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Graze to grain—measuring and modelling the effects of grazed pasture leys on soil nitrogen and sorghum yield on a Vertosol soil in the Australian subtropics

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Abstract. Highly productive sown pasture systems can result in high growth rates of beef cattle and lead to increases in soil nitrogen and the production of subsequent crops. The nitrogen dynamics and growth of grain sorghum following grazed annual legume leys or a grass pasture were investigated in a no-till system in the South Burnett district of Queensland. Two years of the tropical legumes *Macrotyloma daltonii* and *Vigna trilobata* (both self regenerating annual legumes) and *Lablab purpureus* (a resown annual legume) resulted in soil nitrate N (0–0.9 m depth), at sorghum sowing, ranging from 35 to 86 kg/ha compared with 4 kg/ha after pure grass pastures. Average grain sorghum production in the 4 cropping seasons following the grazed legume leys ranged from 2651 to 4012 kg/ha. Following the grass pasture, grain sorghum production in the first and second year was $<$1900 kg/ha and by the third year grain yield was comparable to the legume systems. Simulation studies utilising the farming systems model APSIM indicated that the soil N and water dynamics following 2-year ley phases could be closely represented over 4 years and the prediction of sorghum growth during this time was reasonable. In simulated unfertilised sorghum crops grown from 1954 to 2004, grain yield did not exceed 1500 kg/ha in 50% of seasons following a grass pasture, while following 2-year legume leys, grain exceeded 3000 kg/ha in 80% of seasons. It was concluded that mixed farming systems that utilise short term legume-based pastures for beef production in rotation with crop production enterprises can be highly productive.

Additional keywords: ley legumes, APSIM, modelling, simulation, mixed farming systems.

Introduction

In the northern grainbelt of Australia, which includes northern New South Wales and southern and central Queensland, declining soil fertility, poor and variable returns from grain production, and good returns from cattle enterprises have led many farmers to consider the role of ley pastures in their farming systems. Temperate legumes, the deep-rooted perennial lucerne (*Medicago sative* L.) and the annual *Medicago* spp., are integral components of some dryland mixed farming enterprises in southern Queensland and northern NSW. However, the use of these legumes in comparable systems in central Queensland is limited by their relatively poor adaptation. The annual species are limited by the low and variable winter rainfall environment that limits seed set (Conway *et al*. 2001), and lucerne persistence is restricted by hot conditions and wet soils in the summer that exacerbate root rotting diseases (Cameron 1973; Irwin 1974*a*, 1974*b*, 1977; Lloyd *et al*. 1985). The adoption of all *Medicago* spp. is also restricted by the risk of their causing bloat in cattle (D. L. Lloyd, pers. comm.). As an alternative to these temperate legume species, tropical annual legumes such as lablab (*Lablab purpureus* cvv. Highworth and Rongai) and cowpeas (*Vigna unguiculata*) have played a limited role as pasture leys to date.

A number of perennial summer-growing legumes are now known to be well adapted to lower rainfall (700–800 mm mean annual rainfall) areas in central and southern Queensland (Clem *et al*. 1996, 2001; Jones and Rees 1997; Pengelly and Conway 2000). These legumes have a range of characteristics that complement or provide alternatives to the temperate and tropical species described above. These include perennial legumes such as Milgarra butterfly pea (*Clitoria ternatea* cv. Milgarra), Endurance lablab (*Lablab purpureus* cv. Endurance), and burgundy bean (*Macroptilium bracteatum* cvv. Cardaga and Juanita) described by Whitbread *et al*. (2005). Self-regenerating legumes such as *Vigna trilobata* and *Macrotyloma daltonii* previously tested by the Queensland Department of Primary Industries and CSIRO remain unreleased but may be useful germplasm in the future.

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In a grazed pasture experiment described by Clem (2004) and Whitbread and Clem (2004) the animal production of cattle grazing tropical legumes, mixed perennial legume–grass pastures, and grass-only pastures was measured. This author found that both the longer term perennial legumes that persist with grass, and the forage legumes used in shorter-term leys, could provide high quality forage to finish cattle for premium beef markets.

The aim of this study was to assess the effect of grazed short-term legume leys and grass-only pastures on soil nitrogen dynamics and production of a 4-year grain sorghum phase following these pasture systems. To further understand the dynamics of mineral nitrogen (N), soil water, and crop growth of the sorghum phase, the farming systems model APSIM (Agricultural Production Systems Simulator) (Keating *et al.* 2003) was used to simulate the soil–plant system and analyse the potential grain production of sorghum following legume or grass pastures over a range of seasons.

Methodology

As described by Clem (2004), the experiment was located at the Brian Pastures Research Station (25°40′S, 151°45′E, elevation 136 m) on a moderately to strongly self-mulching Black Vertosol on a 3–10% slope, Ug5.34 (Northcote 1979), with weak linear gilgai (Reid *et al.* 1986). From the eight 2.5-ha replicated pasture treatments established in the summer of 1997–98 described by Clem (2004), 4 replicated pasture treatments were selected to test the response of sorghum production following termination of the ley pastures. The treatments selected were the improved grass pasture (*Bothriochloa insculpta* cv. Bisset, *Dichanthium sericeum*, and *Panicum maximum* var. trichoglume cv. Petrie), the annual legume pasture *Lablab purpureus* cv. Highworth, and the self-regenerating legume pastures *Macrotyloma daltonii* CPI 60303 and *Vigna trilobata* CPI 13671. Prior to the establishment of these pasture treatments in 1997–98, the grass treatments had been preceded by a history of grazed grass pasture, whereas the legume treatments had been preceded by 20+ years of crop production and pasture rotation.

The grass pasture treatments were situated slightly higher on the slope at the experimental site than the legume treatments and soil depth was restricted to about 0.90 m, below which clay parent material was found. Total organic carbon (measured by combustion) at the first soil sampling following termination of the grass pasture was 2% in the 0–0.15 m layer and 1.5% in the 0.15–0.3 m layer. The 3 legume treatments were located slightly lower on the slope where the soil depth varied between 0.9 and 1.2 m. On the legume treatments, total organic carbon at the first soil sampling was 1.7% in the 0–0.15 m layer and 1.4% in the 0.15–0.3 m layer.

Soil was characterised for plant-available water capacity (PAWC) following the procedures of Dalgliesh and Foale (1998). The drained upper limit (DUL, 392 mm at 0–0.9 m) was determined by wetting the soil to saturation, allowing drainage to take place over 2–3 weeks, and determining soil moisture content (Table 1). The crop lower limit (CLL, 221 mm), for sorghum was determined by placing a rainout shelter over a section of the 1999–2000 sorghum crop at flowering and determining the soil water content after the crop had reached maturity. Bulk density was measured on large cores collected during the determination of CLL. PAWC in the 0–0.9 m profile was therefore 171 mm.

