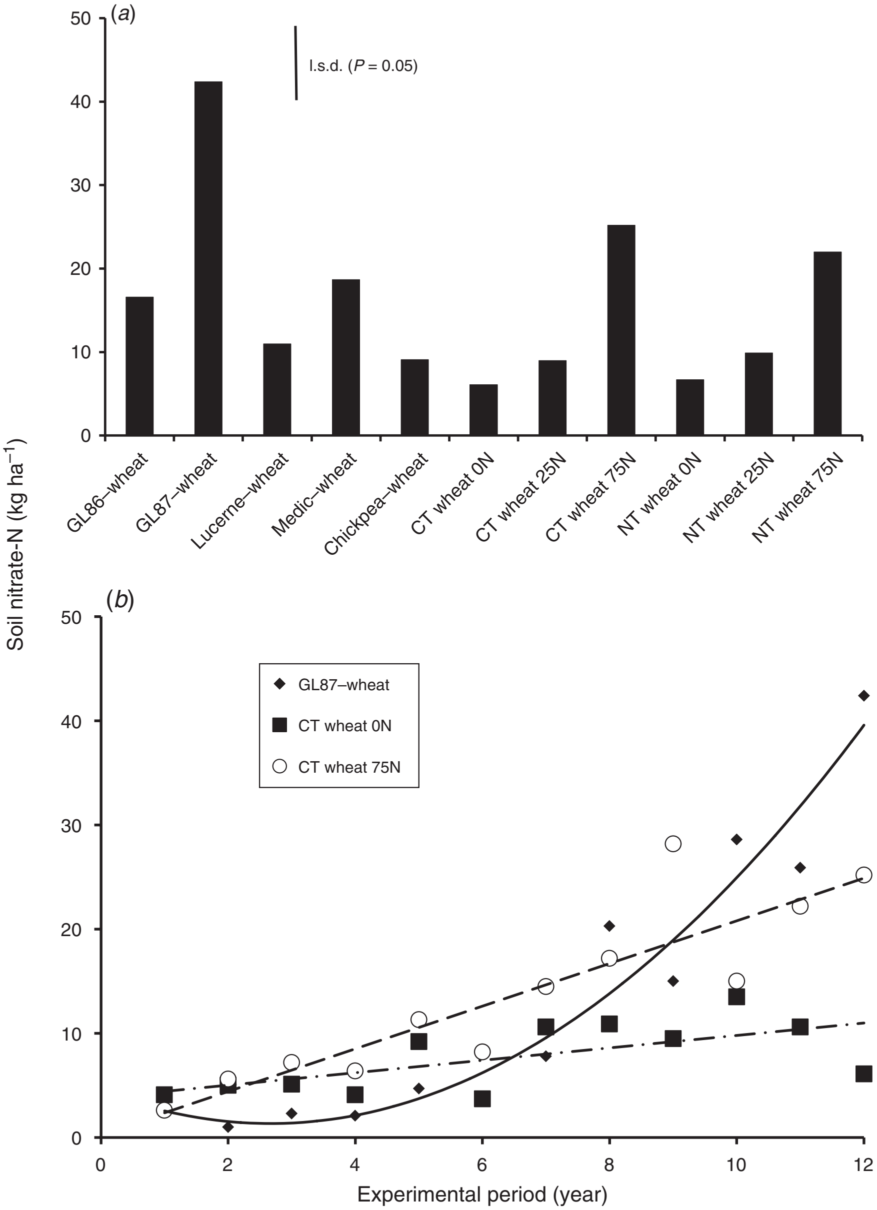

Fig. 5. (*a*) Amount of residual nitrate-N present at the end of the 12-year experiment in the 1.2 to 1.5-m depth interval in each rotation and (*b*) the trend in nitrate-N accumulation during the 12-year period shown for three different treatments. (◆), grass + legume (GL)–wheat rotation for pasture established in 1987 (GL87–wheat; $y = 0.44x^2 - 2.34x + 4.46$; $r = 0.97$, $P < 0.01$); (■), control (conventional tillage continuous wheat fertilised at a rate of 0 kg N ha^{-1} (CT wheat 0N; $y = 0.60x + 3.8$; $r = 0.64$, $P < 0.05$); (○), conventional tillage continuous wheat fertilised at a rate of 75 kg N ha^{-1} (CT wheat 75N; $y = 2.05x + 0.32$; $r = 0.89$, $P < 0.01$).

boost in grain protein concentrations following the pasture legumes (Table 2).

