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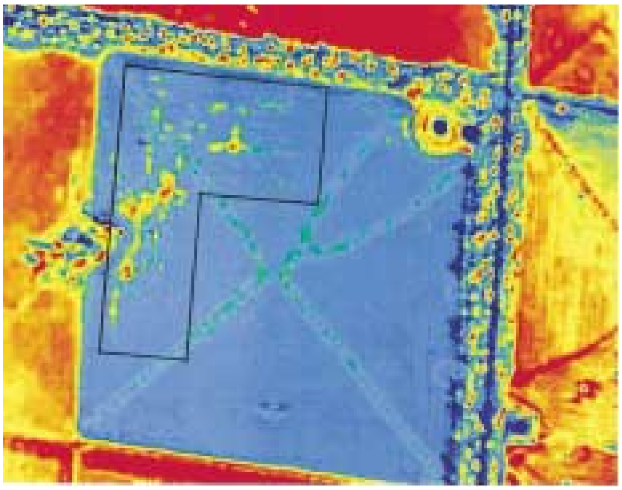

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Sustaining productivity of a Vertisol at Warra, Queensland, with fertilisers, no-tillage or legumes. 6. Production and nitrogen benefits from annual medic in rotation with wheat

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Abstract. Continuous cereal production in the summer-dominant rainfall region of north-eastern Australia has depleted native soil nitrogen fertility to a level where corrective strategies are required to sustain wheat grain yields and high protein levels for domestic and export markets. Annual medic pastures, along with other strategies, were evaluated from 1986 to 1998 on a Vertisol at Warra, southern Queensland, for their benefit to subsequent grain yield and protein content of wheat.

Annual medic production and nitrogen yields were closely correlated with the growing season rainfall (March–September). Each 100 mm of growing season rainfall resulted in 1.39 t/ha of dry matter and 40 kg/ha of N yield.

There were significant increases in soil mineralisable nitrogen following annual medic leys compared with continuous wheat in most years, but increases in total soil nitrogen were only observed in 1990, 1991 and 1992. However, pre-plant nitrate-nitrogen following an annual medic ley was always higher than that of continuous wheat without nitrogen fertiliser. This resulted in significant increases in wheat yield (6 of 9 seasons) and grain protein (in all seasons) compared with continuous wheat. The overall responses in yield and protein were similar to those of 50 kg/ha of fertiliser nitrogen applied to continuous wheat crops. A nitrogen harvest budget for the annual medic–wheat rotation over 11 years showed that it contributed 131 kg N/ha more than continuous wheat. Thus, using the seasonal conditions experienced from 1987 to 1998 as a reasonable representation of the rainfall range in the region, sustainable productivity can be maintained where annual medics are grown in short rotations with wheat.

Introduction

The cropping lands of subtropical Queensland that have been used for grain production for up to 100 years are based on a summer fallow–winter crop system. Dalal and Mayer (1986*a*) reported the run-down in soil organic matter status with continuous cultivation and cropping for a range of soil types in southern Queensland. Associated with this change, the levels of available nitrogen (N) also declined to the extent that wheat yields and protein levels were not commensurate with plant available water and rainfall.

While virgin arable land was available, fertility depleted soils could be retired from cropping and regional production maintained. However, with expansion of cropping, new fertile land is becoming scarce (Weston *et al*. 1981) and the need to develop sustainable management systems has become an imperative for maintaining productivity. Components of these systems include the use of fertilisers, changes in tillage techniques, the use of grain legumes, and the development of crop–pasture rotations.

Ley pastures (defined here as legume, grass, or grass + legume pastures grown in rotation with crops) have traditionally been a preferred method for maintaining soil fertility in temperate regions. They became widely adopted in the cereal belt of temperate Australia in the 1950s (Schultz 1996) and provided the basis for a relatively stable pattern of land use. In the subtropics, however, pasture–crop rotations have received less commercial acceptance. This is despite more than 4 decades of investigation and the reporting of significant benefits in grain yield and protein in subsequent sorghum (Holford 1989) and wheat crops (Hossain *et al*. 1996*b*; Weston *et al*. 2000).

Annual medic, a hard seeded self-regenerating temperate legume is available to modify soil fertility when grown in rotation with wheat. Between 1930 and 1940 annual medic pastures (annual *Medicago* species) were adopted into southern Australian cereal farming systems (Puckridge and French 1983). The use of various annual *Medicago* species, together with superphosphate applications to the southern

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Australian Chromosols (red brown earths) and Kandosols (red earths), improved soil fertility and led to increased cereal yields and increased sheep and cattle production (Peoples *et al*. 2001).