Table 1. Soil properties of the experimental site near Mt Brambling, Brian Pastures, and the values used to specify the APSIM simulation at initialisation after the pasture phases

Layer number	1	2	3	4	5
Layer depth (mm)	150	150	300	300	300
Water content at air dry (mm/mm)	0.10	0.23	0.20	0.20	0.24
Crop lower limit (mm/mm)	0.24	0.26	0.24	0.24	0.28
Drained upper limit (mm/mm)	0.45	0.43	0.44	0.43	0.38
Saturated watercontent[A] (mm/mm)	0.48	0.46	0.47	0.46	0.41
Swcon[B]	0.3	0.3	0.3	0.3	0.3
Bulk density (g/cm^3)	1.23	1.29	1.28	1.30	1.44
Organic carbon (%)					
Legume	1.7	1.4	1.0	0.9	0.5
Grass	2.0	1.5	1.0	0.9	0.5
pH	7.0	7.0	7.0	7.0	7.0
NO_3-N (μg/g)					
M. daltonii	7.6	3.3	5.2	5.9	2.0
V. trilobata	5.2	2.2	2.2	3.4	2.0
L. purpureus	13.3	10.3	7.8	2.9	2.0
Grass	1.3	0.2	0.2	0.1	0.1
Finert[C]	0.45	0.55	0.80	0.99	0.99
Fbiom[D]	0.04	0.02	0.02	0.01	0.01

[A] Saturated water content calculated from total porosity – 0.05. Total porosity = 1 – (bulk density/particle size density assumed to be 2.65).

[B] Swcon determines the proportion of water above the DUL that will be drained each day. The Mt Brambling soil was considered have better drainage than the swcon = 0.2 of the Warra Vertosol soil described by Probert *et al.* (1998).

[C] Finert describes the proportion of initial organic carbon assumed to be inert. Assuming that all organic C measured at depth is essentially inert, this quantity is assumed to remain the same at all depths.

[D] Fbiom describes the initial biom as a proportion of non-inert C. These values are based on Probert *et al.* (1998).

Transition from pasture to sorghum

On 12 November 1999, following a heavy grazing by cattle, the plots previously sown to *M. daltonii*, *V. trilobata*, or *L. purpureus* or grass pasture were sprayed with a knockdown herbicide and kept free of weeds. On 7 January 2000, grain sorghum (Pioneer S75) was planted at 3.2 kg/ha into 0.25-m rows using a no-till planter into the pasture residues that remained on the surface. In the 3 subsequent seasons, sorghum was planted at 3.0–3.6 kg/ha into 0.9-m row spacings using sorghum variety Buster MR in 2000–01 and Pioneer M43 in 2001–02 and 2002–03 at the dates indicated in Table 2. In the final 2002–03 season, only the *M. daltonii*, and *L. purpureus* treatments were continued due to resource constraints.

Table 2. Timing of cropping operations during the 4 sorghum crops following the legume and grass pastures

Season	Planting	N split 1	N split 2	Harvest
1999–2000	7/01/00	28/01/00	3/03/00	18/04/00
2000–01	3/01/01	9/02/01	12/03/01	3/05/01
2001–02	13/12/01	24/01/02	13/02/02	22/04/02
2002–03	12/02/03	7/03/03	16/04/03	16/06/03

Within each plot, an area 20 by 5 m, representative of the larger plot was selected. This plot was split into 2 plots 10 by 5 m with one half receiving 80 kg N/ha (80N) (applied as urea by hand to the soil surface in 2 splits at the dates indicated in Table 2) and the other half no N (0N). These test areas remained in the same location during all 4 sorghum crops and N was applied to the same plot each year.

Seasonal conditions

During the period of the field trials, annual rainfall was generally near or below the average annual rainfall of 710 mm (Table 3). The in-crop rainfall received during the 1999–2000 sorghum crop was 138 mm, 222 mm during the 2000–01 season, 276 mm during the 2001–02 season, and 232 mm during the 2002–03 season.

Sampling of the sorghum crops

At physiological maturity, sorghum grain and stover were harvested for the determination of yield and N concentration. Two separate and centrally located 5-m rows within each plot were selected and the number of plants and grain heads were counted. The heads were cut from the plants, removed, and bagged and the remaining stover was cut at ground level and removed for weighing. Stover was dried in a forced-air dehydrator at 80°C for 48 h and weighed to determine dry matter. The sorghum heads were dried, threshed to remove grain, and weighed. Grain yield is expressed on an oven-dry basis. The straw and husk material from the threshed heads was added to the stover weights.

Total N content of the grain and stover samples were determined by colourimetric analysis (Crooke and Simpson 1971) after Kjeldahl digestion (Bremner 1965). Protein concentration of sorghum grain was calculated as %N in grain × 6.25.

Following each sorghum harvest, regrowth was sprayed with a knockdown herbicide, and after the withholding period, cattle grazed the plant residues.

Soil sampling for water and mineral N

Soil samples were taken in each test plot prior to planting and following harvest of the 4 sorghum crops and analysed for nitrate-N and water content. All samples were taken using a vehicle-mounted hydraulic soil sampler with cores to 0.9 m being sampled and partitioned into 0–0.15, 0.15–0.3, 0.3–0.6, and 0.6–0.9 m depth increments for analysis. Soil nitrate-N was determined using the method of Keeny and Nelson (1982) described in Raymond and Higginson (1992). Soil water content was determined after drying the soil samples at 100°C.

In-crop mineralisation (ICM) was calculated using Eqn 1 for the 0N treatments as suggested by Armstrong *et al*. (1999*b*):

$$\mathrm{ICM}\,(\mathrm{kg\,N/ha}) = (C_N \times 1.3) + \mathrm{Nitrate}_{\mathrm{AH}} - \mathrm{Nitrate}_{\mathrm{Sow}} \qquad (1)$$

where C_N is the above-ground N uptake by sorghum, and $\mathrm{Nitrate}_{\mathrm{AH}}$ and $\mathrm{Nitrate}_{\mathrm{Sow}}$ is the soil nitrate N measured to 0.9 m depth after harvest and before sowing of each sorghum crop, respectively. According to McNeill *et al*. (1998) a correction factor of 1.3 applied to the above-ground material will account for the likely proportion of plant N located below ground. The ICM calculation assumes no loss of N (via such mechanisms as volatilisation, denitrification, and leaching).

APSIM simulation

APSIM Version 3.6 was used to simulate the soil N and water dynamics and sorghum growth from the time of pasture termination until harvest of the fourth sorghum crop in June 2003. The *M. daltonii*, *V. trilobata*, and *L. purpureus* treatments were initialised using the parameters outlined in Table 1 for a soil profile of 1.2 m depth. Simulations of the grass treatment used the parameters in Table 1 but for a soil profile of 0.9 m. Only the unfertilised (0N) treatments were simulated. Daily climatic records (maximum and minimum temperatures, rainfall, solar radiation) for the duration of the experiment and for the period 1954–2004 were obtained from a weather station situated <500 m from the experimental site.