Economic analysis

Thomas *et al.* (2010) showed that net returns from wheat following grain legumes (chickpea, faba beans), pasture legumes (lucerne, annual medics) and fertiliser N applications generally resulted in positive gross margins in this semi-arid environment for dryland agriculture. Similar results were obtained in the present study. For example, in the 1992 season, when both water and N supply to the wheat crop were adequate following long fallow, the highest gross margin (A\$483 ha^{-1}) and net return (A\$2.18 $\text{ha}^{-1}\,\text{mm}^{-1}$) were obtained as compared with all the years (1992–98; mean A\$229 ha^{-1} and A\$1.01 $\text{ha}^{-1}\,\text{mm}^{-1}$ respectively). The average gross margins were higher in the GL87–wheat, CT wheat 75N, GL86–wheat, medics–wheat, NT wheat 75N and chickpea–wheat treatments than the CT wheat 0N treatment (additional income of A\$100–180 ha^{-1} year^{-1}). Furthermore, Thomas *et al*. (2010) showed that gross margins could be further increased in the chickpea–wheat treatment if fertiliser N was applied to the following wheat crop to match plant-available water and nitrogen at sowing according to the relationship developed by Dalal *et al*. (1997). It appears that optimising crop water use is also associated with increasing gross margin (Fig. 3). This is consistent with the findings of Dalal *et al*. (2013), who showed that water use efficiency and nitrogen use efficiency in the N-fertilised wheat crops were interlinked. These observations also possibly apply to the legume-N supply to the following wheat crops (Thomas *et al*. 2010).

Thomas *et al*. (2010) suggested a potential benchmark of net return of A\$1 ha^{-1} mm^{-1} for the cropping system in this environment. In the present study, this long-term target was achieved or exceeded for the GL–wheat, medics–wheat, chickpea–wheat, CT wheat 25N, CT wheat 75N and NT wheat 75N treatments (1992–98; Table 3). For the lucerne–wheat treatment, it was usually the soil water deficit after lucerne, in some years, that adversely affected the yield of the following wheat crop (McCallum *et al*. 2001; Dalal *et al*. 2004*b*), which resulted in the average net return of less than A\$1 ha^{-1} mm^{-1} (A\$0.87 ha^{-1} mm^{-1}). However, in the CT wheat 0N and NT wheat 0N treatments (average net return A\$0.60 ha^{-1} mm^{-1}), the lack of sufficient N supply to the wheat crop limited both yield and protein concentrations (Strong *et al*. 1996*b*).

Negative gross margins and net returns were obtained in seasons when in-crop rainfall was insufficient to produce optimum yields commensurate with N supply, either from pasture legume or fertiliser N. For example, the in-crop rainfall from sowing to anthesis was only 11 mm in 1994 and 48 mm in 1995. This reduced income from the sale of grains because variable costs were similar to those in the good in-crop rainfall season. One option, especially for fertiliser N, is to reduce the rate of N application when there is either not enough soil water at sowing or in-crop rainfall is likely to be low (although, in this region, seasonal in-crop rainfall is difficult to predict). Dalal *et al*. (1997) suggested that grain protein concentration can be predicted from crop-available water and nitrogen in the soil profile at sowing so that fertiliser N applications are made at sowing to achieve target protein levels (11.5–12%) that are optimum for grain yields (Strong *et al*. 1996*b*), and PH wheat (≥13%). Admittedly, such adjustments are not feasible following pasture legumes (Holford *et al*. 1998) such as lucerne–wheat, where there is sufficient N supply but a deficit in plant-available water in some seasons (McCallum *et al*. 2001; Dalal *et al*. 2004*b*).