Although annual medics are mainly found in zones with a Mediterranean climate, they have naturalised widely in the subtropics of eastern Australia (southern Queensland and northern New South Wales). While they are less exposed to a range of insect pests, which reduce plant production in southern Australia (such as red-legged earth mite, Sitona weevil and flea), in this environment they have to contend with a highly variable, summer dominant rainfall (Weston 1988). Clarkson *et al*. (1987) observed that annual medics are adapted to a large area of southern inland Queensland. They measured annual medic above ground dry matter (DM) yield of 4.8 t/ha.year over a 4-year period near Warwick while Lloyd and Hilder (1985) recorded annual medic DM of 4.1 t/ha.year over 6 years on a Vertisol near Toowoomba.

The amount of N fixed by annual medic is closely associated with the total amount of DM produced (Ledgard and Peoples 1988; Holford 1989; Peoples and Baldock 2001), and therefore, N benefits to subsequent wheat crops depend on the productivity of the legumes in the ley phase. Using an enriched-^{15}N method, Hossain *et al*. (1995) found that 56 kg/ha of N_2 was fixed by annual medic in its above-ground DM at Warra, southern Queensland, in 1988; a similar value (50 kg N/ha) was measured using a natural abundance ^{15}N method. Following the annual medic phase, substantial increase in mineral N was also observed (Hossain *et al*. 1996*a*) and this was reflected in increased wheat grain yield and protein in 1989 (Hossain *et al*. 1996*b*). Unfortunately, long-term effects of annual medic in the annual medic–wheat rotation were not measured in that study. Since seasonal variability is a strong feature of the subtropical environment, it is necessary to measure annual medic production, fertility restoration and wheat crop yields following annual medic over a longer term for assessing the sustainability of annual medic–wheat rotation in this environment.

In this study at Warra in southern inland Queensland, research was commenced in 1986 that aimed to arrest and/or correct soil fertility decline. It involved a comparison of alternative farming practices (Dalal *et al*. 1995; Strong *et al*. 1996*a*, 1996*b*; Weston *et al*. 2000) on crop production and soil fertility. While wheat grain yields and grain proteins were increased by the application of N fertilisers and/or chickpea (*Cicer arietinum*) in rotation with wheat, soil fertility restoration was not significant (Dalal *et al*. 1995). An alternative strategy was to use ley pasture rotations (Hossain *et al*. 1995). We report in this paper annual medic production and its N benefits to the following wheat crop in annual medic–wheat rotations, commencing in 1987 and terminating with the second or third wheat bioassay crop following 4 cycles of the rotation.

Materials and methods

Site details

The study was carried out at Warra (26°47′S, 150°53′E) in southern Queensland. Soil at the site had been cultivated for cereal cropping since about 1935 and the organic matter of this Vertisol (Typic Chromustert) was depleted from 2.23% organic C to 0.68% organic C and from 0.203% total N to 0.06% total N from the 0–10 cm layer (Dalal and Mayer 1986*b*, 1986*c*). The site represents 0.7 million ha of cultivated lands in southern and central Queensland that originally supported brigalow (*Acacia harpophylla*) and belah (*Casuarina cristata*) vegetation and where there is an arable potential of 4 million ha (Weston *et al*. 1981). Details of the soil characteristics, mean monthly maximum and minimum temperatures, and mean monthly rainfall at the field site (1987–94) are described in earlier papers of this series (Dalal *et al*. 1995; Strong *et al*. 1996*a*). Briefly, the soil is alkaline at the surface (pH 8.6) trending to strongly acidic (pH 4.9) at 1.2 m depth, and with 56% clay content. Mean annual rainfall and annual medic growing season rainfall (Mar.–Sept.) are shown in Table 1. Annual rainfall varied from 439 mm in 1997 (28% below average), to 800 mm in 1998 (30% above average).

Experimental design

The experimental details of this study are given in Dalal *et al*. (1995). Briefly, annual medics (self-regenerating, temperate annual legumes of the genus annual *Medicago*) were grown in rotation with wheat (Table 2) as one of several options for maintaining and/or improving the fertility of depleted soil and sustaining productivity. Other types of pastures were leys, and grass + legume leys. Options were studied in a core experiment of 17 treatments with 4 replicates, which was not grazed. Plot size was 6.75 by 25 m, which was 3 runs of a 2.25 m wheat planter. In addition, pasture treatments were repeated as duplicate plots in an area adjacent to the core experiment where they were grazed by sheep.