The simulation was initialised on 12 November 1999, corresponding with the time when the pastures were terminated in the field. In the *M. daltonii*, *V. trilobata*, and *L. purpureus* treatments, 4866, 2268, and 2398 kg/ha of legume residues, respectively, were added to the soil residue pool (fresh organic matter, FOM in APSIM). Dimes *et al*. 1996 found that under a *Stylosanthes hamata* cv. Hamata legume pasture, root biomass was 1829 kg/ha with a C : N of 23–25. We use this as the basis for assuming that 2000 kg of legume root residues at a C : N of 20 was added to the soil residue pool at initialisation of the model run.

In the grass treatments, 4427 kg/ha of surface residue was present (C : N 40) and added to the soil residue pool with an addition of 10 000 kg/ha of root material (C : N 50). The C : N ratios of the added residues for the grass pastures were obtained from the studies of Robertson *et al*. (1994) for *P. maximum* and root residue amount was assumed to be similar to that reported in Dimes *et al*. (1996). Soil nitrate-N and water was initialised to the measured values obtained at the first sampling (Tables 1 and 4). Soil ammonium-N was assumed to be negligible as suggested by Myers (1975).

From the point of initialisation, simulations were run continuously with no further resets. All management parameters in the model (i.e. time of sowing, sorghum variety, plant population) mimicked field management (Table 2). The model determined harvest on the basis of the simulated crop reaching physiological maturity. Weeds were not included in the model simulations and it was assumed that the low weed populations in the field during the sorghum crops did not limit growth. In the simulations, sorghum residue was managed by removing 60% of the residue at 14 days after harvest and a further 50% of the remainder at 30 days after harvest. This was to mimic the crash grazing of residues by cattle in the field. No attempt was made to simulate the effect of faecal return on soil organic matter and soil N.

Long-term simulations

To analyse the long-term effect of seasonal conditions on unfertilised sorghum production in the first season following the termination of

Table 3. Monthly rainfall (mm) received at Brian Pastures Research Station from July 1998 to June 2003 and the monthly and yearly long-term average (1963–2002)

	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Year
1998–99	22	26	119	21	107	90	35	51	49	5	30	37	592
1999–2000	84	14	33	107	118	53	78	61	27	33	27	26	661
2000–01	5	3	0	171	70	66	7	138	120	32	46	1	659
2001–02	46	1	38	33	155	52	18	164	60	5	49	70	691
2002–03	0	91	0	64	24	58	0	113	63	61	43	10	527
Average	35	29	29	61	70	105	110	94	71	37	40	29	710

a pasture, APSIM was initialised with the soil water and mineral N conditions that were measured following each of the pasture treatments. The inputs of pasture residues and root materials were also initialised as described in the previous section. Simulations were then run from 1954 to 2004 using the long-term weather data collected at the station during this period. Each year, the sorghum crop was sown between 15 November and 15 January when at least 30 mm of rain was received over 5 consecutive days. As all soil conditions were reset to the same parameters each season, the effect of climate on sorghum grain production was predicted following each pasture treatment. It was assumed that all treatments (including the grass treatment) had a soil depth of 1.2 m and therefore a PAWC of 202 mm. An additional simulation of the grass treatment was done with the soil water being reset to the DUL before sowing each year to investigate sorghum growth without the bias of lower soil water in that treatment.

Statistical analysis

The experiment was a split-plot design with pasture type (*M. daltonii*, *V. trilobata*, *L. purpureus*, or grass pasture) as main plots (replicated twice) which were split into 2 fertiliser rates (0N, 80N) during the sorghum phase. For the data generated during the seasons 1999–2000, 2000–01, and 2001–02, comparison of the 4 pasture treatments is against the residual (pasture type × replicate). The sub plots and interactions were tested against the residual term (pasture type × replicate × year × fertiliser). In the final year (2002–03), only the main plot treatments *M. daltonii* and *L. purpureus* continued, so data analysis was confined to within that year. Where there was significance, the least significant difference (l.s.d.) at $P = 0.05$ was used to test for mean separation. All data were tested for the assumption of common variance and transformed if necessary. The soil nitrate content data in Table 8 were statistically analysed after log transformation to achieve normal distribution.

To assess the goodness of fit of the sorghum yield, soil nitrate, and water simulations, the root mean square error (RMSE) between predicted and observed data was calculated as:

$$\mathrm{RMSE} = [(\Sigma(\mathrm{O} - \mathrm{P})^2/n)]^{0.5} \qquad (2)$$

where O and P are the paired observed and predicted data and n is the number of observations.

Results

Soil water content at sorghum sowing

The soil water measurements taken at pre-planting of sorghum showed no significant difference between the treatments in any of the years (Table 4). These measurements, expressed as a percentage of the PAWC, were generally >50% with the driest soil profiles being measured at the beginning of the trial soon after pasture termination. Despite no statistical difference between the treatments, the grass treatments were consistently drier than the treatments following the legume pastures in every year (range 10–57, 39–67, and 16–67 mm less soil water in years 1, 2, and 3, respectively). Since soil depth under the legume treatments was up to 0.30 m deeper than the grass treatments, PAWC was potentially up to 28 mm greater.

Table 4. Total soil water (mm) in the 0–0.9 m profile prior to the sowing of sorghum

This is shown in parentheses as a % of PAWC (PAWC = 171 mm)

	1999–2000	2000–01	2001–02	2002–03
M. daltonii	293 (42)	317 (65)	316 (56)	283 (36)
V. trilobata	246 (15)	302 (47)	278 (33)	–
L. purpureus	283 (36)	330 (64)	329 (63)	288 (40)
Grass	236 (9)	263 (25)	262 (24)	–

Sorghum production

In the first sorghum crop after the pasture phase, grain and stover growth following the *L. purpureus* treatments were significantly higher than the *M. daltonii*, *V. trilobata*, and grass treatments with no difference found between the last 3 treatments (Tables 5 and 6). In the second sorghum crop, the *L. purpureus* treatments continued to outyield all other treatments with an exceptional grain yield of 5254 kg/ha. The *V. trilobata* treatment also outyielded the grass treatment. By the third sorghum crop, grain and stover production was similar for all treatments. In 2002–03, only the *M. daltonii* and *L. purpureus* treatments continued and there were no differences in grain yield and stover measured.

No significant yield responses to the 80N fertiliser treatments were measured in any of the seasons and the data in Table 5 are therefore an average of the 0 and 80 kg/ha N treatments. This lack of response to N in the grass treatments was despite the low and obviously limiting

Table 5. Grain production (average of the 0N and 80N treatments) of the 4 sorghum crops following a grass pasture or 2 year legume leys (kg/ha)

Data for 2002–03 analysed within that year and no significant difference between the means found

	1999–2000	2000–01	2001–02	2002–03
M. daltonii	2825	3056	2825	3154
V. trilobata	2401	3727	2492	–
L. purpureus	4098	5254	2637	3165
Grass	1858	1776	3455	–
l.s.d. ($P \leq 0.05$) (pasture treatment × year)		1434		n.s.