Soil organic C and total N

As reported previously for measurements made until 1994 in the present study (Dalal *et al*. 1995), soil organic C stocks significantly increased in the GL pasture treatments (GL86, GL87 and GL88) compared with the CT wheat 0N treatment in the 0- to 0.1-m depth interval only (Fig. 4). Similar findings have been reported for other experiments and pasture systems in this environment and soil type (Hossain *et al*. 1996*a*; Holford *et al*. 1998; Armstrong *et al*. 1999; Thomas *et al*. 2009), as well as in other regions and soil types (Chan *et al*. 2011; Salvo *et al*. 2014; Robertson *et al*. 2016). No consistently significant increase in soil organic C was observed in the 2-year pasture–crop rotations (lucerne–wheat, medics–wheat), the 2-year chickpea–wheat rotation or the continuous CT and NT wheat at 25 and 75 kg N ha^{-1} applications, thus corroborating the findings of Robertson and Nash (2013) for different cropping systems in Victoria, Australia.

Dalal *et al*. (1995) observed that the root biomass of the GL pastures (GL86, GL87 and GL88) was approximately 10 t ha^{-1} compared with approximately 4 t ha^{-1} for lucerne and medics and <2.5 t ha^{-1} for chickpea and wheat crops in the 0- to 1.2-m profile in a good pasture and crop growth season (December 1990). We found a significant relationship between soil organic C and root biomass at depths of 0–0.1 and 0–1.2 m at this site in 1990 (Fig. 6*a*, *b*). Assuming roots contained 40% C, except for the GL pastures, only <0.6 t ha^{-1} (0–0.1 m) of C was added to the soil from these farming systems. Because root biomass C is the primary contributor to soil organic C (Rasse *et al*. 2005; Fig. 6), to maintain soil organic C stocks even at a depth of 0–0.1 m in this soil requires >0.6 t C ha^{-1} each year (Dalal and Mayer 1986*b*) or >1.5 t ha^{-1} root biomass (0–0.1 m depth). This was achieved only during the GL pasture phase (>2 t C ha^{-1}; Fig. 6*a*). Thus, increases in soil organic C were only consistently achieved under the GL pasture phase, corroborating the findings of Chan *et al*. (2011) and Salvo *et al*. (2014).

Rabbi *et al*. (2015) also found that increases in soil organic C stocks in agricultural soils could only be achieved if cropping lands were converted to pastures, although climate and soil properties limited the magnitude of the soil organic C storage that could be achieved (Robertson *et al*. 2016). Once the legume phase was terminated in the present study, soil organic C declined during the cropping phase for six wheat crops until it reached the original soil organic C stock, and reached similar levels to that in the CT wheat 0N treatment at the end of the experiment (12 years; Fig. 4). Based on these observations, we propose that 4 years of the GL phase followed by 4–6 years of wheat crop phase may maintain soil organic C stocks in this and possibly other soils (Grace *et al*. 1995; Holford *et al*. 1998). Studdert *et al*. (1997) also suggested that in their pasture–crop rotations, a maximum of 7 years of conventional cropping should be followed by a minimum of 3 years of pasture phase to maintain soil organic C levels on a loess soil (Argiudoll) in Argentina. For increasing soil carbon levels, fewer than four crops may be desirable following the pasture phase if carbon stocks are to be increased or at least maintained in the long term.