Rotations

Two short annual medic–wheat rotations of 2 years duration (i.e. 1 year annual medic and 1 year wheat), in treatments 6 and 7 were repeated 4 times between 1988 and 1996 (Table 2). The sequence of annual medic years in treatment 6 was 1988, 1990, 1992 and 1994, and that of subsequent wheat cropping was 1989, 1991 (drought, no wheat crop), 1993 and 1995. In treatment 7, the annual medic sequence was 1989, 1991, 1993 and 1995, and that of subsequent wheat cropping was 1990, 1992, 1994 and 1996. Treatment 6 plots were sown to wheat (wheat bioassay) in 1996–98 and treatment 7 in 1997–98.

Table 1. Annual rainfall and annual medic growing season (Mar.–Sept.) rainfall at the Warra study site from 1987 to 1998

Year	Total rainfall (mm)	Mar.–Sept. rainfall (mm)
1987	578	207
1988	759	412
1989	734	338
1990	560	360
1991	545	74
1992	485	166
1993	597	212
1994	578	161
1995	726	136
1996	767	348
1997	439	129
1998	800	492
Mean	612	241

Pasture establishment

Wheat was undersown with annual medic in 1987 to provide an annual medic sward in 1988 (taken as the commencement year and described as treatment 6) and a wheat crop followed this in 1989. In treatment 7, wheat was undersown with annual medic in 1988 to be followed by an annual medic sward in 1989 (the commencement year for that treatment) and this was followed by wheat in 1990 (Table 2). In subsequent annual medic swards and wheat crops, the annual legume was self-regenerating.

Annual medics were composed of both snail annual medic (*M. scutellata* L.Mill. cvv. Robinson, Sava, Essex and Kelson) and barrel annual medic (*M. truncatula* Gaertn. cvv. Jemalong, Cyprus, Paraggio, and Sephi). The under-sowing of 5 kg/ha of the seed mixture was adjusted for seed numbers to give equal opportunities to both snail and barrel annual medics in the sward.

Pasture management

Ungrazed (core experiment) plots were forage harvested to a height of 10 cm at 3-monthly sampling intervals. Pastures in the adjacent study were grazed by sheep to a similar height during the 4 weeks before sampling.

Senescence occurred each year in early October, the commencement of the summer fallow. Weeds were controlled during the summer fallow in the core experiment by hand chipping. Sheep provided weed control for the adjacent grazed pasture plots. Wheat plots were fallowed using stubble retention machinery (Strong *et al.* 1996*a*).

Pasture measurements

At quarterly intervals, in March, June, September and December, legumes and weeds were sampled for DM yield and composition. Five quadrats of 1 by 1 m were used for sampling. At annual medic senescence in October, an additional DM measurement was made. Plant material was dried at 75°C, weighed and ground to pass through a 1 mm sieve and DM %N determined by Kjeldahl analysis (Crooke and Simpson 1971).

Table 2. Sequence of pasture and crop in the two treatments of two-year annual medic–wheat rotations (AM–W) and wheat–wheat rotations (W–W), with and without fertiliser application

Wm, wheat undersown with annual medic in the first year; M, annual medic ley; W, wheat; W50, wheat with 50 kg/ha of fertiliser N per crop; d, wheat not sown due to drought [see Dalal *et al*. (1995) for full treatment details]

In 1997 and 1998, wheat was sown to assay residual nitrate-N

Year	Treatment 6 AM–W	Treatment 7 AM–W	Treatment 10 W–W 0 kg N/ha	Treatment 13 W–W 50 kg N/ha
1987	Wm	W	W	W50
1988	M	Wm	W	W50
1989	W	M	W	W50
1990	M	W	W	W50
1991	d	M	d	d
1992	M	W	W	W50
1993	W	M	W	W50
1994	M	W	W	W50
1995	W	M	W	W50
1996	W	W	W	W50
1997	W	W	W	W50
1998	W	W	W	W50

Crop and soil management

Following a 6–7 month summer fallow, wheat (variety Hartog) was sown (0.25 m row spacing) at a rate of 40 kg/ha when sown in May or June or 50 kg/ha when sown in July (1990, 1993). Little weed control was required during wheat cropping, thus allowing annual medic to contribute a small amount of dry matter and seed in the wheat phase to the overall rotation.

A basal rate of 10 kg of phosphorus as superphosphate, fortified with copper and zinc, was applied at wheat sowing annually. Pastures were top-dressed with the same fertiliser annually and at the same rate.

Crop measurements

Above ground DM yields were estimated just before wheat harvest from 1 m lengths of 2 adjacent plant rows. After drying at 75°C and separation of grain and straw, weights of each were recorded. Grain yield was measured by machine harvesting a 23 m length of the central 7 rows of each plot. Grain yields were adjusted to 12% moisture content and grain and straw %N determined by Kjeldahl analysis.