Table 6. Stubble production (average of the 0N and 80N treatments) of the 4 sorghum crops following a grass pasture or 2 year legume leys (kg/ha)

Data for 2002–03 analysed within that year and no significant difference between the means found

	1999–2000	2000–01	2001–02	2002–03
M. daltonii	3409	6614	5755	2755
V. trilobata	3781	7560	4128	–
L. purpureus	6309	11 300	5039	2654
Grass	2619	4402	5454	–
l.s.d. ($P \leq 0.05$) (pasture treatment × year)		2311		n.s.

nitrate concentrations measured at sowing described in the following sections.

Grain protein

Although sorghum yield showed no response to N fertiliser, average grain protein was consistently higher in the 80N treatments, being significantly ($P < 0.05$) so in the second and fourth sorghum crops (Table 7). Total N uptake in the plant shoots also increased in the 80N treatments (data not shown).

Dynamics of nitrate during the sorghum phase

Pre-sowing sampling

Soil nitrate measured after the termination of the grass pasture treatment was 4 kg N/ha compared with significantly higher values of 35–86 kg N/ha of following the legume leys (Table 8). During the first 2 years of the trial, soil nitrate remained in the order *L. purpureus* > *M. daltonii* > *V. trilobata* > grass. By the third season, soil nitrate in the grass treatment had increased to a mean of 43 kg/ha, which was higher than the *V. trilobata* treatment. Despite no significant effect of fertiliser treatment, soil nitrate in the 0N fertiliser treatments of the grass plots was 15 (see Fig. 4*b*) compared with 72 kg/ha on the 80N treatments; large variation in replicates and between years made this effect non significant.

Post harvest samplings

The main effects of previous pasture type, fertiliser application, and year were found to be significant; however, there were no significant treatment interactions. Averaged over the 3 years, soil nitrate increased at harvest from 18 kg/ha in the 0N treatment to 59 kg/ha in the 80N treatments. Averaged over the pasture treatments, soil nitrate decreased with each harvest from 57 kg/ha in year 1 to 36 kg/ha in year 2 and 22 kg/ha in year 3. In the treatment continued into the fourth year, soil nitrate declined further to 19 kg/ha. Averaged over fertiliser treatments and year, post harvest soil nitrate remained lowest in the grass treatments (17 kg/ha), compared with 65, 46, and 25 kg/ha in the *M. daltonii*, *L. purpureus*, and *V. trilobata* treatments, respectively.

Following the first harvest, high concentrations of nitrate were found in the 0–0.15 m soil layers of all 80N treatments (average of 28 mg/kg in the 80N treatments compared with 7 mg/kg in the 0N treatments). This indicates that most of the surface-applied fertiliser had not been leached into the root zone and therefore was not available to the crop; this N was not detected at sowing in the following season. As mentioned in the section on sorghum production, the ineffective application of 80N did not result increased yield in the grass treatments as expected.

The calculated ICM of soil N showed no significant differences between treatments in any of the years (Table 9) The highest average ICM was measured in the second crop (mean 109 kg/ha N) and this declined to a mean of 41 kg N/ha by the fourth crop.

Table 7. Sorghum grain protein (%) in response to 0 or 80 kg/ha of N fertiliser applied to each sorghum crop

N rate (kg/ha)	1999–2000	2000–01	2001–02	2002–03
0	11.2	8.9	10.6	6.5
80	11.9	11.0	12.2	11.0
l.s.d. ($P \leq 0.05$)	n.s.	1.1	n.s.	1.5

Table 8. Soil nitrate N (kg/ha) in the 0–0.9 m profile prior to the sowing of sorghum

Data in all years are the mean of the 0 and 80N treatments that were not significantly different (analysis of variance performed on raw data transformed using a log function to achieve normal distribution). Data for 2002–03 analysed within that year and no significant difference between the means found

	1999–2000	2000–01	2001–02	2002–03
M. daltonii	63	97	99	64
V. trilobata	35	58	33	–
L. purpureus	86	98	88	56
Grass	2	12	43	–
l.s.d. ($P \leq 0.05$) (pasture treatment × year)		2		n.s.

Simulation of sorghum growth, N dynamics, and soil water using APSIM

The simulation of the grain yield, soil nitrate, and soil water for the unfertilised treatments of the sorghum phase of the experiment was undertaken from the point of pasture termination (12 Nov. 1999) until the final soil sampling (16 June 2003) for the 3 legume systems and the grass pasture system (Figs 1–4). Observed data for the 4 sorghum crops are presented along with the standard error of the mean (s.e.m.) for each data point. These data are for the individual treatments and may therefore differ from the means of treatments presented in Tables 4, 5, 8, and 9.

Grain yield

There is considerable variation in the measured mean yields of sorghum for the *M. daltonii* treatment in the second

Table 9. In-crop mineralisation (ICM) of N (kg/ha) calculated using Eqn 1 for each the unfertilised sorghum crops following 4 pasture histories

	1999–2000	2000–01	2001–02	2002–03
M. daltonii	71	104	78	33
V. trilobata	74	84	45	–
L. purpureus	127	134	33	49
Grass	37	113	83	–
Mean	77	109	60	41

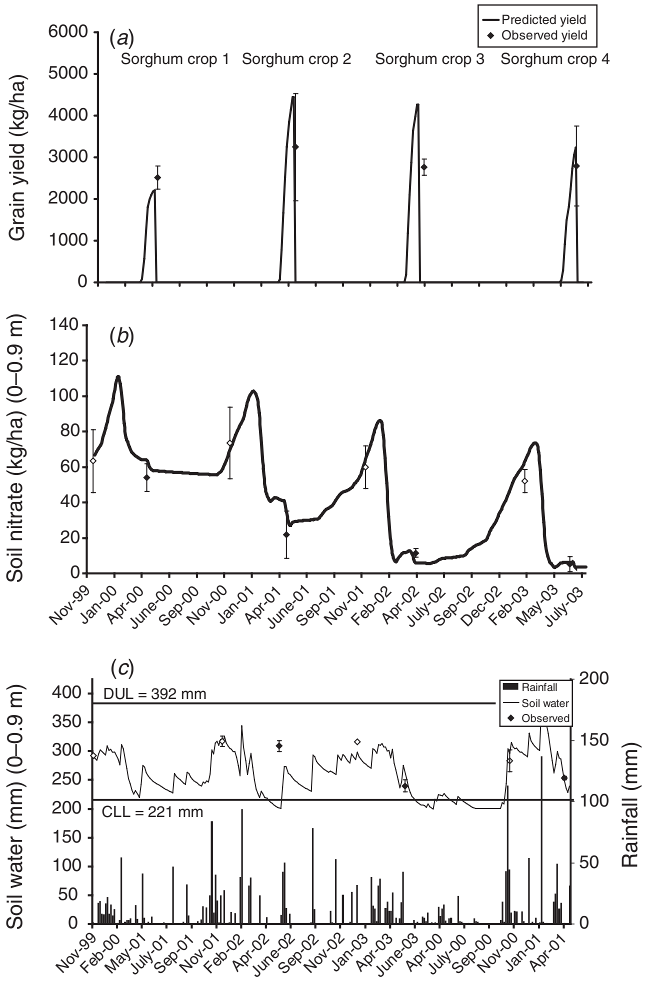

Fig. 1. (*a*) Sorghum grain yield, (*b*) soil nitrate N content (0–0.9 m), and (*c*) soil water (0–0.9 m) and cumulative rainfall (over 5 days) during a cropping phase (0N) that was preceded by 2 years of *M. daltonii* pasture.