The total soil N stocks under different treatments, especially those in the GL86–wheat, GL87–wheat and GL88–wheat treatments followed similar trends to that of soil organic C (C : N ratio 9.5–10.5 during the experimental period). Hossain *et al*. (1996*a*), in an adjacent grazing experiment, found that after 4 years the soil under GL pastures had 258 kg ha^{-1} N more than the continuous wheat treatment (at a depth of 0–0.1 m), which is similar to that measured in the present study for the GL86–wheat, GL87–wheat and GL88–wheat at the end of the pasture phase (mean (± s.e.m.) 215 ± 90 kg ha^{-1}; Fig. 4*b*). The N accreted under the legume phase when mineralised to nitrate-N during the cropping phase not only increases both grain

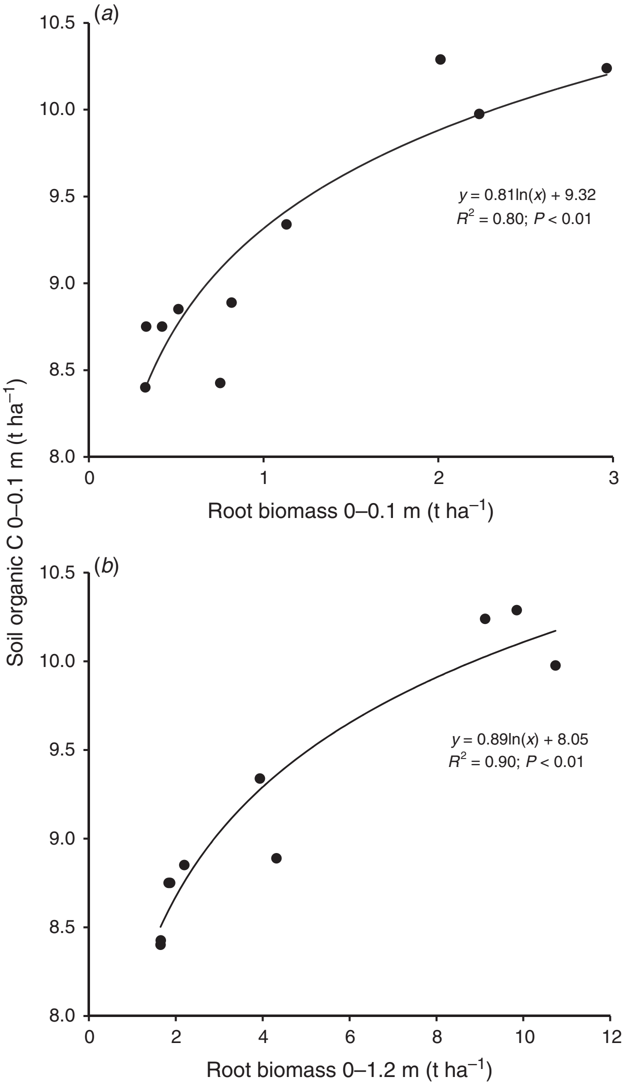

Fig. 6. Relationships between soil organic C at a depth of 0–0.1 m and root biomass at depths of (*a*) 0–0.1 m and (*b*) 0–1.2 m. Treatments included a 4-year rotation of grass + legume pasture followed by wheat (GL–wheat) for pastures established in 1986, 1987 and 1988, 2-year rotations of lucerne–wheat, medic–wheat and chickpea–wheat and continuous conventional tillage (CT) or no-tillage (NT), without or with fertiliser N application at rates of 0, 25 (25N) and 75 kg N ha^{-1}. Root biomass was not measured for the CT wheat 25N and NT wheat 25N treatments.

yield and grain protein (Strong *et al.* 2006), but also provides a potential source of N_2O production as a greenhouse gas (Dalal *et al.* 2003), as well as deep leaching of nitrate-N.