Nitrogen fixation by the annual medic was estimated in 1988 and 1992 using ^{15}N natural abundance (Ledgard and Peoples 1988). Milk thistle (*Sonchus oleraceus* L.) was used as a reference plant (Hossain *et al*. 1995; Dalal *et al*. 1997*a*).

Soil sampling and analysis

Soil was sampled annually to a depth of 1.5 m in May and November for soil water and nitrate contents. Two soil cores of 50 mm diameter were pooled by 0.1 m layers to a depth of 0.3 m and by 0.3 m layers below 0.3 m depth and stored at 4°C until analysis. Soil was dried at 35°C under draught, and ground to <2 mm for colorimetric determination of nitrate (Best 1976) after extraction of 10 g of soil in 100 mL of 2 mol KCl/L. Soil moisture content was determined gravimetrically and converted to volumetric soil moisture content (mm/layer) using a bulk density adjusted for the soil moisture content for the layer (Strong *et al*. 1996*a*).

Soil was sampled annually in May to a depth of 0.1 m to determine total-N by modified Kjeldahl method (Dalal *et al*. 1984) after fine grinding to <0.25 mm and mineralisable-N by the waterlogged procedure of Waring and Bremner (1964).

Nitrogen harvest budget

A balance sheet of N budget was calculated for the 11 years from 1988 to 1998 from the N removed in the produce (wheat grain N, N removed in forage from cut and removal treatment), and residual nitrate-N in the soil profile (0–1.5 m depth) after the 1998 wheat harvest since total soil N levels at the end of the experiment in 1998 were similar for all treatments. No account was taken of possible N losses due to volatilisation and/or denitrification in either annual medic–wheat or wheat–wheat rotations. Nitrate-N losses below 1.5 m depths were negligible.

Results

Above-ground dry matter production and nitrogen yield

A comparison of DM and plant N yields indicated no significant difference between the ungrazed (core experiment) and the grazed annual medic leys (data not shown), thus confirming the earlier observations of Hossain *et al*. (1995, 1996*a*, 1996*b*). Therefore, only the results for the ungrazed experiment are presented below.

Total annual DM yield of annual medic varied from 0.63 t/ha in 1991 to 6.32 t/ha in 1988 (Table 3). Total N yield was correspondingly highest in 1988 (161 kg N/ha), falling to 15 kg/ha in 1991. There was only a small contribution to DM yield from the annual medic in the cropping years with

N yields less than 8 kg N/ha.year. Both DM and N yields were significantly correlated with growing season rainfall (March to September inclusive). The slopes of the regression lines were 13.9 ± 1.3 kg DM/ha.mm rainfall ($r^2 = 0.82$), and 0.4 ± 0.03 kg N/ha.mm rainfall ($r^2 = 0.95$).

Pasture production and total N yields were greatest in the first part of the study period (1988 to 1990 inclusive) but very low thereafter except for 2 years of moderate production (1993 and 1994), thus reflecting the pattern of growing season rainfall. In most years, the September medic harvest provided the highest DM yield. Forage was removed only when annual medic swards grew taller than 10 cm at the time of sampling. This occurred almost exclusively during 1988–90. The amount of DM removed varied from 2.73 t/ha in 1988 to 1.01 t/ha in 1990; none was removed during 1991–95. The amount of N removed in the forage varied from 27 kg/ha in 1990 to 73 kg/ha in 1988.

Total soil nitrogen and mineralisable nitrogen

Total soil N (Fig.1*a*) was higher after the annual medic sward than the continuous wheat. However, the increase due to the annual medic ley was significant ($P<0.05$) for only 2 of the 4, 2-year cycles commencing in 1988 (treatment 6) and for only 1 of the 4, 2-year cycles commencing in 1989 (treatment 7). Increases in other years (1989, 1993) just failed to reach significance. Soil total N increases ranged from 60 kg/ha to 150 kg/ha.

Mineralisable N was also higher after the annual medic swards than the continuous wheat (Fig. 1*b*). Effects were significant ($P<0.05$) in all years except the first year (treatment 6 in 1989). Thus, mineralisable N was a more sensitive indicator than total N in demonstrating the ability of annual medic to increase the supply of potentially available soil N. The increases in mineralisable N ranged from <10 kg/ha to >30 kg/ha, which were usually lower than nitrate-N values (Table 4).