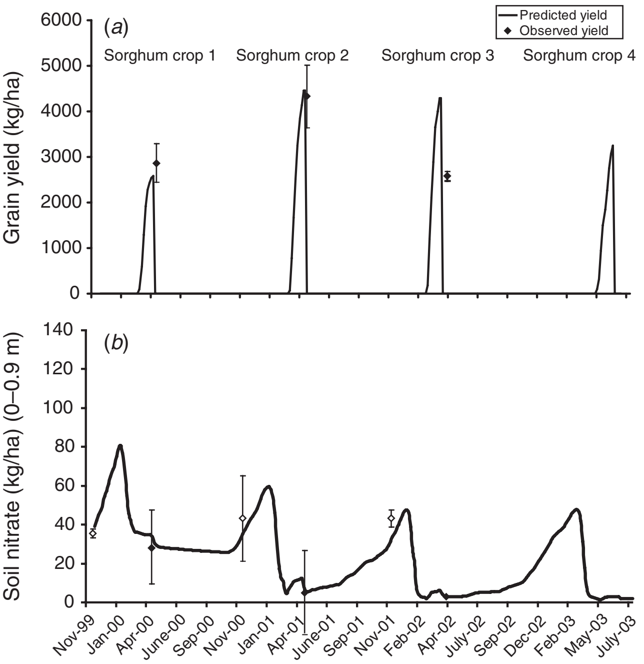

Fig. 2. (*a*) Sorghum grain yield and (*b*) soil nitrate-N content (0–0.9 m) during a cropping phase (0N) that was preceded by 2 years of *V. trilobata* pasture.

and fourth crops (Fig. 1*a*), in the *L. purpureus* treatment in the first and third crops (Fig. 3*a*), and in the grass treatment for the third crop (Fig. 4*a*). Simulated sorghum yields are overestimated in the third crop for these 3 treatments. The prediction of grain yields following the *V. trilobata* (Fig. 2*a*) was close in the 3 measured seasons. The RSME for the pooled dataset (predicted and observed yields for the 4 treatments) was 1065 kg/ha, which represents 35% of the mean. The predicted *v.* observed data together with the 1 : 1 line are plotted in Fig. 5*a*.

Simulation of the sorghum crops grown after the grass treatment shows a general increase in grain yield (in agreement with the observed data) with the increasingly available mineral N suggested by the model (not in agreement with the observed data). By the third crop, predicted grain yield exceeds the measured by >1 t/ha, which is probably due to the overestimation of soil nitrate at sowing (Fig. 4*b*).

For all crops, the simulated maturity date is generally within 7 days of the field harvest date, with the exception of the third crop where maturity was 16 days earlier than the field harvest. This discrepancy is of little importance, as the field date of harvest may be later than physiological maturity.

Soil nitrate dynamics in the legume treatments

With the exception of the year 1 harvest nitrate value following the lablab pasture (Fig. 3*b*), each of the measured values of nitrate at sowing and harvest are in close agreement with the simulated data for the 3 legume treatments (Figs 1*b*, 2*b*, and 3*b*). In the legume treatments there was a general decline in the amount of nitrate in the profile after harvest with each succeeding sorghum crop. This is in close agreement with the 0N treatments of the field data. N accumulation between crops is significant and varies between 26 and 43 kg N/ha. When crop N uptake exceeds soil N mineralisation rate, the soil nitrate content declines until such a time that crop N demand is reduced and the soil water and temperatures are adequate for soil N mineralisation.

Soil nitrate dynamics in the grass treatment

After the termination of the grass pasture, soil nitrate remains very low (<8 kg/ha N) until after the pre-sowing measurement in the second sorghum crop. The nitrate simulation in Fig. 4*b* indicates that there is some

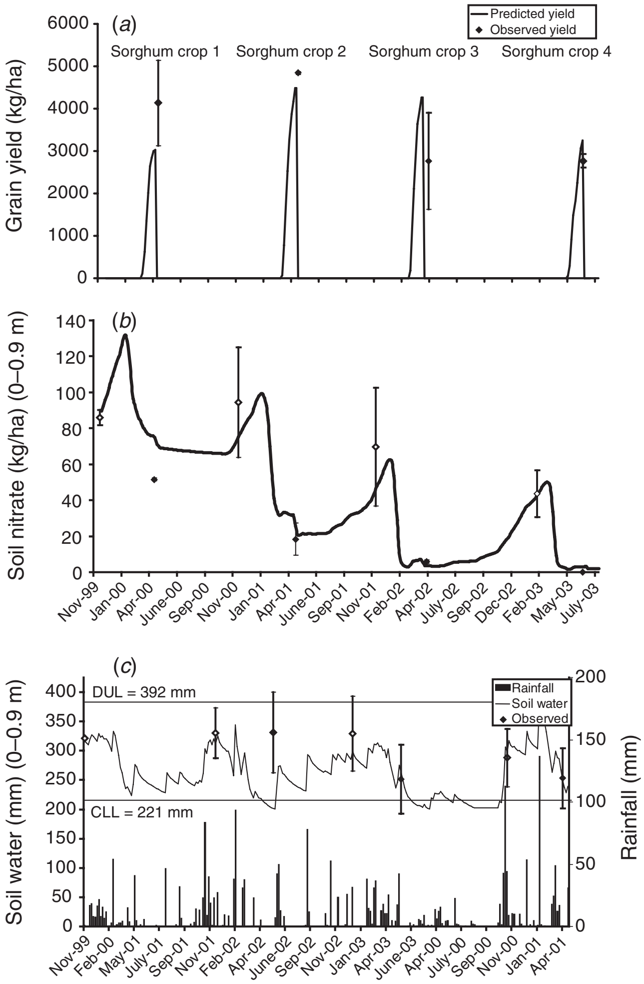

Fig. 3. (*a*) Sorghum grain yield, (*b*) soil nitrate N content (0–0.9 m), and (*c*) soil water (0–0.9 m) and cumulative rainfall (over 5 days) during a cropping phase (0N) that was preceded by 2 years of *L. purpureus* pasture.

accumulation in sorghum crops 2, 3, and 4. The simulated soil nitrate accumulation around sowing time of the third crop exceeds the measured value by almost 65 kg N/ha. This large discrepancy may be due to the model mineralising N in this treatment too rapidly—substantial N was mineralised during the crop (ICM of nitrate, 83 kg/ha, Table 9), so a small error in the rate of mineralisation may account for some of this overestimation.