Deep leaching of nitrate-N

Deep leaching of nitrate-N occurred when there was an increased level of residual nitrate-N in the soil profile. High residual nitrate-N levels were present in legume-based pastures (Hossain *et al.* 1996*b*; Holford *et al.* 1998; Strong *et al.* 2006) or with continuous wheat where fertiliser N was applied (Campbell *et al.* 1994; Strong *et al.* 1996*a*). Nitrate-N build-up in the soil profile generally occurred during the period when crop growth was poor due to inadequate water supply, and the crop could not effectively use soil and/or fertiliser available N. Subsequent rainfall during the fallow period and further N mineralisation and/or fertiliser N addition resulted in nitrate-N accumulation at depths below 1.2 m. Consequently, significant amounts of nitrate-N accumulation occurred in the GL87–wheat and the CT wheat 75N and NT wheat 75N treatments (Fig. 5*a*, *b*). In these treatments, for example, the proportion of nitrate-N and fertiliser N in the fertilised treatments (kg N ha^{-1}) to that of the plant-available water at sowing (mm) at a depth of 0–1.2 m was close to 1 or higher (0.9–1.27), compared with <0.4 in the other treatments (data not shown). In their earlier work, Dalal *et al.* (1997) recommended that PH wheat (≥13% grain protein) can be produced when the plant-available water (mm) is matched by nitrate-N (plus fertiliser N; kg ha^{-1}) at a depth of 0–1.2 m. However, in the long term such a recommendation could also lead to excess nitrate-N accumulation in the soil profile, N_2O emissions and potential nitrate leaching below the root zone.

Conclusion

The comparative productivity of the different farming systems examined in the present 12-year study showed that wheat grain yields on this soil are maintained by either 4-year GL pasture–wheat rotations, 2-year chickpea–wheat rotations or CT or NT wheat with 75 kg N ha^{-1} fertiliser application. However, long-term deep leaching of nitrate-N needs to be monitored. Soil organic C stocks could only be increased under the grass + pasture phase. The 4-year pasture phase followed by 4–6 years of continuous wheat cropping may maintain the initial soil organic C and N stocks in the long term. A shorter wheat cropping phase is required if soil organic C stocks are to be increased over the long term under GL–wheat rotations in this soil. Partial economic analysis (gross margin, net return) of the treatments showed that restoring or maintaining soil N fertility, either through legume-based pastures, grain legume and/or N fertiliser, provides long-term sustainable yields and a positive economic return.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

The authors thank the farmers (Peter Bock and Tim Reid) for their permission to set up the Warra Experiment on their land, the Queensland Wheat Research Committee and Grains Research and Development Corporation for their financial support, and Christine Holmes, Ainslie Pumfrey, Judy Glasby, Errol Best, John Hagedorn, John Standley and Alison Cockburn for field assistance and laboratory analysis. The authors thank Greg Thomas for his assistance in obtaining background information on grain prices and variable costs, Kathryn Page for proof reading and the reviewers for their valuable comments.

References

Armstrong RD, Kuskopf BJ, Millar G, Whitbread AM, Standley J (1999) Changes in soil chemical and physical properties following legumes and opportunity cropping on a cracking clay soil. *Australian Journal of Experimental Agriculture* **39**, 445–456. doi:10.1071/EA99014

Best EK (1976) An automated method for the determination of nitrate-nitrogen in soil extracts. *Queensland Journal of Agricultural and Animal Sciences* **33**, 161–166.

Campbell CA, Lafond GP, Zentner RP, Jame YW (1994) Nitrate leaching in a udic haploboroll as influenced by fertilisation and legumes. *Journal of Environmental Quality* **23**, 195–201. doi:10.2134/jeq1994.00472425002300010030x

Campbell CA, Zentner RP, Basnyat P, Wang H, Selles F, McConkey BG, Gan YT, Cutforth HW (2007) Water use efficiency and water and nitrate distribution in soil in the semi-arid prairie: effect of crop type over 21 years. *Canadian Journal of Plant Science* **87**, 815–827. doi:10.4141/CJPS06034

Chan KY, Conyers MK, Li GD, Helyar KR, Poile G, Oates A, Barchia IM (2011) Soil carbon dynamics under different cropping and pasture management in temperate Australia: results of three long-term experiments. *Soil Research* **49**, 320–328. doi:10.1071/SR10185