Table 3. Total above-ground dry matter (DM) and N yields (kg/ha) of annual medic in the medic–wheat rotations

The DM production and total N yield of self regenerating annual medic under the wheat crop in 1987 averaged 204 and 4.45 kg/ha, respectively

Year	DM (t/ha)	N (kg N/ha)
1988	6.32	161
1989	5.36	137
1990	3.59	96
1991	0.63	15
1992	1.74	45
1993	2.36	56
1994	3.09	70
1995	0.75	22
Mean	2.98	75
l.s.d. ($P = 0.05$)	0.53	13

Available nitrogen

In May, before wheat sowing, nitrate-N in the wheat–wheat rotation ranged from 35 to 89 kg N/ha while following the annual medic leys, nitrate-N ranged from 92 kg N/ha to 240 kg N/ha to a depth of 1.2 m (Table 4). Therefore, more nitrate-N was present following annual medic leys; additional nitrate-N ranged from 49 to 180 kg N/ha. Over the 8-year period (1989–96), mean nitrate-N after the medic phase was 88 kg/ha greater than in the wheat–wheat rotation. In treatment 6, nitrate-N accumulated to very high levels following good annual medic growth at the start of the study and low N removal associated with poorer wheat growing seasons. Increases in soil nitrate-N were observed down to 0.9 m depth early in the rotation years but in 1995 there were increases down to 1.5 m depth (Fig. 2). In contrast, treatment 7 displayed very little accumulation except in 1996, as its wheat crops were grown in better seasons and produced higher grain yields, thus utilising more nitrate-N.

Plant available soil water

Available soil water to 1.2 m depth at wheat sowing in May (Table 4), and its distribution within the soil profile to 1.5 m (Fig. 2) were similar for the annual medic–wheat rotations (treatments 6 and 7) and the wheat–wheat rotation for all years except 1995 and 1996. Only at the harvest of wheat crops in 1989 and 1990 was plant available water lower in the annual medic–wheat rotations than in the wheat–wheat rotation. This is consistent with greater water removal associated with higher grain yields. Overall, about

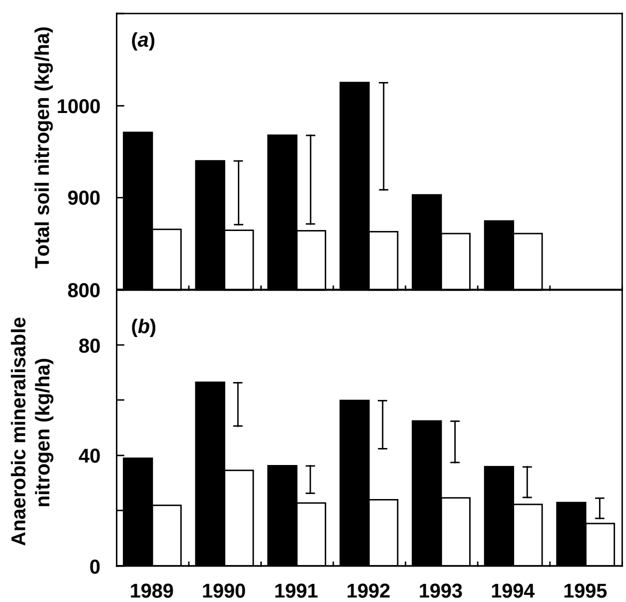

Figure 1. (*a*) Total soil N and (*b*) mineralisable N after the annual medic (solid bars) in annual medic–wheat rotations and wheat–wheat rotation (open bars) with 0 kg N/ha fertiliser application. The bar heights represent the l.s.d. at $P = 0.05$ between treatments.

Table 4. Soil nitrate-N and plant available water (both 0–1.2 m) in May (pre-sowing time) following 6 months of fallow after annual medic in the annual medic–wheat rotation (AM–W) compared with wheat–wheat rotation (W–W) without fertiliser N

Year	Nitrate-N (kg/ha)			Plant available soil water (mm)		
	AM–W	W–W	l.s.d. (P = 0.05)	AM–W	W–W	l.s.d. (P = 0.05)
1989	92	35	13	192	195	n.s.
1990	118	38	18	170	165	n.s.
1991	96	38	34	90	95	n.s.
1992	138	89	47	148	151	n.s.
1993	134	35	55	88	85	n.s.
1994	77	47	ns	164	176	n.s.
1995	240	62	73	93	124	26
1996	190	40	59	190	168	23
Mean	136	48		142	145	

30 mm less water was present in the annual medic–wheat rotation than in the wheat–wheat rotation in 1995 (0.3–0.9 m depth). In 1996 the reverse occurred and the wheat–wheat rotation had 30 mm less moisture than the annual medic–wheat rotation (0.6–1.2 m depth). However, over the 8-year period (1989–96), plant available soil water at sowing was essentially identical (142 *v.* 145 mm) in both the medic–wheat and wheat–wheat rotations (Table 4).