Figure 5*b* shows the generally good agreement between the predicted and observed soil nitrate data; the outlining data points are from the grass treatments. The RSME of the soil nitrate dataset calculated using the predicted and observed data for the legume treatments only was 11 kg/ha of nitrate, representing 28% of the mean. The RSME increased to 14 kg/ha with the inclusion of nitrate data from the grass treatment, representing 44% of the mean (Fig. 5*b*).

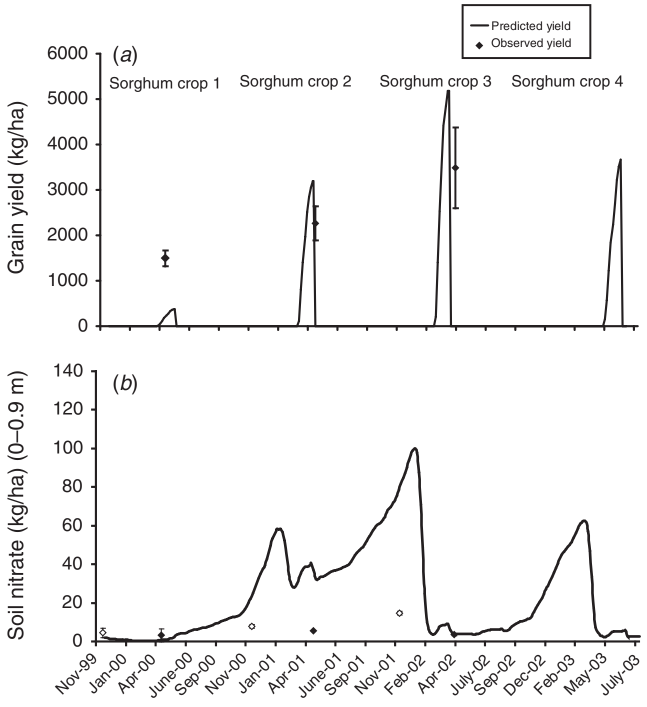

Fig. 4. (*a*) Sorghum grain yield and (*b*) soil nitrate N content (0–0.9 m) during a cropping phase (0N) that was preceded by 2 years of grass pasture. In each figure, the solid line represents the simulated value. The open points are the measured soil nitrate values prior to sorghum sowing and the closed points are the measured soil nitrate values after harvest. Vertical bars represent the s.e.m. of the measured data where bars are absent, the s.e.m. is smaller than the symbol.

Soil water

Soil water content (0–0.9 m) was also simulated for the 0N treatments from initialisation in November 1999 until July 2003. These results are displayed for the *M. daltonii* and *L. purpureus* treatments where a full set of measured field values was available (Figs 1*c* and 3*c*). The simulated soil water remains within the bounds of the DUL and CLL (indicated on the figures by lines), except after harvest where air-drying of the surface soil layers may reduce the soil water content to below CLL. Increases in the predicted total soil water correspond well with the rainfall events indicated in these figures.

The simulation of soil water resulted in generally good agreement with the measured points at sowing with most predictions within the error of the measured points. These error values were very substantial for the *L. purpureus* treatments (Fig. 3*c*). Soil water balance parameters such as runoff, evaporation, and drainage appear to be well simulated as indicated by the good correlations at sowing between observed and simulated soil water after the fallow.

At sorghum harvest, simulated water extraction was consistently overestimated relative to the observed data (Figs 1*c* and 3*c*). While the simulation only allowed water extraction to 1.2 m, PAWC below this depth was low; for example, PAWC in the 1.2–1.5 depth was 3 mm (data not shown), so it is unlikely that the sorghum plots accessed much water below 1.2 m. This discrepancy in the simulation may therefore indicate excessive water use in this version of the sorghum model. RMSE of the predicted and observed data was 36 mm, representing 12% of the mean. The predicted *v.* observed data are plotted with the 1 : 1 line in Fig. 5*c*.

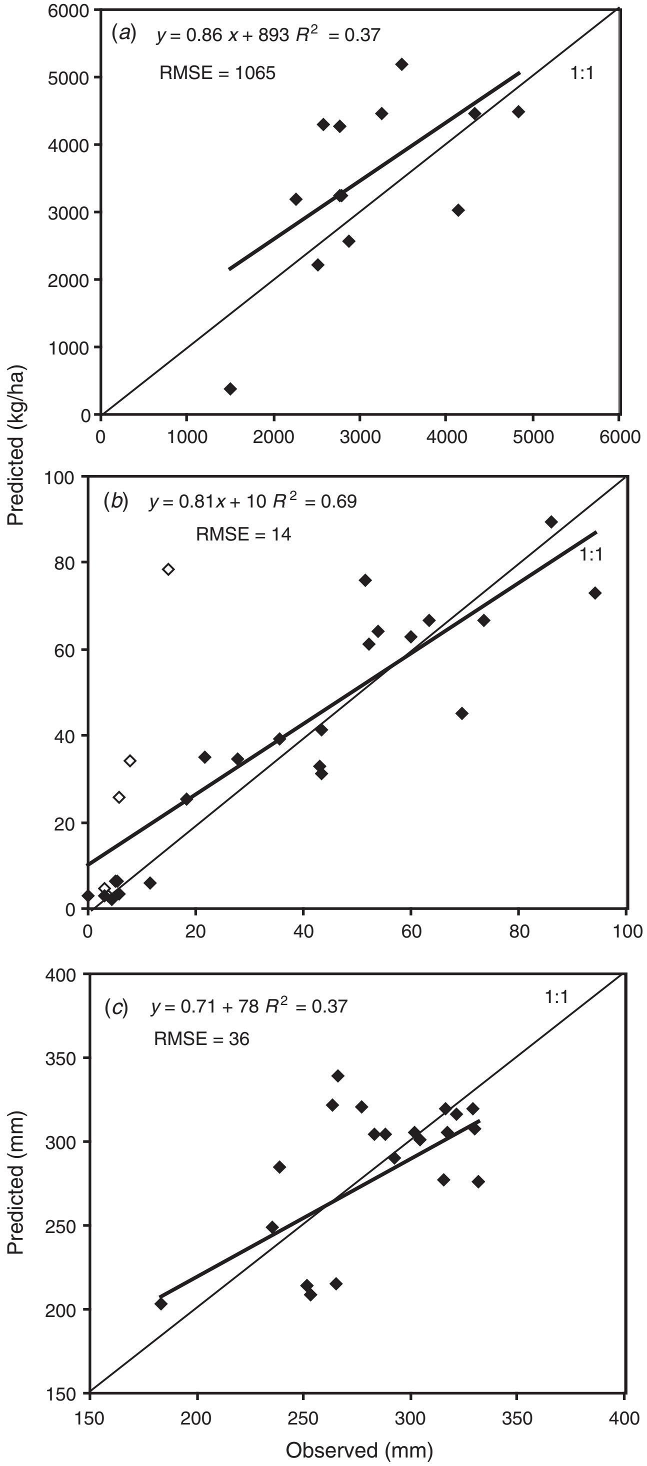

Fig. 5. Predicted *v.* observed (*a*) grain yield of sorghum, (*b*) soil nitrate (open points are the values of the grass treatments), and (*c*) soil water of the 0N treatments.