Cook GD, So HB, Dalal RC (1992) Structural degradation of two Vertisols under continuous cultivation. *Soil & Tillage Research* **24**, 47–64. doi:10.1016/0167-1987(92)90071-I

Crooke WM, Simpson WE (1971) Determination of ammonium in Kjeldahl digests of crops by an automated procedure. *Journal of the Science of Food and Agriculture* **22**, 9–10. doi:10.1002/jsfa.2740220104

Dalal RC, Mayer RJ (1986*a*) Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. II. Total organic carbon and its rate of loss from the soil profile. *Australian Journal of Soil Research* **24**, 281–292. doi:10.1071/SR9860281

Dalal RC, Mayer RJ (1986*b*) Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. V. Rate of loss of total nitrogen from the soil profile and changes in carbon–nitrogen ratios. *Australian Journal of Soil Research* **24**, 493–504. doi:10.1071/SR9860493

Dalal RC, Sahrawat KL, Myers RJK (1984) Inclusion of nitrate and nitrite in the Kjeldahl nitrogen determinations of soils and plant materials using sodium thiosulphate. *Communications in Soil Science and Plant Analysis* **15**, 1453–1461. doi:10.1080/00103628409367572

Dalal RC, Strong WM, Weston EJ, Gaffney J (1991) Sustaining multiple production systems. 2. Soil fertility decline and restoration of cropping lands in sub-tropical Queensland. *Tropical Grasslands* **25**, 173–180.

Dalal RC, Strong WM, Weston EJ, Cooper JE, Lehane KJ, King AJ, Chicken CJ (1995) Sustaining productivity of a Vertosol at Warra, Queensland, with fertiliser, no-tillage, or legumes. 1. Organic matter status. *Australian Journal of Experimental Agriculture* **35**, 903–913. doi:10.1071/EA9950903

Dalal RC, Strong WM, Weston EJ, Cooper JE, Thomas GA (1997) Prediction of grain protein in wheat and barley in a subtropical environment from available water and nitrogen in Vertosols at sowing. *Australian Journal of Experimental Agriculture* **37**, 351–357. doi:10.1071/EA96126

Dalal RC, Strong WM, Weston EJ, Cooper JE, Wildermuth GB, Lehane KJ, King AJ, Holmes CJ (1998) Sustaining productivity of a Vertisol at Warra, Queensland, with fertilisers, no-till or legumes. 5. Wheat yields, nitrogen benefits, and water-use efficiency of chickpea–wheat rotation. *Australian Journal of Experimental Agriculture* **38**, 489–501. doi:10.1071/EA98027

Dalal RC, Wang W, Robertson GP, Parton WJ (2003) Nitrous oxide emission from Australian agricultural lands and mitigation options: a review. *Australian Journal of Soil Research* **41**, 165–195. doi:10.1071/SR02064

Dalal RC, Weston EJ, Strong WM, Lehane KJ, Cooper JE, Wildermuth GB, King AJ, Holmes CJ (2004*a*) Sustaining productivity of a Vertosol at Warra, Queensland, with fertiliser, no-tillage and legumes. 7. Yield, nitrogen and disease-break benefits from lucerne in a two-year lucerne–wheat rotation. *Australian Journal of Experimental Agriculture* **44**, 607–616. doi:10.1071/EA02115

Dalal RC, Weston EJ, Strong WM, Probert ME, Lehane KJ, Cooper JE, King AJ, Holmes CJ (2004*b*) Sustaining productivity of a Vertosol at Warra, Queensland, with fertiliser, no-tillage and legumes. 8. Effect of duration of lucerne ley on soil nitrogen and water, wheat yield and protein. *Australian Journal of Experimental Agriculture* **44**, 1013–1024. doi:10.1071/EA03166