Wheat yields and grain protein concentrations

Significant (P<0.05) grain yield increases were measured following annual medic in most years (7 of 10 crops) compared with the wheat–wheat rotation with no N fertiliser (Table 5). Application of 50 kg N/ha.crop (treatment 13) also increased grain yields in 1989, 1990, 1994 and 1996. Wheat yields following annual medic were higher than those from wheat–wheat with 50 kg N/ha.crop application in 1996, 1997 and 1998 in treatment 6 and in 1990 in treatment 7. However, in 3 dry years (1993, 1994 and 1995), wheat grain yields following annual medic were significantly lower than those of wheat–wheat with 50 kg N/ha.crop application. The mean annual grain yields for crops grown during 1989–98 were 2.36 t/ha, 2.91 t/ha, 2.41 t/ha and 1.96 kg/ha for wheat in rotation with annual medic in treatments 6 and 7, wheat–wheat with 50 kg/ha of fertiliser N annually (treatment 13), and wheat–wheat without fertiliser (treatment 10), respectively.

Table 5. Wheat grain yield (t/ha) in annual medic–wheat rotations (AM–W), compared with non-N-fertilised and N-fertilised wheat–wheat rotations (W–W)

Year	AM–W	W–W 0 kg N/ha	W–W 50 kg N/ha	l.s.d. (P = 0.05)
1989	2.70	2.07	2.82	0.27
1990	3.59	2.23	3.14	0.28
1991[A]				
1992	3.84	3.48	3.72	0.59
1993	1.33	1.88	1.88	0.18
1994	1.34	1.02	1.58	0.20
1995	0.49	1.20	0.80	0.18
1996	4.17	2.27	3.79	0.34
1997	2.79	2.11	2.21	0.37
1998	2.18	1.40	1.71	0.38
Mean	2.63	1.96	2.41	—

[A]Drought, with no wheat crop sown.

Wheat grain proteins following the annual medic leys were always significantly higher than those from the wheat–wheat rotation without N fertiliser (Table 6). Overall, annual medic in the rotation increased grain proteins by 32% compared with a 25% increase in protein from 50 kg/ha.year of N fertiliser.

Nitrogen harvest

During the 11 years of the experiment (1988–98), the 2 annual medic–wheat rotations had similar N removal in grain and forage, with an average value of 483 kg N/ha, and exceeded the N removal in the wheat–wheat rotation without N fertiliser by 131 kg N/ha (Table 7). The N harvest in continuous wheat with 50 kg N/ha annual fertiliser application was slightly higher (540 kg/ha) than that from the annual medic–wheat rotation (Table 7). Water shortage in the dry seasons from 1992 to 1995, accompanied by N accumulation, caused yield suppression and poor N fixation and crop utilisation. However, this was offset by stronger production in the N enhanced treatments when seasonal conditions became favourable.

Discussion

Ungrazed and grazed pasture management

Managing the forage production from a ley pasture in a rotation experiment is always difficult. Grazing of plots, randomised within a major experimental layout, is costly and operationally difficult. Cutting and removing of forage production on a regular basis is easier but leaves an unanswered question of the impact of grazing on pasture production and composition. In this study ‘cut and remove’ (non-grazed) was the management method used in the core experiment and grazed plots were established in an adjacent area to provide grazing impact information. There was no dry matter yield difference between annual medic leys managed by grazing with sheep and non-grazed leys. Hossain *et al*. (1996*a*) reported no significant differences in soil organic carbon or total N between the grazed and the non-grazed management at this site in the first 4 years. Vallis *et al*. (1982) found that almost 75% of the N from urine patches was volatilised as ammonia in a subtropical pasture. Since the soil at the Warra site was alkaline (pH 8.6), losses of this magnitude were to be expected and were comparable with the N removed by cutting and removal of annual medic in the core experiment.