Long-term simulations

Simulation of the first sorghum crop following a legume or grass ley was conducted by resetting soil water and soil nitrate to the same values that were measured in 1999 after 2 years of the pasture treatments and allowing for the additions of plant residues and root material for each pasture system. This allowed the effect of seasonal conditions experienced in each year from 1954 to 2004 to determine the sorghum growth (Fig. 6). Following a grass pasture, grain production did not exceed 3000 kg/ha, and approximately 60% of the time, grain production was 1000–2000 kg/ha. Initialising the model with the soil nitrate and water data measured after any of the 2-year legume leys, grain production was found to range from 3000 to 4500 kg/ha in >75% of the seasons between 1954 and 2004. By simulating the grass treatment with the soil water content reset to the DUL each season, the bias of low soil water following a grass pasture was removed. The 'grass DUL' line on the cumulative distribution function does increase the average by 362 kg/ha, but grain production continues to be limited by the low starting soil N concentrations following the grass pasture.

Discussion

This paper contrasts 2 grain and graze systems; one is a legume based rotational pasture–crop system, which is highly

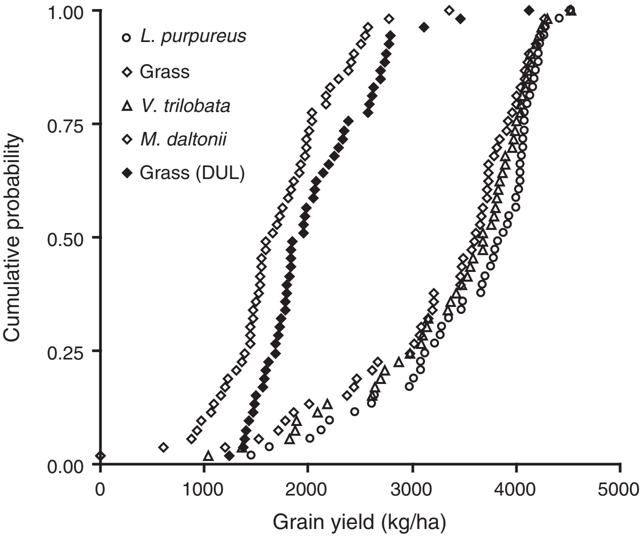

Fig. 6. Cumulative probability of sorghum grain yield (with no added fertiliser N) in the seasons from 1954 to 2003 using the soil water and nitrogen starting measured in the field after 2 seasons of *M. daltonii*, *L. purpureus*, *V. trilobata*, or a grass pasture (grass DUL).

productive in terms of both animal and crop production. This productivity is driven largely by biological N fixation resulting in legume residues of high feed value (high digestibility and protein) and, via the cycling of N in faeces and decomposing plant residues, high soil N. The other system, a perennial grass based pasture, was highly productive in terms of beef liveweight gain (Clem 2004; Whitbread and Clem 2004), but upon termination of the pasture phase, low soil mineral N limited sorghum production for 2 seasons (Table 5).

N dynamics

High levels of soil nitrate N were measured in the legume treatments within 12 days of the termination to the legume pastures (Table 8). This indicates that the rapid decomposition of the legume residues, the recycling of N through the previous seasons of legume pasture growth, and animal grazing and defecation have enabled the build-up of mineral N. Whitbread *et al.* (2005) also found that soil nitrate levels increased following the termination of grazed tropical legumes such as *L. purpureus* cv. Endurance and *Macroptilium bracteatum* (burgundy bean) to 101 and 59 kg/ha (0–1.5 m), respectively, compared with only 46 kg/ha under a continuous wheat system. The studies by Armstrong *et al.* (1999*b*) on Vertosol soils in Central Queensland showed that 1–3 seasons of legumes (mungbean, siratro, lucerne, lablab, and desmanthus) progressively increased soil nitrate levels to 47–82 kg/ha compared with <25 kg/ha in a continuous sorghum system.

In contrast to the legume systems, soil nitrate N remained very low in the first 2 seasons following termination of the grass system, and only in the third year did soil nitrate N reach concentrations comparable to the legume systems (Table 8). During the grass pasture, there were no N inputs and N in the system would be recycled largely through grazing and faecal return and residue turnover. N deficiency in grassland pastures has been well documented in the Brigalow landscapes of Central Queensland by Robertson *et al.* (1993*a*, 1992*b*, 1994). Robertson *et al.* (1993*a*) found that up to 20 t/ha of surface litter and root residues of high C : N ratio (40–50) accumulated under these pastures. Using incubation techniques, they found that pasture soil respired more CO_2 and mineralised less N than cultivated soils. Since the C : N ratio of pasture residues is high (>40), immobilisation of mineral N occurs.

In the unfertilised treatments that followed the grass pasture, soil nitrate-N content measured at pre-sowing remained low (Fig. 4*b*). ICM of N in 2000–01 and 2001–02 was, however, comparable to the legume treatments (Table 9) and does indicate that N is becoming available over time. Substantial mineralisation could be expected from the high soil C concentrations measured in the grass treatments (Table 1).

Sorghum grain production

In the system described in this study, sorghum was established using a no-till planter. This results in minimal soil disturbance and slower decomposition of the surface and buried plant residues than under conventional tillage. While Blair and Crocker (2000) recommended that no-till practices combined with the residue returns from primary and rotational crops could potentially increase soil C concentration and soil structural stability, a no-till system could exacerbate N deficiency in a system where grass pasture is converted to crop production.

High-yielding sorghum crops were grown after all legume pastures over the 4 seasons (Table 5). The exceptional grain yield of 5254 kg/ha achieved in the *L. purpureus* treatment in the second sorghum crop corresponded with high starting soil nitrogen (98 kg/ha N) a 65% full profile of water and good in-crop rainfall (222 mm). Using APSIM to simulate the soil–plant system, the effect of water and N stress on leaf expansion and phenology can be derived. Interestingly for this high-yielding *L. purpureus* crop, there was no stress at any stage during crop growth, indicating that water or N did not limit crop growth.

Utilising the APSIM-derived stress indices (Carberry and Abrecht 1991) to help interpret the measured data, N stress was found not to limit the yield of the unfertilised or fertilised legume crops at any stage of growth during the 4 sorghum crops. In contrast, water stress generally occurred during flowering and grainfill, indicating that water was limiting crop growth. This is further supported by the measured data showing the soil water content to be at CLL near harvest in each season.