Dalal RC, Strong WM, Cooper JE, King AJ (2013) Relationship between water use and nitrogen use efficiency discerned by ^{13}C discrimination and ^{15}N isotope ratio in bread wheat grown under no-till. *Soil & Tillage Research* **128**, 110–118. doi:10.1016/j.still.2012.07.019

Department of Primary Industries (2000) ‘Winter crop management notes.’ (Kingswood Press: Underwood, Qld)

Grace PR, Oades JM, Keith H, Hancock TW (1995) Trends in wheat yields and soil organic carbon in the permanent rotation trial at the Waite Agricultural Research Institute, South Australia. *Australian Journal of Experimental Agriculture* **35**, 857–864. doi:10.1071/EA9950857

Herridge DF, Marcellos H, Felton WI, Turner GL, Peoples MB (1995) Chickpea increases soil N fertility in cereal systems through nitrate sparing and N_2 fixation. *Soil Biology & Biochemistry* **27**, 545–551. doi:10.1016/0038-0717(95)98630-7

Holford ICR, Crocker GJ (1997) A comparison of chickpea and pasture legumes for sustaining yields and nitrogen status of subsequent wheat. *Australian Journal of Agricultural Research* **48**, 305–315. doi:10.1071/A96072

Holford ICR, Schweitzer BE, Crocker GJ (1998) Comparative effects of subterranean clover, medic, lucerne, and chickpea in wheat rotations, on nitrogen, organic carbon, and moisture in two contrasting soils. *Australian Journal of Soil Research* **36**, 57–72. doi:10.1071/S97036

Hossain SA, Dalal RC, Waring SA, Strong WM, Weston EJ (1996*a*) Comparison of legume-based cropping systems at Warra, Queensland. I. Soil nitrogen and organic carbon accretion and potentially mineralisable nitrogen. *Australian Journal of Soil Research* **34**, 273–287. doi:10.1071/SR9960273

Hossain SA, Strong WM, Waring SA, Dalal RC, Weston EJ (1996*b*) Comparison of legume-based cropping systems at Warra, Queensland. II. Mineral nitrogen accumulation and availability to subsequent wheat crop. *Australian Journal of Soil Research* **34**, 289–297. doi:10.1071/SR9960289

Marcellos H, Felton WL, Herridge DF (1998) Chickpea in wheat-based cropping systems of northern New South Wales. 1. N_2 fixation and influence on soil nitrate and water. *Australian Journal of Agricultural Research* **49**, 391–400. doi:10.1071/A97066

McCallum MH, Connor DJ, O’Leary GJ (2001) Water use by lucerne and effect on crops in the Victorian Wimmera. *Australian Journal of Agricultural Research* **52**, 193–201. doi:10.1071/AR99164

Newman EI (1966) A method of estimating the total length of root in a sample. *Journal of Applied Ecology* **3**, 139–145. doi:10.2307/2401670

Page K, Dalal RC, Menzies NW (2002) Nitrification in a Vertisol subsoil and its relationship to the accumulation of ammonium-nitrogen at depth. *Australian Journal of Soil Research* **40**, 727–735. doi:10.1071/SR01087

Rabbi SMF, Tighe M, Delgado-Baquerizo M, Cowie A, Robertson F, Dalal R, Page K, Crawford D, Wilson BR, Schwenke G, Mcleod M, Badgery W, Dang YP, Bell M, O’Leary G, Liu DL, Baldock J (2015) Climate and soil properties limit the positive effects of land use reversion on carbon storage in Eastern Australia. *Nature Scientific Reports* **5**, 17866. doi:10.1038/srep17866

Rasse DP, Rumpel C, Dignac MF (2005) Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. *Plant and Soil* **269**, 341–356. doi:10.1007/s11104-004-0907-y

Robertson F, Nash D (2013) Limited potential for soil carbon accumulation using current cropping practices in Victoria, Australia. *Agriculture, Ecosystems & Environment* **165**, 130–140. doi:10.1016/j.agee.2012.11.004