Annual medic dry matter production and nitrogen yield

Growing season rainfall conditions were the major contributing factor to the annual medic production pattern, and hence to the N yield. Both annual dry matter yields and N yields were closely correlated with growing season rainfall. Each mm of growing season rainfall increased DM by 13.9 kg/ha and N yields by 0.4 kg N/ha. These relationships are similar to those obtained by Clarkson (1986), and those summarised by Peoples and Baldock (2001) for southern Australia. Also, on average 23 kg N/ha was contained in each tonne of DM produced by the annual medic; again, this value is within the range of 20–25 kg N/ha

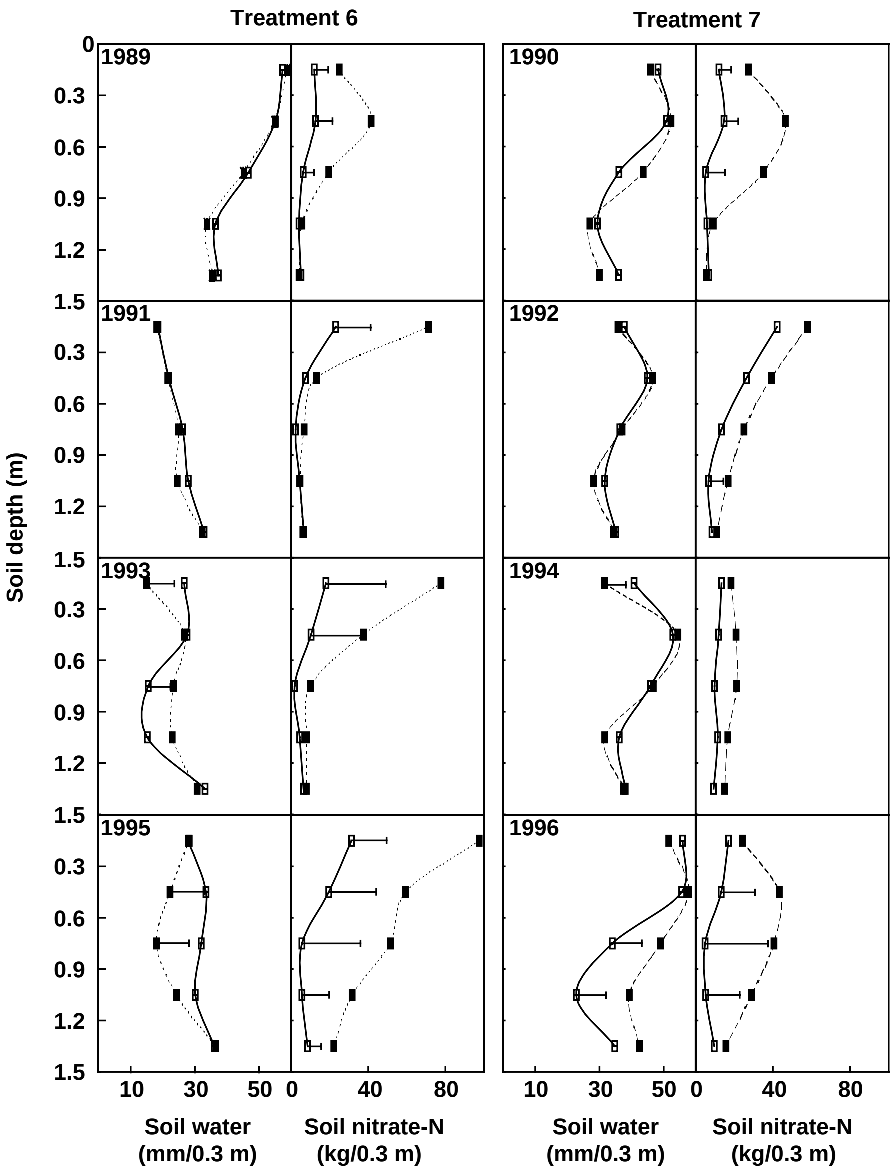

Figure 2. Distribution of plant available water and nitrate-N in the soil profile in May (pre-sowing for wheat), measured after 6 months' summer fallow following annual medic leys in annual medic–wheat rotation (---) and wheat–wheat rotation with 0 kg N/ha fertiliser application (—). The bar width represents l.s.d. at $P = 0.05$.

Table 6. Wheat grain protein (%) in annual medic–wheat rotations (AM–W), compared with non-N-fertilised and N-fertilised wheat–wheat rotations (W–W)

Year	AM–W	W–W 0 kg N/ha	W–W 50 kg N/ha	l.s.d. (P = 0.05)
1989	13.2	8.0	10.7	0.9
1990	12.1	8.3	10.0	0.8
1991[A]				
1992	12.7	10.8	12.7	1.0
1993	16.3	9.6	15.1	0.6
1994	12.1	8.7	11.2	1.0
1995	15.6	11.8	14.4	0.6
1996	12.6	10.2	12.2	0.9
1997	11.8	9.0	11.0	1.1
1998	11.9	10.6	11.5	0.6
Mean	12.9	9.7	12.1	—

[A]Drought year with no wheat crop sown.

for pasture legumes reported by Peoples and Baldock (2001).