In the grass treatments, low soil N content at sowing of the first crop did severely limit crop growth. As explained previously in the *Results*, the application of 80N did not ameliorate this N deficiency due to the unavailability of fertiliser N to the crop in year 1. This effect was certainly exacerbated by not applying N fertiliser in a band next to the seed. Low rainfall for the period following the second application of N on 3 March 2000 (a dry period of 16 days and thereafter 2 small rainfall events of <4 mm) also reduced the effectiveness of the fertiliser. Despite the continued low pre-sowing N content measurements on the unfertilised treatments, substantial in-crop mineralisation of N in years 2 and 3 (Table 9) and water limitation as suggested by APSIM help to account for this lack of response to N fertiliser.

Despite no yield responses to N fertiliser, grain protein was maintained at a much higher concentration in the treatments that received 80 kg/ha of fertiliser N. Grain protein in the fourth sorghum crop without additional N fertiliser was low at 6.7%. Currently, the market does not differentiate pricing on the basis of protein concentration so there is no economic advantage for producing sorghum grain of higher protein concentration. In central Queensland, low grain protein (as low as 4.4%) found in sorghum crop surveys reported by

Garside *et al*. (1992) were related to declining soil fertility levels and age of cultivation.

Residual effects of the ley pastures

In the legume systems, soil nitrate-N was shown to decline with successive sorghum crops (Figs 1*b*, 2*b*, 3*b*), indicating crop growth and removal of N was depleting the initially high soil nitrate N levels. ICM in the *M. daltoni* and *L. purpureus* treatments declined from peaks in 1999–2000 of 71 and 127 kg/ha of N, to lows of 33 and 49 kg/ha in 2002–03, respectively (Table 9). Despite these declines, there was no response in yield to additional N fertiliser (80N) and the experiment did not continue for long enough to measure this effect. Responses to N in 2002–03 may have also been masked by low soil water content at sowing (Table 4).

The effect of legume-based pasture leys on subsequent crop production in the northern grains belt of eastern Australia has been well documented in the literature. At Tamworth, Holford (1992) reported beneficial effects on wheat lasting for up to 9 years following a lucerne phase of 2.5–5.5 years on a Calcic Vertosol. In central Queensland on a Black Vertosol, Armstrong *et al*. (1999*a*) investigated the effect of 1-year tropical legume leys on subsequent sorghum production and found the effects to persist up to 3 crops. On much less fertile Alfisol soils in northern NSW, Whitbread *et al*. (2003) studied the effects of 1-season legume or fallow periods on subsequent wheat yields. They found the effects to be restricted to 1 subsequent wheat crop and explained this by the highly transient flushes of labile carbon measured after the legume phase. In the literature cited above, the beneficial effects of the legume leys have been strongly related to increases in N availability and soil organic matter. Soil water and seasonal conditions have also determined the response of cereal phase to the increased N availability. While other beneficial soil effects such as improvements in aggregate stability and hydraulic conductivity have been reported (Blair and Crocker 2000), soil structural stability of the inherently structurally stable clay soils of the northern grains belt is likely to be dominated by the management of crop residues and cover.

Simulation of the crop phase

For a cropping systems model to be useful for crop rotation studies in the semi-arid tropics, it is important that it can accurately simulate the main drivers of plant growth, namely the soil water balance, the soil N supply, and changes in soil organic matter, over a timeframe of several years. Importantly, this should be achievable without the need to reset soil parameters to measured values of soil water and soil nitrate-N during the simulation runs. To date, the APSIM modelling framework has been the only systems model capable of capturing these carry-over processes between successions of crops and rotations. In most situations tested in this paper, APSIM generated good estimates of grain production (Fig. 5*a*) and soil water (Fig. 5*b*), and an accurate simulation of nitrate N dynamics. The simulation of soil nitrate improved substantially when the grass treatments were removed from the comparison (RSME decreased from 14 to 11 kg/ha), which may suggest that the soil organic matter and decomposition dynamics were not simulated well under this situation of prolonged immobilisation of mineral N by large quantities of low quality grass residues.

Probert and McCown (2000) showed APSIM to be capable of simulating crop yields and N and water dynamics of dryland rotational cropping systems in southern Queensland over several seasons. The goodness of fit between measured and observed data was similar for a continuous wheat system that was modelled as either a single run from 1987 to 1996 or as a reinitialised run from measured pre-sowing water and N data. Foale *et al*. (2004) monitored soil water and N dynamics over 2–3 years on several on-farm fields. While there was often large variation in the measured on-farm datasets, there was generally good agreement with the long-term simulations that were developed for each of the sites.

To date, APSIM has been used to simulate the effect of preceding legume leys on subsequent crop production using 2 different approaches. In the first approach, Jones *et al*. (1996) used the model to simulate the entire rotation (1978–83) by simulating the legume pasture phase, its effects on soil organic matter, and the subsequent crop production. In the second method, which is the method used in this paper, Turpin *et al*. (1996) estimated the changes that a lucerne ley had on the soil organic matter pools and modelled crop production only during the subsequent 8 wheat crops. Both of these methods resulted in the authors concluding that the model was capable of accurately simulating crop response to N inputs following a legume ley. There have, however, been limited attempts to test whether the modelled legume phase changed the soil organic matter status of the soil accurately and if this can be measured and validated in the field. If simulating a grazed ley phase, the effects on soil organic matter and water are complicated by the impacts of grazing on plant production, plant litter, and manure returns and N losses from the system (Turpin *et al.* 1998).

Although the field trial described in this paper was able to measure the response of sorghum to various phases of legume pasture in 4 seasons, the long-term simulation was able to extend this to the many different climatic conditions experienced between 1954 and 2001. In all but the worst seasons, grain production following a legume ley was high and far exceeded grain produced following the grass pasture.

Conclusions

The potential for highly productive grain systems sustained by phases of productive legume pastures and beef production have been demonstrated through this paper and the study of Clem (2004). With widespread evidence that soil fertility is declining in this region (Dalal and Mayer 1986), and the availability of well-adapted forage legumes, it is timely that agriculturalists in the northern grains belt re-examine the potential of grain–graze systems. This paper demonstrated that APSIM is well suited to examining crop rotation systems in the semi-arid tropics. APSIM simulated the main drivers of plant growth, namely the soil water balance, the soil N supply and changes in soil organic matter, over a timeframe of several years without resetting the model. APSIM showed that sorghum production following a grass pasture was risky and unlikely to exceed 2000 kg/ha of grain in 60% of seasons. Whether the effect of N immobilisation after a grass pasture could be overcome with effective N fertiliser applications should be further investigated. Sorghum production following 2-year legume leys could be expected to exceed 3000 kg/ha of grain produced in 80% of seasons.

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