Robertson F, Crawford D, Partington D, Oliver I, Rees D, Aumann C, Armstrong R, Perris R, Davey M, Moodie M, Baldock J (2016) Soil organic carbon in cropping and pasture systems of Victoria, Australia. *Soil Research* **54**, 64–77. doi:10.1071/SR15008

Salvo L, Hernandez J, Ernst O (2014) Soil organic carbon dynamics under different tillage systems in rotations with perennial pastures. *Soil & Tillage Research* **135**, 41–48. doi:10.1016/j.still.2013.08.014

Sims JR, Haby VA (1971) Simplified colorimetric determination of soil organic matter. *Soil Science* **112**, 137–141. doi:10.1097/00010694-197108000-00007

Snedecor GW, Cochran WG (1967) 'Statistical methods.' 6th edn. (Iowa State University Press: Ames, IA)

Strong WM, Dalal RC, Cahill MJ, Weston EJ, Cooper JE, Lehane KJ, King AJ, Chicken CJ (1996*a*) Sustaining productivity of a Vertosol at Warra, Queensland, with fertiliser, no-tillage or legumes. 3. Effect of nitrate accumulated in fertilised soil on crop response and profitability. *Australian Journal of Experimental Agriculture* **36**, 675–682. doi:10.1071/EA9960675

Strong WM, Dalal RC, Weston EJ, Cooper JE, Lehane KJ, King AJ, Chicken CJ (1996*b*) Sustaining productivity of a Vertosol at Warra, Queensland, with fertiliser, no-tillage and legumes. 2. Long-term fertiliser needs to enhance wheat yields and grain protein. *Australian Journal of Experimental Agriculture* **36**, 665–674. doi:10.1071/EA9960665

Strong WM, Dalal RC, Weston EJ, Lehane KJ, Cooper JE, King AJ, Holmes CJ (2006) Sustaining productivity of a Vertosol at Warra, Queensland, with fertiliser, no-tillage and legumes. 9. Production and nitrogen benefits from mixed grass and legume pastures in rotation with wheat. *Australian Journal of Experimental Agriculture* **46**, 375–385. doi:10.1071/EA05007

Studdert GA, Echeverria HE, Casanovas EM (1997) Crop–pasture rotation for sustaining the quality and productivity of a Typic Argiudoll. *Soil Science Society of America Journal* **61**, 1466–1472. doi:10.2136/sssaj1997.03615995006100050026x

Thomas GA, Dalal RC, Weston EJ, Lehane KJ, King AJ, Orange DN, Holmes CJ, Wildermuth GB (2009) Pasture–crop rotations for sustainable production in a wheat and sheep-based farming system on a Vertisol in south-west Queensland, Australia. *Animal Production Science* **49**, 682–695. doi:10.1071/EA07170

Thomas GA, Dalal RC, Weston EJ, King AJ, Holmes CJ, Orange DN, Lehane KJ (2010) Crop rotations for sustainable grain production on a Vertisol in the semi-arid subtropics. *Journal of Sustainable Agriculture* **35**, 2–26. doi:10.1080/10440046.2011.530195

Tkachuk R (1966) Nitrogen-to-protein conversion factor for wheat flour. *Cereal Chemistry* **43**, 223–225.

Wang WJ, Dalal RC (2015) Nitrogen management is the key for low-emission wheat production in Australia: a life cycle perspective. *European Journal of Agronomy* **66**, 74–82. doi:10.1016/j.eja.2015.02.007

Weston EJ, Dalal RC, Strong WM, Lehane KJ, Cooper JE, King AJ, Holmes CJ (2002) Sustaining productivity of a Vertosol at Warra, Queensland, with fertiliser, no-tillage and legumes. 6. Production and nitrogen benefits from annual medic in rotation with wheat. *Australian Journal of Experimental Agriculture* **42**, 961–969. doi:10.1071/EA01083