Soil water and nitrate-nitrogen

The progressive increase in the amount and downward movement of nitrate-N results from the 1991–95 period of low crop production and N removal due to low growing season rainfall (Fig. 2). This was exacerbated by a crop failure in 1991 when no planting rain was received.

The plant available water in the soil profile following either annual medic or wheat was similar in most years (Fig. 2). Water storage in 1993 and 1995 showed some variability but was inconsistent. In these dry years wheat yields on high N plots were lower than those in the monoculture wheat without additional N, suggesting that the very high levels of nitrate-N may have been detrimental to wheat yields during low rainfall crop seasons (van Herwaarden *et al*. 1998).

Table 7. Estimated N harvest (kg/ha) from the annual medic–wheat rotation (AM–W; mean values of treatments 6 and 7) and the wheat–wheat rotation (W–W; the residual nitrate-N values in 1998 after wheat harvest are given in parentheses)

Year	AM–W	W–W 0 kg N/ha	W–W 50 kg N/ha	l.s.d. (P = 0.05)
1988	56.9	44.5	90.7	10.4
1989	62.4	29.0	52.9	7.6
1990	51.6	32.5	55.1	7.2
1991[A]				
1992	42.2	65.7	82.5	13.6
1993	19.0	31.6	49.6	4.4
1994	14.2	15.6	31.0	5.5
1995	7.2	24.8	20.1	4.4
1996	92.2	40.6	81.5	9.1
1997	55.3	33.2	42.5	7.9
1998	45.5	26.3	35.1	8.5
1998	(36.6)	(8.7)	(20.6)	(28.5)
Total	483.1	352.5	541.6	15.0

[A]Drought year with no grain crop sown.

Wheat yield and protein

The benefits of pasture legumes in rotation with wheat are considerable, almost equivalent to the addition of 50 kg/ha of fertiliser N and 20% greater than wheat–wheat rotation without N fertiliser application despite the non-cropping pasture years (Table 5). Protein increases ranged from 21 to 43% (Table 6).

In the highly seasonal variable environment of the subtropics, although total N removal from the annual medic–wheat rotations from treatments 6 and 7 were similar, the wheat yield and protein outcomes were quite different. While mean grain yield over 10 seasons was 2.36 t/ha in treatment 6, it was 2.91 t/ha in treatment 7; the corresponding mean protein concentrations were 13.9 and 11.8%. This was directly associated with the differences in growing season rainfalls for treatments 6 and 7, which were commenced only 12 months apart. During the late 1980s and 1990s the value of wheat crops was strongly influenced by protein level and >13.0% protein (Prime Hard classification) was important in achieving maximum returns. In treatment 7, the Prime Hard grade wheat yield was never achieved while in treatment 6 it was achieved in all but one year. This was due to the combination of wheat crop pre-sowing differences in nitrate-N and soil water in the soil profile between treatment 6 and treatment 7.

Although wheat grain yield was poorly correlated with pre-sowing plant available water or soil nitrate concentrations (Tables 4 and 5), wheat grain protein (Table 6) was closely correlated with the ratio of plant available water and nitrate-N (r^2 = 0.89) (Dalal *et al*. 1997*b*). Thus, impact on water as well as N must be considered following annual medic in annual medic–wheat rotations.

Nitrogen harvest and sustainable farming systems

Over the 11-year period, an extra 131 kg/ha of N was removed from the rotations with annual medic pastures compared with continuous wheat receiving no fertiliser N. This compares favourably with the chickpea–wheat rotation (Dalal *et al*. 1998) and wheat–wheat cropping with 50 kg N/ha.crop fertiliser application. Schultz (1995) in describing a long-term rotation trial at Tarlee, reported that the best wheat yields were always in rotations that include a grain legume or pasture legume phase.

Conclusion

Annual medic in rotation with wheat was part of a larger rotation experiment that involved comparisons between fertiliser N, tillage methods, grain legumes, and other short-term as well as longer-term pasture leys. In favourable cropping seasons, the treatments that provided the top quartile of wheat yields and protein concentrations always included the annual medic–wheat rotations.

The benefits from annual medic in annual medic–wheat rotation were due to N accretion and moderate demands on soil water use. Wheat yields and proteins were increased by incorporating annual medic in rotation and significantly out-performed wheat–wheat rotations without fertiliser N application, with a positive N balance compared with the latter over an 11-year period of this study. The annual medic–wheat rotation therefore, provides an attractive option for restoring the fertility of N-depleted soils and sustaining wheat production in the eastern subtropical region of the Australian cereal belt.

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